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Guidance for assessing interregional ecosystem service flows

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ABSTRACT

Ecosystem services (ES) assessments commonly focus on a specific biophysical region or nation and take its geographic borders as the system boundary. Most geographical regions are, however, not closed systems but are open and telecoupled with other regions, such that the use of ES in one location is dependent on ecosystem processes and ecological management in other locations. Interregional ES flows often affect national economies and may trigger issues of national security and global equity. To date, however, methodologies for assessing interregional flows of ES have been published in dispersed literature. This paper provides a three-step guidance for how to assess four different types of interregional ES flows (traded goods, passive biophysical flows, species migration and dispersal as well as information flows). This guidance is intended to complement national and regional ecosystem assessments. The three steps are to (i) define the goal and scope of interregional ES flow assessments, (ii) quantify the interregional ES flows using a tiered approach and (iii) interpret results in terms of uncertainties, consequences and governance options. We compile different indicators for assessing interregional ES flows and evaluate their suitability for national and regional ES assessments. Finally, to assess the

Abbreviations: CITES, Convention on International Trade in Endangered Species of Wild Fauna and Flora; COMTRADE, UN Commodity Trade Statistics; CORDIS, Community Research and Development Information Service; ES, ecosystem services; FAOSTAT, Food and Agriculture Organization Corporate Statistical Database; GBIF, Global Biodiversity Information Facility; IPBES, The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; NEA, national ecosystem assessment; SDGs, Sustainable Development Goals; UNESCO, United Nations Educational, Scientific and Cultural Organization; UNWTO, United Nations World Tourism Organization

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[1] Our esteemed colleague Dr. Sebastian Arnhold sadly passed away in November 2017. We appreciate his valuable contributions to this work and always remember him as an enthusiastic researcher.

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implications of interregional ES flows for environmental sustainability and human well-being, we relate our flow indicators to the Sustainable Development Goals. This guidance towards systematic assessment of interregional ES flows provides a first step to measure and quantify externalised environmental costs and can contribute to the development of indicators to address interregional imbalances in trade, foreign policy and beyond.

1. Introduction

Place-based assessments of ecosystem services (ES), the contributions of ecosystems to human well-being, have largely neglected the flows of ES between regions (Schröter et al., 2016; Pascual et al., 2017). Distant regions are tied together via a process called telecoupling (sensu Liu et al., 2016) such that the use of, and dependency on ES in one location, may be impacted by the management of ES in other locations. By failing to account for interregional ES flows, national and regional ES assessments may miss important policy implications for domestic and global sustainability. There is hence a need to consider such interregional ES flows between sending and receiving systems (see Box 1 for definitions) (Koellner, 2011; Lautenbach et al., 2015; Schröter et al., 2018).

A number of global and regional ES assessments recognize the importance of considering interregional flows of ES. Notably the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and its assessments for Europe and Central Asia (IPBES, 2018) and on Land Degradation and Restoration (IPBES, 2018b) addressed interregional ES flows. In their recommendations to policy makers, they spell out clearly that consumption patterns in one part of the world can severely affect ecosystem degradation in another and that direct and indirect drivers of biodiversity loss are also related to global trade flows. Furthermore, the Aichi Target 4 of the Convention of Biological Diversity (UNEP, 2010) and the U.N. Sustainable Development Goal 12 (United Nations, 2015) both aim for improving the sustainability of production and consumption (Marques et al., 2017). The importance of measuring interregional ES flows is also briefly mentioned in the System of Environmental-Economic Accounting-Experimental Ecosystem Accounts, an economic accounting framework for systematic monitoring of the extent and properties of ecosystems providing ES (Edens and Hein, 2013; United Nations et al., 2013). At a regional level, the EU Biodiversity Strategy (Action 17) (European Commission, 2011) aims to “reduce the impacts of EU consumption patterns on biodiversity”.

Given their political and practical relevance, interregional flows should be considered in national and regional ecosystem assessments (Schröter et al., 2016). Interregional ES flows present opportunities to import ES from elsewhere and/or export ES to other places. This may lead to depending a certain country or region on food, resources and ecological processes in other parts of the world (López-Hoffman et al., 2010), which raises national security issues (Kissinger et al., 2011). This may further suggest that importing countries have responsibilities towards the countries from which they receive ES (Schröter et al., 2018), and interdependencies arise on both sides. Assessments of ES can be used to elucidate and evaluate these issues (Pascual et al., 2017) and thereby support the consideration of equity in the use of ES between countries (Schröter et al., 2018).

