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Interregional flows of ecosystem services: Concepts, typology and four cases

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ABSTRACT

Conserving and managing global natural capital requires an understanding of the complexity of flows of ecosystem services across geographic boundaries. Failing to understand and to incorporate these flows into national and international ecosystem assessments leads to incomplete and potentially skewed conclusions, impairing society's ability to identify sustainable management and policy choices. In this paper, we synthesise existing knowledge and develop a conceptual framework for analysing interregional ecosystem service flows. We synthesise the types of such flows, the characteristics of sending and receiving socio-ecological systems, and the impacts of ecosystem service flows on interregional sustainability. Using four cases (trade of certified coffee, migration of northern pintails, flood protection in the Danube watershed, and information on giant pandas), we test the conceptual framework and show how an enhanced understanding of interregional telecouplings in socio-ecological systems can inform ecosystem service-based decision making and governance with respect to sustainability goals.

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1. Introduction

Our increasingly globalized world is characterised by the distant interchange of people, goods, information, and ecosystem services (ES, contributions of ecosystems to human wellbeing). Interregional ES flows are a direct result of the physical links, policies, trade, and resource management decisions in one geographical region that can have significant impacts on ecosystems and biodiversity elsewhere (Kissinger et al., 2011; Koellner, 2011; Liu et al., 2015; Moser and Hart, 2015; Seto et al., 2012). Sustainability challenges are associated with interregional flows, such as the distribution of benefits derived from nature, globally associated costs and interregional dependencies, and broader considerations of equity and responsibilities for sustained ES management.

To date, different aspects of interregional connections have been addressed in largely isolated scientific disciplines. For instance, land system science is studying telecoupling, the complex interrelations between distant coupled socio-ecological systems (Friis et al., 2015; Liu et al., 2013) and displacement of land use (Bruckner et al., 2015; Lambin and Meyfroidt, 2011) or indirect land-use change (iLUC, Lapola et al., 2010). In ecological economics, a discourse on interregional sustainability (Kissinger and Rees, 2010; Kissinger et al., 2011) focuses on accounting for biophysical flows of natural resources, using ecological footprints (Weinzettel et al., 2014) or the human appropriation of net primary production framework (Erb et al., 2009; Haberl et al., 2009). Further, political ecology is addressing societal effects of change in land tenure (termed 'land grabbing') (Rulli et al., 2013). In the policy arena, national and international biodiversity strategies are calling for ecosystem assessments (European Commission, 2011; UNEP, 2010). However, most ecosystem assessments have ignored or underappreciated interregional ES flows (Pascual et al., 2017; Schröter et al., 2016). Considerable progress has been made to prioritize and structure ES research or policy action, and to support communication about ES among disciplines and sectors (Potschin-Young et al., 2017). Ever since the Millennium Ecosystem Assessment (MA, 2005), conceptual frameworks for ES have acknowledged the distinction between ecosystems and social systems, and the need for a connection between these subsystems to attain actual benefits of ES. The ES cascade (de Groot et al., 2010) frames the service itself as this connection and Villamagna et al. (2013) explicitly mention flows from ecosystems to beneficiaries. Several studies have acknowledged different scales in ecosystem service research (Costanza, 2008), and others have quantified or conceptualized flows from providing to benefitting areas (Bagstad et al., 2013; Serna-Chavez et al., 2014). Yet linkages between providing and benefiting areas have mainly been studied at smaller scales (e.g., García-Nieto et al., 2013; Kroll et al., 2012) and there is little knowledge on the magnitude, drivers and effects of interregional ES flows, in particular for regulating and cultural ES, with a few notable exceptions. For instance, López-Hoffman et al. (2010) described provisioning, regulating and cultural ES flows between Mexico and the U.S., and Liu et al. (2016) analysed the telecoupling of water-related ES across China. The UK national ecosystem assessment analysed biomass trade with other world regions and estimated the land requirements in exporting countries (UK NEA, 2011), while Yu et al. (2013) provided virtual land flow analyses for traded crops and timber indicating flows of provisioning services.

Our objective is to synthesise knowledge from various fields to better understand, analyse and support governance of complex interregional ES flows towards interregional sustainability. We develop a framework of interregional ES flows and a typology of four general flow types to guide future ES assessments by building on the concepts of telecoupling (Liu et al., 2013; Liu et al., 2015), also referred to as societal teleconnections (Moser and Hart, 2015) and interregional sustainability (Kissinger and Rees, 2010; Kissinger et al., 2011). We illustrate our framework with four case studies on (a) trade of a provisioning service, coffee, produced under certified schemes in Colombia; (b) flow of cultural and food provision services through migration of the northern pintail duck (*Anas acuta*) between Canada and the U.S.; (c) regulating services through flood protection along the Danube River; and (d) cultural services derived from information flows of the existence of the giant panda (*Ailuropoda melanoleuca*) (Box 1). We then address the linkages between interregional ES flows and sustainability. We conclude with the identification of key knowledge gaps that would enable improved consideration of interregional ES flows in science and policy.

Box 1 Introduction to the case studies. *(a) Biophysical flow of traded goods: Certified coffee from Colombia as provisioning service*

Coffee production, a provisioning service, has been dominated by intensively managed, monoculture, sun coffee plantations, associated with significant environmental implications (Jha et al., 2014). Concerns over the environmental and social impacts of dominant coffee production systems have triggered a shift in consumer preferences in importing countries that has strengthened the market for certified coffee (Manning et al., 2012). Today, Colombia is one of the world's largest coffee producers. During the last decade, over 80% of the coffee produced in Colombia was exported (FAO, 2017). By 2010, more than 25% of farmers and over 30% of Colombian coffee were part of certification schemes (Rueda and Lambin, 2013). Within certification schemes, farmers are offered financial and technical support through donor agencies, research centres, non-governmental organisations and local cooperatives as well as the Colombian government and the Colombian Coffee Growers Federation (Hughell and Newsom, 2013; Rueda and Lambin, 2013).

Photo: Juan Arias

(b) Biophysical flow through species migration and dispersal: Provisioning and cultural services provided by northern pintails migrating between Canada and the U.S.

Northern pintails (*Anas acuta*) are medium-sized dabbling ducks that feed on plants and invertebrates in agricultural and wetland habitats. Due to their beautiful plumage and elongated tail feathers, pintails provide cultural ES through opportunities for bird watching and recreational sport hunting (Austin and Miller, 1995; Mattsson et al., 2012) as well as provisioning services as a food source for Arctic indigenous groups (Goldstein et al., 2014). Pintails migrate in spring from their wintering regions at the coast of California and the

Gulf Coast areas of Texas and Louisiana in the U.S. to their summer breeding sites in the Prairie Pothole region (northern Great Plains), Alaska, and Canada (Mattsson et al., 2012). In fall, they return to wintering sites and the cycle repeats. The distribution of suitable northern pintail habitat in the landscape is determined by the availability of foraging areas.

Photo: USFWS

(c) Passive biophysical flow: Flood protection as regulating service along the Danube River

The Danube River Basin is the second largest river basin in Europe, and the most international worldwide, connecting 19 countries along its course. The occurrence of flood events, triggered by upstream precipitation and exacerbated by effects of manmade alteration of river morphology and land use, has had dramatic impacts on the countries located along the basin, exposing their social, cultural, and economic capital to increased risks (Petrow and Merz, 2009). In response, upstream and downstream countries in the Danube watershed have adopted the Danube Flood Risk Management Plan (DFRM) that facilitates transboundary flood risk management collaboration (under the International Commission for the Protection of the Danube River, ICPDR). Additionally, the European Union's Water Framework and Flood Directive fosters cooperation, prescribing a river basin approach to European countries to protect and enhance aquatic ecosystems.