To date, only a few assessments have considered interregional ES flows between countries, mainly for provisioning services, as these are often associated with trade data and existing national indicators (see Schröter et al., 2016 for a review of European national ecosystem assessments). In Europe, for example, the UK national ecosystem assessment considered interregional flows of biomass (UK NEA, 2011, Chapter 21). This involved an assessment with a baseline and scenarios for biomass imported to the UK, estimated land requirements and overseas water demand. The Flanders assessment mentions indicators for wood trade (INBO, 2014), and the Norwegian assessment considers indicators for national dependence on foreign ecosystems (NOU, 2013). In the Netherlands, ES have been indirectly assessed through comparison of provision and use, which revealed that national ES demand remains unmet or is fulfilled by imports (de Knegt, 2014). Israel’s national ecosystem assessment report devoted a chapter to ‘imported’ services (Kissinger et al., 2018), focusing mostly on biophysical flows of agricultural and forest products into Israel (material flows and their land and water requirements). It identified different sending systems and explores some of the environmental implications of ES provision in different exporting regions. The Israel assessment also addressed some regulating services, such as forest areas outside of Israel, required to offset Israel’s carbon emissions.

Several scientific studies assessed interregional ES flows between nations or regions, again most commonly addressing provisioning services (Yu et al., 2013; Kastner et al., 2014; Kastner et al., 2015; Fridman and Kissinger, 2018). Some studies addressed interregional flows of regulating services through trade of provisioning services (Wolff et al., 2017) or analysed pest control services in the United States by bats that migrate between the US and Mexico (López-Hoffman et al., 2017b). For cultural services, Semmens et al. (2018) quantified spatial flows provided by the migrating Monarch butterfly (*Danaus plexippus*). Bagstad et al. (2018) analysed ES flows of birdwatching, subsistence harvest and hunting of northern pintails (*Anas acuta*). Hulina et al. (2017) examined ES flows through ecotourism related to migratory Kirtland’s warbler (*Setophaga kirtlandii*). Despite these efforts, there are large knowledge gaps on how to assess interregional ES flows of regulating and cultural ES. In order to advance and standardize the assessment of interregional ES flows, a critical evaluation of suitable methods and indicators for their assessment is needed.

This paper provides methodological guidance to assess interregional ES flows. Building on previous conceptual work (Schröter et al., 2018), we provide options for practical applications of interregional ES flow assessments for provisioning, regulating and cultural ES. To facilitate a systematic assessment of flows, we distinguish four different types of interregional ES flows (Schröter et al., 2018):

(i) flows of provisioning services that are traded and transported by humans to a receiving system;
(ii) flows of provisioning, regulating and cultural services provided by animals that migrate or disperse between sending and receiving systems;
(iii) passive biophysical flows, both the provision of beneficial flows (such as freshwater) and the prevention of detrimental flows (such as flooding), across long distances; and
(iv) information flows due to human cognition in the receiving system about species and ecosystems in the sending systems (such as information on the existence of an iconic species or ecosystem).

To the best of our knowledge, this is the first paper to systematically provide guidance for quantifying interregional ES flows in national and regional ES assessments. This guidance provides a tiered approach, allowing users to choose different levels of complexity and feasibility, depending on capacity, data and time availability–ranging from simple proxies to complex models for the assessment of interregional ES flows. For this purpose, we compile different indicators for assessing interregional ES flows and evaluate their suitability for assessments. Finally, in order to understand the implications of telecouplings on human well-being, we relate the indicators for interregional ES flows to the Sustainable Development Goals.

Box 1
Definitions of ES flows (based on Liu et al., 2013; Schröter et al., 2018).

Co-production factors: Input factors based on natural, human, social, technological, and financial capital needed to generate ES.

Embedded ecosystem services: All ES that directly underlie the production of an interregionally flowing ES in the sending system (e.g., pollination for coffee production).

Interregional ES flow: Realized through 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.

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.

Sending system: The region from which ES origin that flow interregionally.

Spill-over system: A system other than sending and receiving systems that is affected by or which affects flows.

Telecoupling: Socioeconomic-environmental interactions between distant coupled socio-ecological systems.

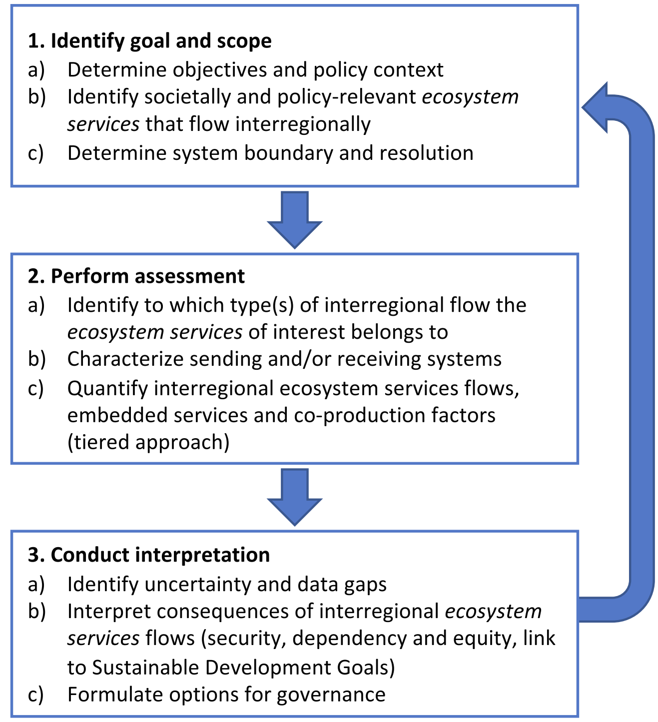

Fig. 1. Flowchart for assessing interregional flows of ecosystem services. These steps should be iterative and incorporated into regular monitoring repeated at certain reporting intervals (e.g., annually or every 5 years).

2. Material & methods

Within the work of the international expert group "sTeleBES – Telecoupled use of biodiversity and ecosystem services: synthesis of concepts, methods and evidence", we conducted two workshops at iDiv, Leipzig (November 27 to December 2, 2016 and September 25 to 28, 2017). Seventeen co-workers covering different expertise from environmental sciences, geography, ecology, life-cycle assessment, (socio-)economics, policy and law as well as diversity in career stage, gender and geographic background convened to conceptualize interregional ES flows in the first workshop (Schröter et al., 2018). In the second workshop, we reviewed different sets of ES indicators to assess their suitability to convey information on interregional ES flows for four different flow types (*flows of traded goods, flows mediated by species through migration and dispersal, passive biophysical flows* and *information flows*). For evaluating to which ES these different flow types apply, we built on the classification of the generalizing perspective of nature's contributions to people proposed by Díaz et al. (2018), covering 18 categories of ES. Complementarily, we specified four ES flow types and created a general guidance for assessing interregional ES flows.

To facilitate the interpretation of results, we linked the assessment of interregional ES flows to indicators of the 17 Sustainable Development Goals (SDGs). Knowledge on the impacts of interregional ES flows on human well-being could facilitate interpretation and use of the results. We interpreted all indicators of the 17 SDGs (United Nations, 2017) and identified those that could be potentially affected in both sending and receiving systems by the four types of interregional ES flows. Specific ES are often not directly mentioned in the SDGs and related indicators; therefore, interpretation was required. Building on similar analyses by Geijzendorffer et al. (2017) and Wood et al. (2018b) who identified general links between ES and SDGs, while not specifically focusing on interregional ES flows, we derived a comprehensive overview of potential links.

3. Guidance for assessments of interregional ES flows

We suggest a three-step process to perform an assessment of interregional ES flows: (i) defining the goal and scope, (ii) conducting the assessment and (iii) interpreting of assessment results (Fig. 1)[2]. We explain each step in the following sections. Generally, the recommendations follow a tiered approach in line with Tallis and Polasky (2009). Tier 1 suggests a literature review to derive simple indicators. Tier 2 gathers existing data with established, basic models, while Tier 3 generates new data via process models, surveys or other advanced methods. We recommend such a tiered approach, as the level of sophistication of each step must be aligned with the importance of the decision to be supported and available resources, which influence feasibility of the assessment.

Whenever possible, the assessment of interregional ES flows should involve relevant stakeholders and experts from society, policy and science at various steps throughout the process. A joint assessment process will ensure knowledge inclusivity as well as broad ownership, offering enhanced relevance and uptake of the assessment results into policy and practice.

3.1. Identify goal and scope

To identify the goal and scope of the assessment, the objectives and policy context of the study need to be clear. This step requires the integration of expertise from different sectors and disciplines from local and regional knowledge systems and valuation approaches that help to properly identify relevant ES, both in the sending and the receiving systems. Depending on the context, this could involve representatives from environmental, forest and agricultural policy, from sectorial interest groups and from development or conservation NGOs, as well as scientists with different disciplinary backgrounds. ES flows are accordingly prioritized and appropriate system boundaries and adequate

[2] The suggested structure is motivated by the ISO Standard 14,040 regulating the execution of Life Cycle Assessment studies (ISO, 2006. ISO 14,040 Environmental Management - Life Cycle Assessment - Principles and Framework. International Organization for Standardization, Switzerland.)

Table 1
Ecosystem services for which interregional flows exist.[a] This table provides examples for the four flow types and is not meant to be comprehensive.