Photo: Michael Clarke

(d) Information flow: Cultural services provided by giant pandas

Giant pandas (*Ailuropoda melanoleuca*) are a globally known iconic species, a national treasure of China, and beloved by people around the world. The current distribution of wild pandas is limited to three provinces in China, and the Chinese government has established 67 nature reserves to conserve the panda. As one of the largest and first reserves, Wolong Nature Reserve is increasingly well-known nationally and internationally due to news outlets such as The New York Times and BBC, publication of books and articles, and visitors from around the world. For example, there were a total of 806 articles containing the term ''Wolong Nature Reserve" in the international news media in English between 1980 and 2012 (Liu et al., 2015). Information flows from Wolong and their pandas have also generated many feedbacks, such as attracting financing for panda conservation projects, e.g., by the World Wildlife Fund (WWF), or donations for disaster relief after the 2008 Wenchuan earthquake that affected Wolong people and panda habitat.

Photo: Kurt Stepnitz, Michigan State University.

2. Conceptual framework

ES flows are spatial movements of ecosystem-derived material, energy and information between a sending and a receiving socio-ecological system (see Table 1 for definitions). Here, we focus on ES flows between socio-ecological systems from different regions. Our framework encompasses three types of socio-ecological systems (receiving, sending and external systems, the latter also referred to as ''spillover systems" (Liu et al., 2013)), the ES flows between these systems, and their facilitation through interregional coproduction flows (Fig. 1). Each system has drivers and impacts of sending and receiving an ES. Flows of ES can also contain coproduction factors (anthropogenic inputs being used to produce an ES) and embedded ES. In the following sections, we synthesise the current understanding of the components of the framework.

2.1. Interregional ecosystem service flows

ES flow from where they are produced to where they are actually received by beneficiaries (Villamagna et al., 2013). ES flow within a system, between sending and receiving systems in close vicinity (e.g., the line of sight when aesthetically enjoying a landscape), or interregionally from sending systems at long distances to receiving systems (see Supplementary Material). Our conceptual framework is focused on the latter type of flow, although by principle it could be applied at any scale. Interregional flows are defined as flows between countries, or large (world) regions. We define a typology of interregional ES flows (Fig. 2).

Biophysical *flows of traded goods*, derived from provisioning services in one region, are distributed via trade on global markets (Kastner et al., 2011). Examples are movements of food (see Box 1), fibre, biomass for energy use, medicinal, ornamental, and genetic resources. For this flow type, a carrier actively (intentionally)

Table 1
Definitions.

ES sending system	The region of origin of ES that flow interregionally
ES receiving system	The region where final ES benefits are enjoyed, by the actual use, consumption or environmental risk reduction provided by the interregional ES flow
External system (spillover system)	A system other than sending and receiving systems that is affected by or which affects flows
Interregional ES flows	Flows of material, energy and information between a sending and a receiving system. There are no hard-and-fast thresholds for defining interregional flows. Such flows occur over large distances between landscapes, regions, countries and world regions. Regions can be defined based on political or biogeographic boundaries
Coproduction	Comprises all forms of human interaction with the natural world (i.e., institutions, social norms and networks, infrastructure) that enable ES provision by means of different forms of capital (e.g., physical resources, labour or technology and knowledge)
Interregional coproduction	Comprises all forms of human input to provision of an ES across regions
Embedded ES	All ES that directly underlie the production of an interregionally flowing ES in the sending system (e.g., pollination for coffee production). This notion includes supporting services but also final services that are directly contributing to other ES
Drivers	Include socio-cultural, economic and environmental factors within a system that trigger changes in interregional ES flows
Impacts	Positive or negative consequences of interregional ES flows on sending and receiving systems

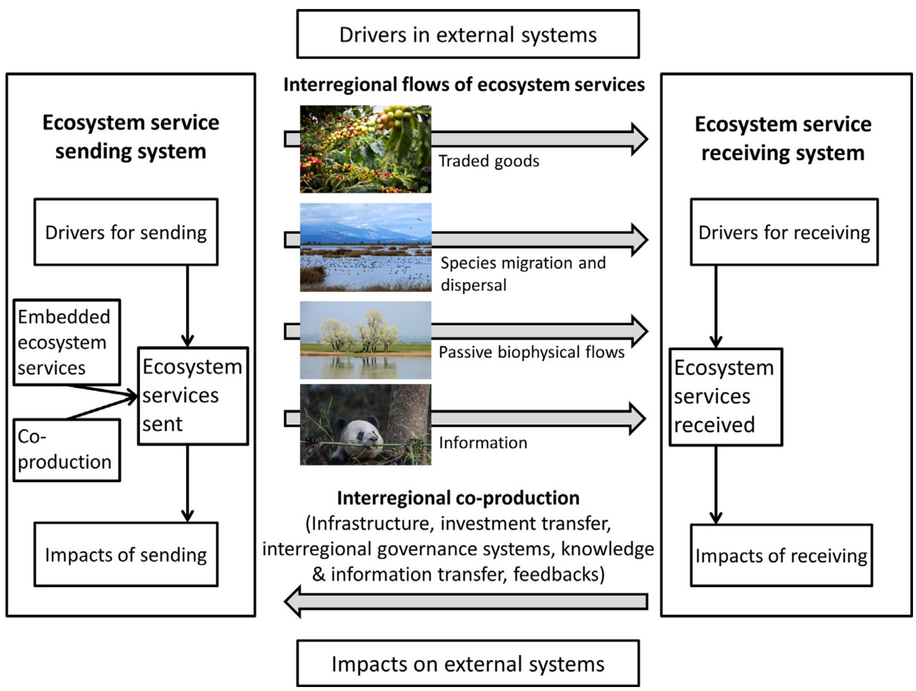

Fig. 1. Conceptual framework for interregional flows of ecosystem services between an ecosystem service sending and receiving system.

transports an ES from A to B using manmade capital such as infrastructure or technology. These carriers include humans, roads and railroads, shipping routes, aviation routes, and other commercial networks (Bagstad et al., 2013).

Flows mediated by species through migration and dispersal comprise various services. Mobile ES providers link sending and receiving systems (López-Hoffman et al., 2017; Semmens et al., 2011). Some take part in regulating processes, others are enjoyed by people (see Box 1), or are harvested. Examples are fish harvested as they migrate (Semmens et al., 2011), pollination, pest control, and seed dispersal through bats (López-Hoffman et al., 2010; Semmens et al., 2011) or pollination through hummingbirds (Semmens et al., 2011), and aesthetic enjoyment of the monarch butterfly (*Danaus plexippus*) (López-Hoffman et al., 2010), Kirtland's warbler (*Setophaga kirtlandii*), and leatherback sea turtles (*Dermochelys coriacea*) (Hulina et al., 2017). For this flow type, a carrier moves between two systems using its own energy.

Passive biophysical flows occur through biotic and abiotic processes such as river, oceanic and atmospheric currents. This type includes both the provision of beneficial flows and the prevention of detrimental flows (Bagstad et al., 2013). The relative provision of the flow to human wellbeing is determined by the sending system that regulates energy and matter potentially causing harm in the receiving system. An example is provision of clean freshwater downstream. The prevention of detrimental flows may benefit distant receiving systems through, e.g., reduced flood risk, prevented erosion and hazards, increased carbon storage, or the retention of water (see Box 1). Passive biophysical flows are mediated by the biotic components of ecosystems without active human interference. The magnitude of a flow of matter and energy is changed as a result of an ES delivered in the sending system, which can act as a sink, a source, or a transformer of matter or energy (Bagstad et al., 2013).

Information flows entail information transport from a sending to a receiving system where this information is received by a beneficiary through cognition. They comprise flows of immaterial ES typically related to knowledge, artistic, or spiritual benefits, e.g., the benefits of knowing about the existence of certain species, of gaining artistic inspiration, or spiritual wellbeing from distant natural characteristics, such as certain species (Box 1) or landscapes. For

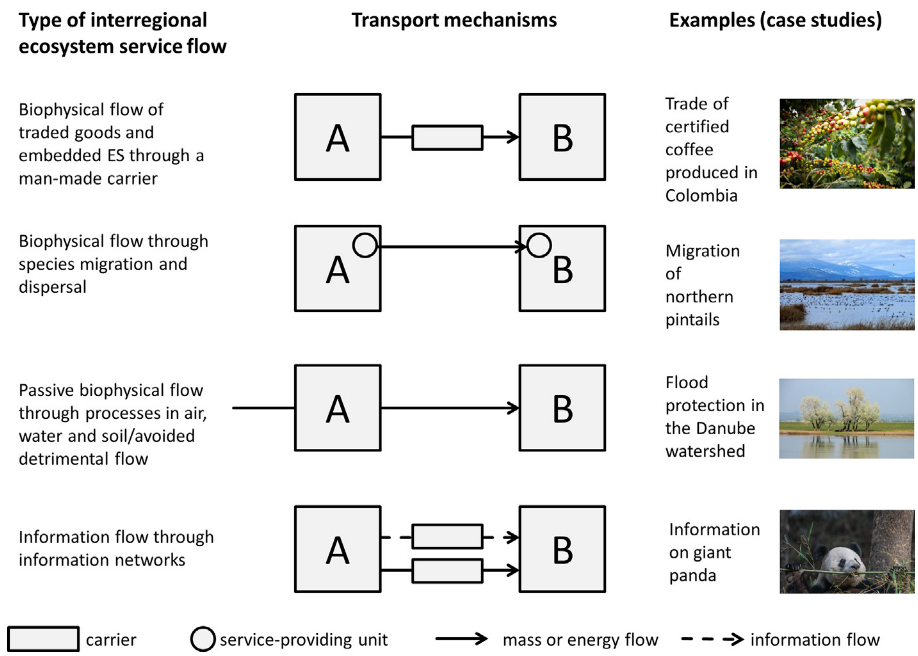

Fig. 2. Conceptual diagram illustrating four types of interregional ecosystem service flows and transport mechanisms. A represents the sending system, B the receiving system.

this flow type, a carrier actively transports an ES from A to B using manmade capital, such as communication channels, including different media (newspaper, magazines, TV documentaries, internet, social media, and books).

2.2. Telecoupled systems

The ES sending system is the origin of interregional ES flows. This is in line with the concept of 'provisioning areas' (Serna-Chavez et al., 2014). The sending system is defined as "origins, sources, or donors" from which "flows of material, energy, or information move outward" (Liu et al., 2013, p.4). Defining the spatial extent of the system depends on the ES considered and the origin and flow of the embedded ES (Hamann et al., 2015; Martín-López et al., 2017). System boundaries might be drawn where ties within a system that contribute to the existence of an ES are stronger than ties to elements outside the system. Governance systems might define systems, e.g., by administrative boundaries, but service-providing regions can also be transboundary (e.g., watersheds of large rivers). Examples for sending systems are breeding sites of pintails in the Arctic and Prairie Pothole regions of the U.S. and Canada, systems surrounding and including the coffee plantations in Colombia (one or all), upstream floodplains and ecosystems in the Danube River watershed, and panda habitat in the Wolong Nature Reserve.

The ES receiving system is defined as the area where final ES benefits are enjoyed, by the actual use, consumption or risk reduction provided by the interregional ES flow. This term is in line with 'benefiting areas' (Serna-Chavez et al., 2014). Receiving systems are "destinations or recipients" that receive flows of material, energy or information from sending systems (Liu et al., 2013). ES receiving systems can be spatially delineated by the characteristics of ES benefit capture. For example, climate regulation benefits flow globally, so the receiving systems are distributed globally. Flood regulation, on the other hand, depends on the location of the risk-exposed population (the receiving system) in relation to upstream floodplains. Examples of receiving systems are the systems around sites where pintails are valued for recreational or subsistence use, coffee-consuming countries that import Colombian coffee (Rueda and Lambin, 2013), downstream land in flood-prone areas of the Danube watershed that benefits from upstream flood protection. For the panda case, receiving systems include places where media (articles, books, news, television, and radio programs) about the Wolong reserve are published.

External systems are systems other than sending and receiving systems that are affected by or which affect flows (Liu et al., 2016). These could be areas with mediators for trade, areas affected by indirect land use change due to ES provisioning decisions, or areas that mitigate the flow of a detrimental matter or energy carrier between sending and receiving systems (i.e., floodplains located between upstream areas and downstream beneficiaries in the Danube or other watersheds).

2.3. Interregional coproduction

ES are coproduced within socio-ecological systems by the combination of different natural, human, social, manufactured, and financial capital (Díaz et al., 2015; Palomo et al., 2016). Human capital comprises people's knowledge and education; social capital includes formal and informal networks, rules and norms; manufactured capital comprises tools, machines, infrastructure or buildings; and financial capital includes investments and payments. Interregional coproduction of ES involves interregional capital flows that can include infrastructure, investment transfers, interregional governance systems, or knowledge transfers through information networks. Table 2 illustrates how interregional transfer of different capitals can contribute to the production of interregional ES flows.

Depending on the context, interregional capital flows are sometimes necessary to facilitate a particular ES, e.g. through manmade carriers (Fig. 2). These capital flows can comprise feedbacks from the receiving system back to the sending system in return for ES flows. This includes financial flows across regions, e.g., donations raised for certain species or payments for ES such as for flood regulation.

Table 2
Interregional coproduction types for the four types of interregional ecosystem service flows.

Type of interregional ES flow	Interregional coproduction: Coproduction type/capital type (Palomo et al., 2016)	Interregional coproduction: Explanation/case study example
Physical flows of traded goods (case: certified coffee from Colombia)	Investment transfer/Financial capital	Financial capital from other countries to Colombia
	Interregional governance system/ Social capital	International trade agreements Certification and fair trade schemes
	Information networks/Human capital	Social media and internet foster the promotion of organic and fair trade coffee
	Infrastructure/Manufactured capital	Transport of coffee
Biophysical flows through species migration and dispersal (case: northern pintail)	Investment transfer/Financial capital	Revenues from duck stamps (hunting license fees in U.S.) fund wetland conservation and restoration in other countries
	Interregional governance system/ Social capital	Embedded in a conservation scheme between U.S. and Canada
	Knowledge transfer/Human capital	Wildlife biologists and agencies from both countries working together
Passive biophysical flows through processes in air, water and soil/prevention of detrimental flows (case: flood protection in Danube watershed)	Investment transfer/Financial capital	Economic incentives foster transboundary cooperation
	Interregional governance system/ Social capital	The International Commission for the Protection of the Danube River (ICPDR) addresses transboundary problems and structures common activities including ecosystem restoration and flood mitigation measures
	Knowledge transfer/Human capital	ICPDR coordinates projects that respond to various environmental threats in the Danube basin
	Infrastructure/Manufactured capital	Infrastructure to make room for the river, monitoring network
Information flows (case: giant panda)	Investment transfer/Financial capital	The Chinese government and international organizations have provided substantial financial and technical support for panda conservation
	Interregional governance/Social capital	The International Union for Conservation of Nature (IUCN) listed and delisted giant pandas as an endangered species
	Knowledge transfer/Human capital	Experts in China and other countries collaborate in panda research and disseminate their findings
	Information transfer/Human capital or social capital	Social media and internet foster the appreciation and knowledge of giant panda

The coffee certification scheme is a form of interregional capital flow that regulates the flow of certified coffee to consumers (Hughell and Newsom, 2013). It involves additional costs in the certification process (e.g., auditing, training, and investment costs) and higher coffee prices (Rueda and Lambin, 2013). Revenues from the sale of Migratory Bird Hunting and Conservation Stamps for the northern pintails (i.e., "duck stamps") in the U.S. finance wetland conservation and restoration in both the U.S. and Canada. Furthermore, hunting license fees paid in the U.S. enable waterfowl habitat conservation in Canada**.** This financial setup is embedded in a formal conservation arrangement established between the U.S. and Canada (i.e., social capital). All countries located along the flow route of the Danube River depend on sound upstream land use and flood management, an example of an interregional governance system (social capital). To protect both up- and downstream communities from flooding, measures are taken through spatial planning, such as by building natural water retention areas or afforesting and revegetating areas prone to erosion. An example for human capital flows is news media coverage on pandas in the Wolong reserve.