Ecosystem services	Ecosystem services flow types			
	Physical flows of traded goods	Species migration and dispersal	Passive biophysical flows	Information flows
1. Habitat creation and maintenance	na	Birds as ecosystem engineers creating habitat for other service-providing species (Sekercioglu, 2006)	Formation of river deltas through sediment transport (Twilley et al., 2016)	Information of overwintering areas for migratory birds and butterflies provided by citizen science (Sullivan et al., 2014)
2. Pollination and dispersal of seeds and other propagules	na	Pollination of agave plants by long-nosed bats *Leptonycteris* sp. (López-Hoffman et al., 2010); Seed dispersal by forest elephants *Loxodonta cyclotis* (Campos-Arceiz and Blake, 2011)	na	na
3. Regulation of air quality	na	na	Ecosystem management preventing transboundary air pollution (Lee et al., 2016)	na
4. Regulation of climate	na	na	Areas benefiting from climate regulation are distant from carbon sequestering ecosystems (Serna-Chavez et al., 2014)	na
5. Regulation of ocean acidification	na	na	na	na
6. Regulation of freshwater quantity, location and timing	na	na	Water supply by upstream ecosystems (Turpie et al., 2008)	na
7. Regulation of freshwater and coastal water quality	na	na	Pollutant retention by upstream wetlands (Mitsch, 1992)	na
8. Formation, protection and decontamination of soils and sediments	na	na	Sediment transport and sedimentation in river systems (Middelkoop et al., 2010)	na
9. Regulation of hazards and extreme events	na	na	Flood mitigation by upstream wetland management (Watson et al., 2016); Mangroves protecting from tsunamis (Alongi, 2008)	na
10. Regulation of detrimental organisms and biological processes	na	Pest-controlling bats migrate between Mexico and the US (López-Hoffman et al., 2014); Removal of carcasses by migratory vultures and raptors, e.g., *Milvus migrans* (Morales-Reyes et al., 2018)	na	na
11. Energy	Efforts to lower reliance on fossil fuels lead to surges in wood pellet trade (Goh et al., 2013)	Movement of bioenergy between sending and receiving systems (breeding and wintering sites) (Hulina et al., 2017)	na	na
12. Food and feed	Global demand of food and feed increases interregional trade of biomass (Kastner et al., 2014)	Pteropid bats (*Pteropus vampyrus*) hunted for food in Malaysia (Epstein et al., 2009)	na	na
13. Materials, companionship and labor	Wood trade influences forest management in many developed countries (Kastner et al., 2011a)	Use of bird feathers birds for fashion purposes (Boardman, 2006)	na	na
14. Medicinal, biochemical and genetic resources	Widespread trade of medicinal plants from Africa to other world regions (Van Wyk, 2015)	Use of different body parts of migratory fish and mammals for medicinal purposes (Zahler et al., 2004; Chakravorty et al., 2011)	na	Natural product/bioprospecting (David et al., 2015); Indigenous peoples' rights and Nagoya Protocol on Access and Benefit Sharing (Gibson, 2016)
15. Learning and inspiration	Museum collections contain samples from distant regions (Löhne et al., 2018)	Monarch butterflies as iconic species inspiring art and teaching (Gustafsson et al., 2015)	na	Use of visual media to increase knowledge of university students regarding the orangutan *Pongo* sp. (Pearson et al., 2011)
16. Physical and psychological experiences	na	Bird festivals coinciding with bird migration in the US (López-Hoffman et al., 2017a)	na	Information provided by social media regarding the contribution of landscapes, habitats or species to recreational and nature-based tourism activities (Hausmann et al., 2018)

(*continued on next page*)

Table 1 (*continued*)

Ecosystem services	Ecosystem services flow types			
	Physical flows of traded goods	Species migration and dispersal	Passive biophysical flows	Information flows
17. Supporting identities	na	Migrating pintail ducks hunted for subsistence by indigenous communities in North America (Goldstein et al., 2014); Satisfaction derived by Spanish farmers from knowing that migratory raptors exist (Morales-Reyes et al., 2018)	na	Community resources and indigenous people's rights (Gibson, 2016); Information provided by social media regarding the contribution of landscapes, habitats or species to develop sense of place and belonging (Martínez Pastur et al., 2016)
18. Maintenance of options	na	Bats slowing pesticide resistance evolution in pests (López-Hoffman et al., 2014)	na	na

a) Crosstabulation of ES flow types (Schröter et al., 2018), with ES type according to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Díaz et al., 2018).
na: Not applicable.

temporal and spatial scales are chosen.