2.4. Embedded ecosystem services and coproduction

Many ES that flow from the sending to the receiving system depend on the provision of multiple ES. ES that directly underlie or are bundled with the production of an interregionally flowing ES are called here "embedded ES." Pollination, for example, plays an essential role for many internationally traded agricultural products (Klein et al., 2007). Making the contributions of embedded services visible can be beneficial for ecosystem management. Most ES are ultimately sustained by complex networks of interdependent ecosystem processes, and setting system boundaries for determining what portion of these constitute embedded ES will be challenging.

Fig. 3 illustrates embedded ES for two hypothetical coffee production systems—intensive and environmentally friendly production. Intensive sun coffee cultivation can produce high yields with high levels of external inputs, but also substantial environmental impacts, such as habitat loss, reduced soil nutrients and reduced erosion regulation. Likewise, embedded ES are low, as sun coffee farms provide less biodiversity to support pollination and pest control, and show greater risk of erosion and downstream water pollution. Production in shade coffee systems typically has reduced environmental impacts through reduced erosion and nutrient runoff, and greater biodiversity (Jha et al., 2014; Rueda and Lambin, 2013). Shade coffee production benefits from greater amounts of embedded ES provided through nutrient cycling or erosion prevention (i.e., greater soil protection and reduced need for chemical fertilizers). However, coffee yield may be lower for environmentally friendly cultivation (Seufert et al., 2012) on a per area basis, which, in turn, could displace pressure to other ecosystems through crop expansion in the sending system or to other distant places.

Coproduction in the sending system comprises all forms of human interaction with the natural world that enable ES provision by means of physical resources, energy or labour (Palomo et al., 2016) and are embedded in interregional ES flows. Examples are technological inputs to coffee production, land management to maintain pintail breeding habitats, land management of Danube floodplains, and infrastructure and social norms that support panda conservation.

2.5. Drivers

In the sending system, physical flows of traded goods are initiated by political, social or market forces (drivers or causes) that foster ES provision by affecting resource and land-use manage-

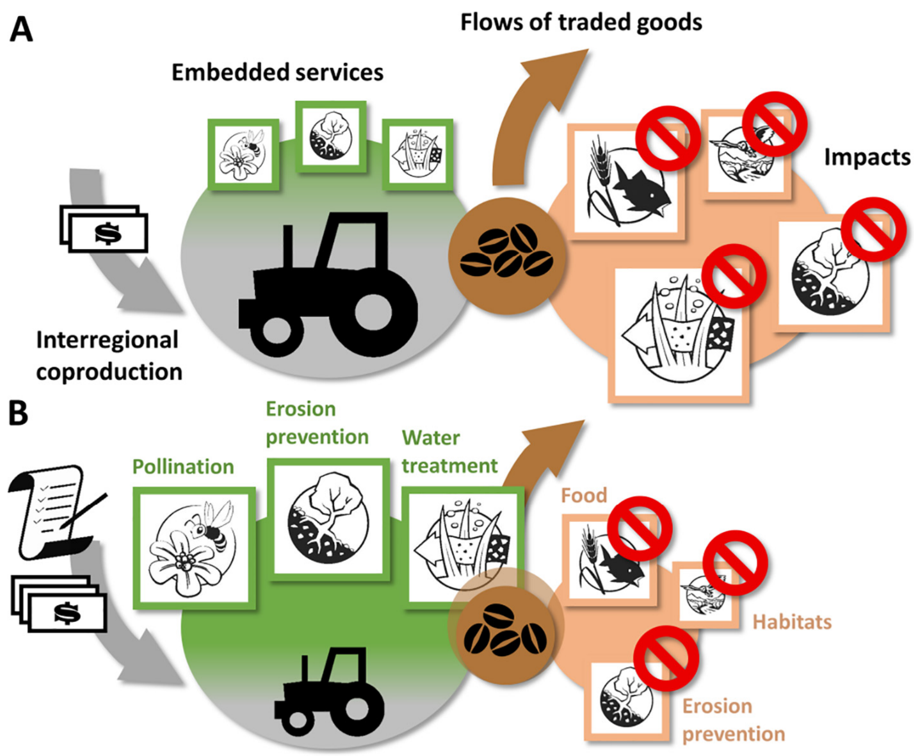

Fig. 3. Concept of embedded ecosystem services, impacts, and the role of interregional coproduction, illustrated for two hypothetical coffee production systems: (A) intensive management with greater technological inputs, and (B) cultivation through certification with greater levels of embedded ecosystem services. The sizes of the ecosystem services symbols in green represent their contribution to production relative to technological inputs shown in grey. Impacts are expressed as losses of ecosystem services (indicated with the 'no-symbol' in red) and their size represent the magnitude of these losses. Symbols were adopted from TEEB (2010).

ment. Expected economic gains drive trade flows, e.g., the production and sale of certified coffee. Passive physical flows, such as flood regulation, can also be influenced by social and political processes including regulations, planning laws, land tenure patterns, and social norms in sending systems. Physical flows through species migration are driven by environmental factors such as resource or habitat availability, itself determined by climatic conditions and land use, and animal behaviour that drives migration. For the pintail case, changing habitat, climate, and human recreation preferences are critical drivers of change in the sending system. Pintails are particularly vulnerable to climate change-induced habitat loss in their key breeding area, the Prairie Pothole region (Podruzny et al., 2002; Withey and Van Kooten, 2013). Another concern is a change in demand for pintails' recreation services, which drives funding for conservation in the sending system. Numbers of waterfowl hunters in the U.S. have declined in recent decades, leading to decreased revenue for waterfowl habitat conservation (Secretariat of the Convention on Migratory Species, 2004). Information flows can be driven by an internal motivation of the sending system to share knowledge and raise awareness for topics of interest in the sending systems. Examples of drivers in the panda case are multiple and diverse. First, as an emblem of China, the panda plays an important role in diplomacy, and further attracts the attention of media, general public and government officials. Second, as a flagship national nature reserve, Wolong has received national and international financial and technical assistance (Chen et al., 2012). Third, when pandas from Wolong are sent to zoos in other countries, there is large international media coverage.

In receiving systems, drivers both influence and respond to changes in ES demand. ES demands include the consumption and use of ES, and preferences for ES attributes responding to socioeconomic development and associated changes in human needs and lifestyles (Wolff et al., 2015). Examples are changes in the societal perceptions, preferences or interest of ES, such as changes in preferences for hunting and viewing pintail, changes in global demand for coffee, and risk exposure and perception of inhabitants in flood-prone areas (Armaş and Avram, 2009). Cultural affinity with the charismatic panda drives the flows of information about pandas from Wolong Nature Reserve. Many people in developed countries are concerned about threatened and charismatic species, especially the panda as a global conservation icon, which leads to a large amount of research on pandas in Wolong and inspires people to learn more about them.