3.1.1. Determine objectives and policy context

The assessment of interregional ES flows should briefly introduce the objectives of the study and the policy framework relevant to understanding its context. This entails establishing whether to focus on the sending or receiving role of the system or both, and place these systems within the appropriate policy context. For example, for flows of traded goods, a country that depends on imports for its food security may focus its assessment on imported food crops and related impacts on ecosystem services and biodiversity (Fridman and Kissinger, 2018). For flows related to species migration, international policies on protection of migratory species can be relevant policy contexts. Interlinkages between areas through species migration is recognized partly in some national and international agreements that refer to biodiversity protection and ES, e.g., the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) or the Man and the Biosphere Programme organized by United Nations Educational, Scientific and Cultural Organization (UNESCO) (López-Hoffman et al., 2017a). For passive biophysical flows, the policy context can comprise international agreements (e.g., UN Convention on the Protection and Use of Transboundary Watercourses and International Lakes and the UN Convention on the Law of the Non-Navigational Uses of International Watercourses, Brels et al., 2008) and related transboundary water treaties (Giordano et al., 2014), as well as agreements on air pollution (e.g., the Canada-United States Air Quality Agreement from 1991, Government of Canada, 2018). For information flows related to genetic resources from wild species, the Nagoya Protocol on Access and Benefit Sharing from 2014 is a relevant policy context (Gibson, 2016).

A common equity issue for all four flow types is the burden to protect ecosystems outside a country, which often has implications between the Global South and Global North, e.g. inequitable distribution of conservation costs and benefits. Such interregional conservation efforts are important, for example, for protecting breeding and overwintering habitats for migratory species that may be enjoyed for recreation in their breeding habitats in other countries or for maintaining interregional regulating services like carbon sequestration in forests or peatland ecosystems to mitigate global climate change.

3.1.2. Identify interregional ES flows relevant for society and policy

Relevant ES should be identified and prioritized for the analysis, specifying whether embedded ES and/or impacts on other ES are included in the assessment (Table 1). Such embedded ES directly underpin and support the provision of other ES, for example pollination supports the provision of certain crops (Schröter et al., 2018). For flows of traded goods, this step entails an identification of their related ES, such as provisioning of food and feed, biomass-based energy, materials and medicinal resources. For species migration and dispersal, this comprises an identification of migratory species present in a country and the ES they provide, e.g., habitat maintenance, pollination and dispersal of seeds or regulation of detrimental organisms (pest control). For passive biophysical flows, this step entails the identification of critical, measurable flows (water, air or mass) with societal relevance, often in terms of risk mitigation (e.g., flood regulation within transboundary watersheds) and their regional boundaries. For information flows, this step involves the identification of disseminated information about landscapes or species that contribute to learning, aesthetic appreciation and physical or spiritual experiences.

3.1.3. Determine system boundary and resolution

The boundary of the analysed system should be specified, both in space and time. The general procedure is to first identify the sending and the receiving system. For flows of traded goods, sending systems may vary between different traded goods and these can be identified using bilateral trade databases. For ES flows mediated through migratory species, sending systems comprise all relevant migratory ranges

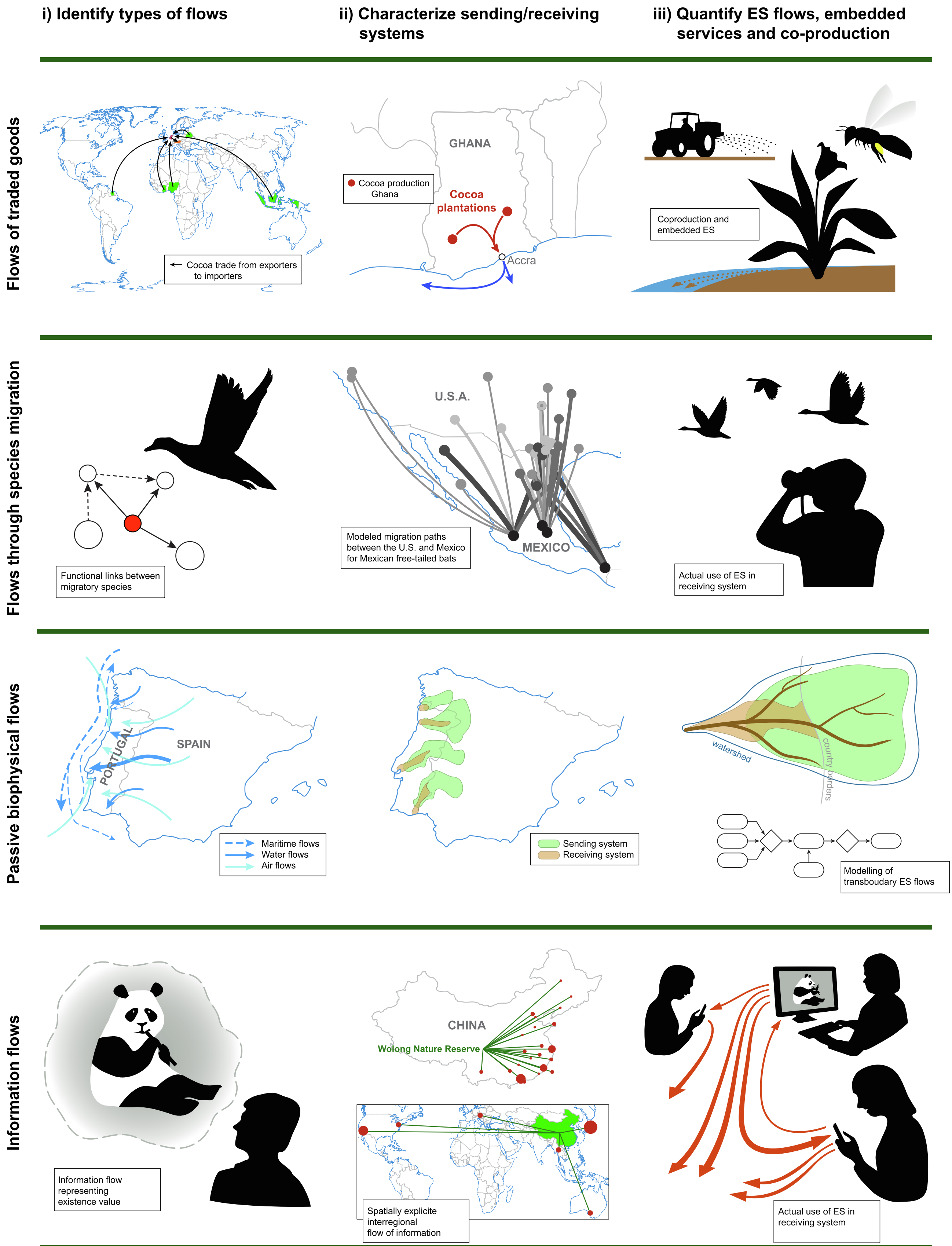

Fig. 2. Schematic representation of the three steps for the analysis and quantification of the four ecosystem service (ES) flow types, including (i) the identification of relevant flows, (ii) the characterization of sending and receiving systems and (iii) their quantification and modelling.

of service-providing species. For passive biophysical flows, one needs to identify which flows (e.g., water, air) are affected by specific natural entities at different scales (species, ecological communities, landscapes and ecosystems). These may include air currents, freshwater flows, marine currents, transnational aquifer or sediment flows, among others. For information flows, system boundaries can range from communities or countries to institutions (e.g., schools, universities) where the cognition of information received from ecosystems contributes to physical experiences, aesthetic enjoyment, spiritual and cultural experiences or learning. Additionally, the resolution of the analysis, e.g., whether results are nationally aggregated for sending or receiving ES or are spatially explicit at a given resolution, should be determined. For instance, for traded goods analysis, subnational scales may be desirable, in particular if impacts on other ES are considered (Fridman and Kissinger, 2018). Data are often only reported nationally, but companies may provide finer-scale data (Godar et al., 2016). For migratory species, typically large and often subnational "migratory regions" can be used (López-Hoffman et al., 2017b; Semmens et al., 2018). Passive physical flows are likely the most amenable to more fine-grained spatially explicit analysis, as models of water, ocean and air currents are often spatially explicit.

For the temporal resolution of the study it is important to identify whether the past, the present and/or future scenarios of ES flows should be analysed and at which frequency of repetition a study should be conducted (see also section 3.3a). A single study can raise awareness of potential problems, while monitoring the impact of policy measures requires either a trend analysis using past available data or a study design with repetitions of, e.g., every 1, 5 or 10 years. The frequency of analysis depends on its aims and on the ES under consideration. Assessment of ES flows facilitated by large-scale biophysical flows that are assumed to be fairly stable over time could suffice with a one-time effort. Other ES depend on seasonal (e.g., species migration) or long-term oscillations, setting a need to assess various moments in the cycle. Some policy-related impact assessments (e.g., reducing a region's consumptive impact on ES elsewhere) require changes to be tracked over time, including offsite or translocation effects. Trend assessments also require an adequate temporal resolution and extent. This often depends on data availability, e.g., trade data are often compiled annually at a national scale, while in-depth species monitoring may be performed less frequently but at a finer spatial resolution.

3.2. Perform assessment

This assessment step identifies a) to which type(s) of interregional flow the ES of interest belongs, b) characterizes sending and/or receiving systems in terms of socio-economic as well as environmental conditions and c) quantifies interregional ES flows, embedded services and co-production (see Fig. 2 for an overview). We describe this process below for the four flow types separately.