ES demand cannot always be met by ecosystems of the receiving system. If ES are undersupplied relative to demand, ecosystems can be managed to increase supply, ES can be imported from another region, or demand may remain unfulfilled. Whether unmet demand will be covered ultimately depends on the scale of the ES flow mechanism, the degree of unmet demand, the availability of (manmade or natural) substitutes, price elasticities and trade-offs with other ES demands in the region. High demand for local ES can reduce land available for other ES. This is often reflected in planning laws, conservation targets or regulations that may prohibit ES exploitation in the ES-receiving system. On the other hand, interregional ES flows can be fostered by government incentives or 'ES markets' (e.g., Reducing Emissions from Deforestation and Forest Degradation, REDD+) for ES that are demanded, yet not locally provided (e.g., carbon, pollination-dependent crops). Taking these drivers into account, different stakeholders mediate ES flows between ES sending and receiving systems, through means such as power relationships (Felipe-Lucia et al., 2015).

Changes in ES flows may also be indirectly driven by sociocultural, economic or environmental factors from external systems. Coffee production is a good example: given the interdependence and networking in coffee markets, independent choices by producers can influence global economic and environmental teleconnections (Eakin et al., 2009). For instance, during the 1990s, decreasing world market prices for coffee fuelled an increasing differentiation of the global coffee market. Due to various climatic and institutional factors, Colombia was predisposed to deliver sustainable and high-quality Arabica coffee, and as a result, exports of certified coffee have increased (Rueda and Lambin, 2013). Outside market forces and shifting corporate strategies were important factors driving the increasing flows between coffee-producing regions of Colombia and consumer markets abroad.

2.6. Impacts

Consequences (or effects) of interregional ES flows can be positive or negative. In sending systems, the ecological and social consequences for sending ES elsewhere are closely related to impacts of land management or extraction, as discussed above. Some areas, for instance, might need protection in order to sustain their (interregional) flows (e.g., for carbon sequestration). Decisions about habitat conservation or changes in hunting demand affect direct or indirect costs. For instance, the distribution of pintail abundance and habitat can be altered, leading to a decrease in service provision, or protection of the Danube watershed's provision of flood protection might lead to reduced agricultural productivity, but also to the enhancement of biodiversity and the provision of other ES such as improved water quality (ICPDR, 2015).

Impacts also include the distribution of benefits among different stakeholder groups. Change in land tenure is a potential impact in the sending system that favours certain groups over others. Land and water grabbing (Rulli et al., 2013) or 'ocean grabbing' (Bennett et al., 2015) are discussed in this context. Benefits can also arise from telecoupled ES production. For example, smallholder producers that have joined Colombian certification schemes were found to enjoy improved working conditions, access to health care and education, and more equal allocation of resources, while more sustainable production practices contributed to gains in tree cover, water quality, and biodiversity (Hughell and Newsom, 2013; Rueda and Lambin, 2013; Rueda et al., 2015). In the panda sending system, local people are hired to assist in scientific research and media reporting, producing benefits for these communities.

Impacts in the receiving system are increases of human wellbeing through the actual use of the ES. Coffee consumers enjoy the coffee, hunters and bird watchers benefit from the presence of the pintail, and downstream regions in the Danube watershed save money on artificial flood protection (e.g., for building dykes). Information about pandas in Wolong helps increase awareness among the general public regarding the plight of the threatened giant panda. Overarching impacts of interregional flows in the receiving system are the degree of system interconnections and a dependency on ES from ecosystems elsewhere.

In external systems, positive and negative consequences of interregional ES flows occur as well. Choices of where and how ES are supplied can drive land-use change. Numerous stakeholders along the coffee supply chain including cooperatives, local traders, and roasters that distribute coffee to coffee shops, supermarkets, hotels, restaurants, and cafeterias benefit from the certification scheme through increased economic revenues, as so called spillover systems (Hughell and Newsom, 2013). Indirect land use and land cover change effects may occur if agricultural production is displaced due to regulation or trade of commodities within a neighbouring region. Flood risk management can affect other ES, leading to positive impacts outside the river basin. Information flows on species such as the giant panda, might increase awareness on conservation needs, from which other wildlife species in other parts of the world might also benefit.

3. Sustainability of interregional flows of ecosystem services

An increased understanding of interregional ES flows could inform decision making that better supports sustainability. For instance, information on interregional flows can raise awareness of the dependence of a receiving system on other countries' ecosystems, making cross-border ecosystem impacts visible and transparent. We use a definition of sustainability as an ideal state in which justice exists in relation to ES use within ecological limits and over the long term (Schröter et al., 2017). Interregional ES flows add complexity to sustainability assessments, as different regions are involved, encompassing different systems including concerned stakeholders (often having different norms, values, and economic and political interests). Interregional dependencies can arise, in which the sustainability of one system depends on the sustainability of systems elsewhere (Kissinger and Rees, 2010). For instance, if a country aims to govern towards sustainability (e.g., reforestation Meyfroidt et al., 2010), it needs to simultaneously consider consequences for other regions (e.g., increased dependence on agricultural or forestry imports from elsewhere that might be connected to deforestation or degradation). Principles or strategies can support efforts to reach sustainability goals or evaluate whether ES appropriation is sustainable (Schröter et al., 2017). We outline five such principles in relation to interregional ES flows below.

First, *equitable intragenerational distribution* plays an important role in achieving sustainable ES flows between systems. Distribution relates to the benefits derived from ecosystems, the opportunity costs of conservation ensuring sustained ES provision, and costs of ES that have been impacted or lost through degradation or land-use change. Benefits derived from ES include income from exporting cash crops and increases in wellbeing from consumption. A fair distribution of opportunity costs of conservation comes into play when one country compensates another to protect land that sustains ES like carbon sequestration or ES provided by pintail ducks. Further, equity would entail fair compensation for people in sending regions related to the costs of ES that they are deprived of due to land-use change (Boerema et al., 2016). ES valuation can be an important tool for highlighting value and designing policy instruments to maintain critical international ES flows. However, due to spatial discounting (respondents typically placing a greater value on locally produced ES) and the income-constrained nature of willingness-to-pay approaches (Dallimer et al., 2015), scientists and practitioners should be aware of the potential to undervalue ES in developing nations and undercompensate these regions, which raises equity concerns.

Second, *fair procedures and recognition* for people in sending, receiving, and external systems are a prerequisite to attaining sustainable interregional ES flows. This comprises ensuring fair procedures in interregional capital flows, such as payments for ES (Pascual et al., 2014). Power relations between actors that underpin governance mechanisms for ES management and access are crucial to consider in this respect (Berbés-Blázquez et al., 2016).

Third, *efficiency* may contribute to sustainability by allocating resources to minimize waste in production, reducing negative externalities. In the receiving system, this would also imply improving transparency of the impacts of consumer and producer buying decisions through the supply chain. Interregional ES flows can increase overall efficiency as many provisioning services are produced with lower costs in sending systems as compared to local provision (Schmitz et al., 2012).

Fourth, *persistence* requires interregional ES flows to be kept within ecological limits. For instance, natural capital stocks need to be maintained within a safe operating space, both regionally and globally and hence leakage, displacement and indirect land use change need to be considered. Persistence also includes consistency, which refers to how ES are coproduced, and whether regrowth and absorption rates match extraction of resources and input of pollutants. Persistence comprises the protection of panda habitat sufficient to keep viable populations in order to continue to provide existence value and opportunities for aesthetic appreciation.

Finally, *sufficiency* relates to the question of how much ES should be transferred via interregional flows in order to satisfy basic needs and a good quality of life. This relates to preferences of beneficiaries on ES from other systems, e.g., certified coffee from Colombia. Sufficiency also asks questions about overconsumption and its consequences for equitable ES distribution between regions.

4. Three emerging research frontiers

Three broad research frontiers currently emerge around interregional flows of ES. These include: (1) improved understanding and analysis of interregional flows with methods and indicators, (2) information translation for decision-makers at the science-policy interface, and (3) how governance can address sustainability of interregional ES flows.