3.2.1. Flows of traded goods

Type of flow. Biophysical flows refer to the transportation of goods between a sending and a receiving system by means of trade (Schröter et al., 2018). For this flow type, a carrier intentionally transports an ES from a sending system to a receiving system, either directly or through a mediating system (spill-over system, e.g., locations where trade goods are processed). Traded goods are biomass based products such as fuel wood, food and feed, materials as well as medicinal and genetic resources (Díaz et al., 2018, see Table 1). After identifying the major traded products and the corresponding sending/receiving systems, the relevant ES flows should be narrowed down in line with the goals and scope of the assessment.

Characterize sending and/or receiving systems. Sending systems refer to the exporting region, where ecosystem services support production of biomass. Receiving systems refer to the region where a quantity of a final product like food and feed is consumed. Characterization of both systems in terms of socio-economic (e.g., population density, average income, land use) and environmental conditions (e.g. biodiversity, climate, soils) supports later interpretation of ES flows.

While the consumption of biomass based products can be measured on multiple scales, trade data are typically provided at the national scale. Identification of links between sending and receiving systems can rely on bilateral trade data, provided either by the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) or the UN Commodity Trade Statistics (COMTRADE) database for many biomass products or on CITES for wildlife products. However, official trade data have limitations in clearly linking sending and receiving systems, as supply chains are becoming increasingly long and complex, involving multiple mediating agents and spill-over systems. Procedures have been developed to address this challenge and to establish clear links between receiving and sending systems, i.e., their interactions and dependencies (e.g., Wiedmann et al., 2007; Kissinger and Rees, 2009; Kastner et al., 2011b; Weinzettel et al., 2013; Bruckner et al., 2015).

Quantify interregional ES flows, embedded services and co-production factors. The amount of ES flowing between sending and receiving systems serves as a basis for the assessment of embedded ES and co-production factors, i.e., the use of different forms of human, social, financial and technological capital in connection with natural capital to produce an ES (Palomo et al., 2016). For this step, the amount of ES or co-production input per unit of traded good is usually assessed, for instance, how much pollination (embedded ES) or fertilizer (co-production factor) are used for the production of one ton of coffee in a sending system. Units typically depend on the ES of focus and the methods used (see Table SI 1.A).

The number of studies of embedded ES is limited to date, owing to conceptual challenges (see e.g., Wolff et al., 2017 for an attempt to quantify the demand for pollination services in sending systems for food consumed around the world). A much larger body of work exists on the interregional flows of co-production factors such as land (Kastner et al., 2014; MacDonald et al., 2015), water (Hoekstra and Mekonnen, 2012; Dalin et al., 2017), energy (Guzmán et al., 2018), and phosphorus (MacDonald et al., 2012). Such flows are often labelled "virtual" (i.e., virtual water and land) in order to stress that the factors are not physically flowing, but are used in sending regions. Or they are linked with the term "footprint" (e.g. water footprint) in order to signal the negative impacts of using those factors in the sending system. The ecological footprint concept takes land area as a proxy indicator for the embedded ES stressing its scarcity (see Mancini et al., 2018). Additionally, work has focused on the (negative) impacts the production of the traded good has on other ES (e.g., Fridman and Kissinger, 2018) and on biodiversity (e.g., Brashares et al., 2004; Chaudhary and Kastner, 2016; Marques et al., 2017).

While data on ES provision and co-production can be developed at finer spatial scales (e.g., Mueller et al., 2012; You et al., 2014; Erb et al., 2017), trade data used to connect sending to receiving regions are largely limited to the national scale. Few studies aim to move to finer spatial scales in the sending systems (e.g., province or municipality within a country, Godar et al., 2015; Fridman and Kissinger, 2018). Identifying sending regions at these scales is most often limited by data availability, restricting the temporal, spatial and product level coverage. For moving to finer scales in the receiving system, Hubacek et al. (2014) suggest using household expenditure surveys, social media and geo-tagged expenditure datasets to understand how lifestyle and local consumption activities are affected by local factors. Looking at finer scales in receiving systems (district, municipal, household) would allow the analyst to virtually 'reduce' the distance between consumers and producers and might support more meaningful local-level decision making.

A tiered approach can overcome some difficulties that emerge due to the trade-off between the assessment's scope, scale and resolution.

Tier 1 would quantify trade flows at the national level using existing databases and describe the systems based on existing literature. Tier 2 would pair existing databases with additional data, relying on available sub-national, spatially explicit information for co-production, embedded ES and impacts where possible. Tier 3 would additionally rely on modelling (Schierhorn et al., 2013) and/or customized analyses of remote sensing data (Vicari et al., 2011) or field work (Gockowski and Sonwa, 2011) in the sending regions to generate local data on embedded ES, co-production and impacts.