4.1. How can we measure interregional flows for a variety of ecosystem services?

While there is considerable knowledge on global flows of provisioning services, it is yet unclear how flows can be measured particularly for regulating and cultural services, due to questions of data availability, methods, and indicators (Meyfroidt et al., 2013; Schaffartzik et al., 2015). Along with reviewing existing indicators, new methods to analyse drivers and impacts for complex causal relationships in interregional ES flows need to be developed. This involves the identification of relevant elements in ES sending and external systems, of flow paths, and of beneficiaries in receiving systems (Wolff et al., 2017). This is particularly challenging for complex interactions and flow paths or when preferences for ES change over space, time, and across cultures or different actors. Such information could be fed into the development of scenarios that predict future interregional ES flows and their land-use impacts that may result from changing consumption and trade patterns.

4.2. How can knowledge on interregional ecosystem service flows be used at the science-policy interface?

Interregional ES flows are currently largely omitted in national ecosystem assessments in Europe (Schröter et al., 2016), and in natural capital accounting (European Commission, 2013). Questions arising in this context are how countries can specifically adapt methods for national assessments and ecosystem accounting exercises. For national purposes, such assessments could focus on questions of system interconnections and dependency on ecosystems of other countries as well as on impacts of these flows in other regions. While national statistical reporting is advanced on provisioning ES, similar statistics are missing for regulating and cultural ES. Future research in this field should investigate what level of detail is relevant and feasible, given current data availability and methodological limitations, and suggest key variables that should be incorporated in future national reporting schemes. The question how to assess trends and scenarios must also be addressed. It is important to develop national indicators or indices to measure the externalisation of consumption pressures, as a prerequisite towards developing policies and management tools to reach interregional sustainability. The ongoing assessments of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), in which several of the authors are involved, are prominently considering the issue of interregional ES flows (IPBES, 2016, 2017). We hence expect the topic to gain importance at the science-policy interface in the future.

4.3. How can interregional ecosystem service flows be governed sustainably?

Management and policy strategies can be informed by scientific insights on interregional flows. In particular, an analysis of underlying (foreign and domestic) policy drivers, interests of specific actor groups, and trade relations pertaining to a broader range of ES is needed. Further, assessments on the (current and future) extent to which interregional ES flows might support or undermine existing conservation and sustainability targets (Aichi biodiversity targets, Sustainable Development Goals), e.g., how consumption of ES in one region impairs ES in other places, are required. Extending national ecosystem accounting (European Commission, 2013) with interregional ES flows will provide essential information on distant interrelations between regions. Such information opens a research avenue on rights and responsibilities across space and between regions as well as equity and trade-offs between societal groups involved in interregional ES flows.

We recognise that established governance mechanisms that address interregional ES flows between regions are still limited. Nevertheless, some aspects of the interregional dimensions discussed here can be identified in some established and emerging governance mechanisms. Countries have long worked together to reduce cross-boundary pollution. Such efforts include bilateral and multilateral pollution prevention agreements such as between the U.S. and Canada to limit acid rain; the China-Russia agreement to limit pollution of the Amur-Heilong River; and the UN Economic Commission for Europe Water Convention. In recent years, acknowledgment of trade-related environmental implications has advanced the development of trade in sustainability-certified products. These include forest products that require producers to adopt improved long-term management strategies and fair trade invarious agricultural commodities (e.g., coffee) to ensure that an adequate share of the consumer price goes to the primary producers. Still, such telecoupled implications for governance should be further developed. Further governance research could address the question of the extent to which future conventions that address transboundary environmental problems can be designed specifically for interregional ES flows, similar to or amending the Convention on Environmental Impact Assessment in a Transboundary Context (Espoo, http://www.unece.org/env/eia/). Governance options include the development of international conventions, transfer of technology and knowledge, and collaborative and network governance (Lenschow et al., 2016).

Information on interregional ES flows can be useful to optimise global ES provision and consumption. Thus, we need to identify assessment tools to address different environmental and social impacts, and provide optimisation tools to improve allocation of ES provision and consumption that allow to depict social, cultural and economic impacts across spatio-temporal scales and allow for the development of mitigation strategies for the emerging trade-offs.

5. Conclusion

Our conceptual framework defines the components of telecoupled socio-ecological systems and interregional ES flows. We contend that the idea and structure of the framework, and a stronger collaboration between disciplines on interregional ES flows can help to move forward from considering ES provision as a static entity at the point of spatial origin to addressing ES as movements of material, energy and information between systems internationally and globally. This has important implications for enhancing national and international ecosystem assessments, which so far have fallen short of including interregional ES flows, and to inform environmental accounting at a national and international scale, including ongoing assessments of IPBES, evaluations of Sustainable Development Goals, and natural capital accounting. With a better understanding of interregional ES flows, informed management decisions can foster more intentional and sustained sourcing of ES in an increasingly telecoupled world. Overall, enhanced understanding of interregional ES flows can allow policy to more comprehensively assess the effects of international trade, foreign policy, and bilateral and multilateral agreements. Ultimately, this understanding can improve individual countries' capacity to assess their external impacts and dependencies, and to move towards strategies for long-term sustainable development.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecoser.2018.02.003.

References

Armaş, I., Avram, E., 2009. Perception of flood risk in Danube Delta, Romania. Nat. Hazards 50, 269–287.
Austin, J.E., Miller, M.R., 1995. Northern Pintail: Anas Acuta. In: Poole, A., Gill, F. (Eds.), The Birds of North America. The Academy of Natural Sciences, Philadelphia, and the American Ornithologists' Union, Washington D.C..
Bagstad, K.J., Johnson, G.W., Voigt, B., Villa, F., 2013. Spatial dynamics of ecosystem service flows: a comprehensive approach to quantifying actual services. Ecosyst. Serv. 4, 117–125.
Bennett, N.J., Govan, H., Satterfield, T., 2015. Ocean grabbing. Marine Policy 57, 61–68.
Berbés-Blázquez, M., González, J.A., Pascual, U., 2016. Towards an ecosystem services approach that addresses social power relations. Curr. Opin. Environ. Sustain. 19, 134–143.
Boerema, A., Peeters, A., Swolfs, S., Vandevenne, F., Jacobs, S., Staes, J., Meire, P., 2016. Soybean trade: balancing environmental and socio-economic impacts of an intercontinental market. PLoS One 11, e0155222.
Bruckner, M., Fischer, G., Tramberend, S., Giljum, S., 2015. Measuring telecouplings in the global land system: a review and comparative evaluation of land footprint accounting methods. Ecol. Econ. 114, 11–21.
Chen, X., Lupi, F., An, L., Sheely, R., Viña, A., Liu, J., 2012. Agent-based modeling of the effects of social norms on enrollment in payments for ecosystem services. Ecol. Modell. 229, 16–24.
Costanza, R., 2008. Ecosystem services: multiple classification systems are needed. Biol. Conserv. 141, 350–352.
Dallimer, M., Jacobsen, J.B., Lundhede, T.H., Takkis, K., Giergiczny, M., Thorsen, B.J., 2015. Patriotic values for public goods: transnational trade-offs for biodiversity and ecosystem services? Bioscience 65, 33–42.
de Groot, R.S., Alkemade, R., Braat, L., Hein, L., Willemen, L., 2010. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecol. Complex. 7, 260–272.
Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., Larigauderie, A., Adhikari, J.R., Arico, S., Báldi, A., Bartuska, A., Baste, I.A., Bilgin, A., Brondizio, E., Chan, K.M.A., Figueroa, V.E., Duraiappah, A., Fischer, M., Hill, R., Koetz, T., Leadley, P., Lyver, P., Mace, G.M., Martin-Lopez, B., Okumura, M., Pacheco, D., Pascual, U., Pérez, E.S., Reyers, B., Roth, E., Saito, O., Scholes, R.J., Sharma, N., Tallis, H., Thaman, R., Watson, R., Yahara, T., Hamid, Z.A., Akosim, C., Al-Hafedh, Y., Allahverdiyev, R., Amankwah, E., Asah, S.T., Asfaw, Z., Bartus, G., Brooks, L.A., Caillaux, J., Dalle, G., Darnaedi, D., Driver, A., Erpul, G., Escobar-Eyzaguirre, P., Failler, P., Fouda, A.M.M., Fu, B., Gundimeda, H., Hashimoto, S., Homer, F., Lavorel, S., Lichtenstein, G., Mala, W.A., Mandivenyi, W., Matczak, P., Mbizvo, C., Mehrdadi, M., Metzger, J.P., Mikissa, J.B., Moller, H., Mooney, H.A., Mumby, P., Nagendra, H., Nesshover, C., Oteng-Yeboah, A.A., Pataki, G., Roué, M., Rubis, J., Schultz, M., Smith, P., Sumaila, R., Takeuchi, K., Thomas, S., Verma, M., Yeo-Chang, Y., Zlatanova, D., 2015. The IPBES conceptual framework—connecting nature and people. Curr. Opin. Environ. Sustain. 14, 1–16.
Eakin, H., Winkels, A., Sendzimir, J., 2009. Nested vulnerability: exploring cross-scale linkages and vulnerability teleconnections in Mexican and Vietnamese coffee systems. Environ. Sci. Policy 12, 398–412.
Erb, K.-H., Krausmann, F., Lucht, W., Haberl, H., 2009. Embodied HANPP: mapping the spatial disconnect between global biomass production and consumption. Ecol. Econ. 69, 328–334.
European Commission, 2011. Our life insurance, our natural capital: an EU biodiversity strategy to 2020. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. In: European Commission (Ed.), COM(2011) 244 final, Brussels. p. 17.
European Commission, Organisation for Economic Co-operation and Development, United Nations, World Bank, 2013. System of Environmental-Economic Accounting 2012, Experimental Ecosystem Accounting.
FAO, 2017. FAOSTAT. Food and Agriculture Organization of the United Nations.
Felipe-Lucia, M.R., Martín-López, B., Lavorel, S., Berraquero-Díaz, L., Escalera-Reyes, J., Comín, F.A., 2015. Ecosystem services flows: why stakeholders' power relationships matter. PLoS One 10, e0132232.
Friis, C., Nielsen, J.Ø., Otero, I., Haberl, H., Niewöhner, J., Hostert, P., 2015. From teleconnection to telecoupling: taking stock of an emerging framework in land system science. J. Land Use Sci., 1–23
García-Nieto, A.P., García-Llorente, M., Iniesta-Arandia, I., Martín-López, B., 2013. Mapping forest ecosystem services: from providing units to beneficiaries. Ecosyst. Serv. 4, 126–138.
Goldstein, J.H., Thogmartin, W.E., Bagstad, K.J., Dubovsky, J.A., Mattsson, B.J., Semmens, D.J., López-Hoffman, L., Diffendorfer, J.E., 2014. Replacement Cost Valuation of Northern Pintail (Anas acuta) Subsistence Harvest in Arctic and Sub-Arctic North America. Human Dimens. Wildlife 19, 347–354.
Haberl, H., Erb, K.-H., Krausmann, F., Berecz, S., Ludwiczek, N., Martínez-Alier, J., Musel, A., Schaffartzik, A., 2009. Using embodied HANPP to analyze teleconnections in the global land system: conceptual considerations. Geografisk Tidsskrift-Danish J. Geogr. 109, 119–130.
Hamann, M., Biggs, R., Reyers, B., 2015. Mapping social–ecological systems: identifying 'green-loop' and 'red-loop' dynamics based on characteristic bundles of ecosystem service use. Global Environ. Change 34, 218–226.
Hughell, D., Newsom, D., 2013. Impact of Rainforest Alliance certification on coffee farms in Colombia. Rainforest Alliance, New York.
Hulina, J., Bocetti, C., Campa III, H., Hull, V., Yang, W., Liu, J., 2017. Telecoupling framework for research on migratory species in the Anthropocene. Elem. Sci. Anth. 5.
ICPDR, 2015. The Danube River Basin District Management Plan. Part A – Basin-Wide Overview. ICPDR, Vienna.
IPBES, 2016. Decision and Scoping Report for the IPBES Global Assessment on Biodiversity and Ecosystem Services: IPBES/4/8.
IPBES, 2017. Assessment Report on Biodiversity & Ecosystem Services in Europe and Central Asia: A Primer.
Jha, S., Bacon, C.M., Philpott, S.M., Ernesto Méndez, V., Läderach, P., Rice, R.A., 2014. Shade coffee: update on a disappearing refuge for biodiversity. Bioscience 64, 416–428.
Kastner, T., Erb, K.-H., Nonhebel, S., 2011. International wood trade and forest change: a global analysis. Global Environ. Change 21, 947–956.
Kissinger, M., Rees, W.E., 2010. An interregional ecological approach for modelling sustainability in a globalizing world—Reviewing existing approaches and emerging directions. Ecol. Modell. 221, 2615–2623.
Kissinger, M., Rees, W.E., Timmer, V., 2011. Interregional sustainability: governance and policy in an ecologically interdependent world. Environ. Sci. Policy 14, 965–976.
Klein, A.-M., Vaissière, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Tscharntke, T., 2007. Importance of pollinators in changing landscapes for world crops. Proc. Roy. Soc. B: Biol. Sci. 274, 303–313.
Koellner, T., 2011. Ecosystem Services and Global Trade of Natural Resources. Ecology, Economics and Policies. Routledge, Abingdon.
Kroll, F., Müller, F., Haase, D., Fohrer, N., 2012. Rural–urban gradient analysis of ecosystem services supply and demand dynamics. Land Use Policy 29, 521–535.
Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proc. Natl. Acad. Sci. U.S.A. 108, 3465–3472.

Lapola, D.M., Schaldach, R., Alcamo, J., Bondeau, A., Koch, J., Koelking, C., Priess, J.A., 2010. Indirect land-use changes can overcome carbon savings from biofuels in Brazil. Proc. Natl. Acad. Sci. U.S.A. 107, 3388–3393.
Lenschow, A., Newig, J., Challies, E., 2016. Globalization's limits to the environmental state? Integrating telecoupling into global environmental governance. Environ. Polit. 25, 136–159.
Liu, J., Hull, V., Batistella, M., DeFries, R., Dietz, T., Fu, F., Hertel, T.W., Izaurralde, R.C., Lambin, E.F., Li, S., Martinelli, L.A., McConnell, W.J., Moran, E.F., Naylor, R., Ouyang, Z., Polenske, K.R., Reenberg, A., de Miranda Rocha, G., Simmons, C.S., Verburg, P.H., Vitousek, P.M., Zhang, F., Zhu, C., 2013. Framing sustainability in a telecoupled world. Ecol. Soc. 18.
Liu, J., Hull, V., Luo, J., Yang, W., Liu, W., Viña, A., Vogt, C., Xu, Z., Yang, H., Zhang, J., An, L., Chen, X., Li, S., Ouyang, Z., Xu, W., Zhang, H., 2015. Multiple telecouplings and their complex interrelationships. Ecol. Soc. 20.
Liu, J., Yang, W., Li, S., 2016. Framing ecosystem services in the telecoupled Anthropocene. Front. Ecol. Environ. 14, 27–36.
López-Hoffman, L., Varady, R.G., Flessa, K.W., Balvanera, P., 2010. Ecosystem services across borders: a framework for transboundary conservation policy. Front. Ecol. Environ. 8, 84–91.
López-Hoffman, L., Chester, C.C., Semmens, D.J., Thogmartin, W.E., Rodriguez McGoffin, M.S., Merideth, R., Diffendorfer, J.E., 2017. Ecosystem services from transborder migratory species: implications for conservation governance. Ann. Rev. Environ. Resour. 42, 509–539.
MA, 2005. Ecosystems and Human Well-Being: Synthesis Report. Washington D.C., USA.
Manning, S., Boons, F., von Hagen, O., Reinecke, J., 2012. National contexts matter: the co-evolution of sustainability standards in global value chains. Ecol. Econ. 83, 197–209.
Martín-López, B., Palomo, I., García-Llorente, M., Iniesta-Arandia, I., Castro, A.J., García Del Amo, D., Gómez-Baggethun, E., Montes, C., 2017. Delineating boundaries of social-ecological systems for landscape planning: a comprehensive spatial approach. Land Use Policy 66, 90–104.
Mattsson, B., Runge, M., Clark, R., Boomer, G., Eadie, J., 2012. A modeling framework for integrated harvest and habitat management of North American waterfowl: case-study of northern pintail metapopulation dynamics. Ecol. Modell. 225, 146–158.
Meyfroidt, P., Rudel, T.K., Lambin, E.F., 2010. Forest transitions, trade, and the global displacement of land use. Proc. Natl. Acad. Sci. U.S.A. 107, 20917–20922.
Meyfroidt, P., Lambin, E.F., Erb, K.-H., Hertel, T.W., 2013. Globalization of land use: distant drivers of land change and geographic displacement of land use. Curr. Opin. Environ. Sustain. 5, 438–444.
Moser, S.C., Hart, J.A.F., 2015. The long arm of climate change: societal teleconnections and the future of climate change impacts studies. Clim. Change 129, 13–26.
Palomo, I., Felipe-Lucia, M.R., Bennett, E.M., Martín-López, B., Pascual, U., 2016. Chapter Six – Disentangling the Pathways and Effects of Ecosystem Service Co-Production. In: Woodward, G., Bohan, D.A. (Eds.), Adv. Ecol. Res.. Academic Press, pp. 245–283.
Pascual, U., Phelps, J., Garmendia, E., Brown, K., Corbera, E., Martin, A., Gomez-Baggethun, E., Muradian, R., 2014. Social equity matters in payments for ecosystem services. Bioscience 64, 1027–1036.
Pascual, U., Palomo, I., Adams, W., Chan, K.M.A., Daw, T., Garmendia, E., Gómez-Baggethun, E., de Groot, R., Mace, G., Martin-Lopez, B., Phelps, J., 2017. Off-stage ecosystem service burdens: a blind spot for global sustainability. Environ. Res. Lett. 12, 075001.
Petrow, T., Merz, B., 2009. Trends in flood magnitude, frequency and seasonality in Germany in the period 1951–2002. J. Hydrol. 371, 129–141.
Podruzny, K.M., Devries, J.H., Armstrong, L.M., Rotella, J.J., 2002. Long-term response of northern pintails to changes in wetlands and agriculture in the Canadian Prairie Pothole Region. J. Wildl. Manage., 993–1010
Potschin-Young, M., Haines-Young, R., Görg, C., Heink, U., Jax, K., Schleyer, C., 2017. Understanding the role of conceptual frameworks: Reading the ecosystem service cascade. Ecosyst. Serv.
Rueda, X., Lambin, E.F., 2013. Responding to globalization: impacts of certification on Colombian small-scale coffee growers. Ecol. Soc. 18.
Rueda, X., Thomas, N.E., Lambin, E.F., 2015. Eco-certification and coffee cultivation enhance tree cover and forest connectivity in the Colombian coffee landscapes. Reg. Environ. Change 15, 25–33.
Rulli, M.C., Saviori, A., D'Odorico, P., 2013. Global land and water grabbing. Proc. Natl. Acad. Sci. U.S.A. 110, 892–897.
Schaffartzik, A., Haberl, H., Kastner, T., Wiedenhofer, D., Eisenmenger, N., Erb, K.-H., 2015. Trading land: a review of approaches to accounting for upstream land requirements of traded products. J. Ind. Ecol. 19, 703–714.
Schmitz, C., Biewald, A., Lotze-Campen, H., Popp, A., Dietrich, J.P., Bodirsky, B., Krause, M., Weindl, I., 2012. Trading more food: implications for land use, greenhouse gas emissions, and the food system. Global Environ. Change 22, 189–209.
Schröter, M., Albert, C., Marques, A., Tobon, W., Lavorel, S., Maes, J., Brown, C., Klotz, S., Bonn, A., 2016. National ecosystem assessments in Europe: a review. Bioscience 66, 813–828.
Schröter, M., Stumpf, K.H., Loos, J., van Oudenhoven, A.P.E., Böhnke-Henrichs, A., Abson, D.J., 2017. Refocusing ecosystem services towards sustainability. Ecosyst. Serv. 25, 35–43.
Secretariat of the Convention on Migratory Species, 2004. 25 years of journeys: a special report to mark the silver anniversary of the Bonn Convention on Migratory Species (1979–2004). In: Program, U.N.E. (Ed.), Bonn.
Semmens, D.J., Diffendorfer, J.E., López-Hoffman, L., Shapiro, C.D., 2011. Accounting for the ecosystem services of migratory species: quantifying migration support and spatial subsidies. Ecol. Econ. 70, 2236–2242.
Serna-Chavez, H., Schulp, C., van Bodegom, P., Bouten, W., Verburg, P., Davidson, M., 2014. A quantitative framework for assessing spatial flows of ecosystem services. Ecol. Indic. 39, 24–33.
Seto, K.C., Reenberg, A., Boone, C.G., Fragkias, M., Haase, D., Langanke, T., Marcotullio, P., Munroe, D.K., Olah, B., Simon, D., 2012. Urban land teleconnections and sustainability. Proc. Natl. Acad. Sci. U.S.A. 109, 7687–7692.
Seufert, V., Ramankutty, N., Foley, J.A., 2012. Comparing the yields of organic and conventional agriculture. Nature 485, 229–232.
TEEB, 2010. The Economics of Ecosystems and Biodiversity for Local and Regional Policy Makers.
UK NEA, 2011. The UK National Ecosystem Assessment Technical Report. UNEP-WCMC, Cambridge.
UNEP, 2010. The Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets. Decision UNEP/CBD/COP/DEC/X/2, adopted by the Conference of the Parties to the Convention on Biological Diversity.
Villamagna, A.M., Angermeier, P.L., Bennett, E.M., 2013. Capacity, pressure, demand, and flow: a conceptual framework for analyzing ecosystem service provision and delivery. Ecol. Complex. 15, 114–121.
Weinzettel, J., Steen-Olsen, K., Hertwich, E.G., Borucke, M., Galli, A., 2014. Ecological footprint of nations: comparison of process analysis, and standard and hybrid multiregional input–output analysis. Ecol. Econ. 101, 115–126.
Withey, P., Van Kooten, G.C., 2013. The effect of climate change on wetlands and waterfowl in western canada: Incorporating cropping decisions into a bioeconomic model. Nat. Resour. Model. 26, 305–330.
Wolff, S., Schulp, C.J.E., Verburg, P.H., 2015. Mapping ecosystem services demand: a review of current research and future perspectives. Ecol. Indic. 55, 159–171.
Wolff, S., Schulp, C.J.E., Kastner, T., Verburg, P.H., 2017. Quantifying spatial variation in ecosystem services demand: a global mapping approach. Ecol. Econ. 136, 14–29.
Yu, Y., Feng, K., Hubacek, K., 2013. Tele-connecting local consumption to global land use. Global Environ. Change 23, 1178–1186.