3.2.2. Flows mediated through species migration and dispersal

Type of flow. This type of ES flow is mediated through species migration and dispersal that move between sending and receiving regions (see Table 1). Migratory species spend a significant part of their annual cycle (e.g., breeding, wintering) in both sending and receiving regions. Receiving regions denote the area where ES from those species are enjoyed by their human beneficiaries.

Characterize sending and/or receiving systems. The identification of sending systems is a crucial step in locating the ecosystems that support migrating species' provision of ES elsewhere. In principle, a service-providing species' entire range can be included. For passive dispersal of species, sending systems are the regions from which plant propagules or seeds, animals, fungi or microbes originate.

Areas identified as receiving systems are locations of actual ES use and can be regions or countries along a species' migratory path. Various types of data can be used to quantify ES use, such as aesthetic appreciation of migratory species in (social) media, birdwatching data from platforms such as eBird (*ebird.org*) and other citizen science data sources (Schröter et al., 2017), views on wildlife webcams for cultural ES (Loomis et al., 2018), hunting license or harvest data for provisioning or cultural ES and number of crop types pollinated and their area or value or pests controlled by migratory species for regulating ES. Advanced tier analyses may include details on the number of individuals providing the service (viewed, hunted/fished, providing pollination or pest control) through counts or species distribution models, combined with population density or survey data about human uses and preferences for ES.

Quantify interregional ES flows, embedded services and co-production factors. Interregional flows can be assessed through a combination of indicators, such as quantifying the number of migratory species and their ranges in the sending systems. These species can, for instance, be hunted, provide pest control or be enjoyed through birdwatching in a receiving system (Table SI 1.B). Due to limited data availability on migratory species, we suggest that the number of ES-providing migratory species with distinct sending and receiving regions can be used as a proxy for the flow. We distinguish four different ways of identifying sending and receiving systems, ranked by relative technical intensity. First, the range of identified migratory species can be quantified using species distribution models or expert-based occurrence extent maps (BirdLife International, International Union for the Conservation of Nature (IUCN) Red List). Second, within such rough assessments, the amount of habitat for each species in each location (e.g., in square kilometre) can be more specifically quantified and located (Rondinini et al., 2011). Third, the relative importance of each location can be quantified, e.g., the dependence of the species on that particular habitat in the sending system as compared to habitat elsewhere. This approach can be expert-based or, fourth, be modelled (Erickson et al., 2018; Wiederholt et al., 2018).

An example using a Tier 1 approach can include a literature review on ES provided by migratory species (Kunz et al., 2011; Green and Elmberg, 2014; López-Hoffman et al., 2017a). Another straightforward approach is the indication of service-providing migratory species ranges through expert-based maps that extend beyond the receiving system. Flows are approximated between the different seasonal areas of a species' annual range (breeding, non-breeding, passage). In this case, the information includes a spatial approach that allows a qualitative or quantitative assessment of interregional flows. Tier 2 includes more information on the actual use and value of the ES, quantities of the ES actually being provided by species (e.g., quantified pest species reduction) and quantities of beneficiaries making use of the ES (e.g., number of people participating in birdwatching). Tier 3 embraces a fully quantitative approach called the *spatial subsidies* method. It shows the relative mismatch between regions where a species provides ES value and regions of its greatest habitat dependence (Semmens et al., 2011). The method allows quantification of whether areas *subsidize* ES values elsewhere or *are subsidized by* other locations and can help guide rangewide conservation planning and investments. The method requires quantification, throughout the species' range, of ES values provided and the species' proportional dependence on each region. For example, spatial subsidies have been quantified for three North American species–Mexican free-tailed bats (Tadarida brasiliensis mexicana, López-Hoffman et al., 2017b), monarch butterflies (Danaus plexippus, Semmens et al., 2018) and northern pintail ducks (Anas acuta, Bagstad et al., 2018). A somewhat less data-intensive approach to spatial subsidies would use expert-based quantification, rather than habitat modelling (Wiederholt et al., 2018) and monetary valuation. To do so, experts would need to rank the relative importance of a species' rangewide habitat (summing to a value of one) and ES provision. An expert-based quantification would likely be easier to apply to a large number of species/taxa than a more data-intensive empirical approach.

An assessment of embedded ES can be conducted through spatial overlap analyses of ES in the sending regions, such as habitat creation and maintenance important for migrating birds. Co-production assessment for species migration and dispersal would include all types of land management influencing habitat in sending regions.

3.2.3. Passive biophysical flows/avoidance of detrimental flows

Type of flow. This type of flow is mediated by riverine, oceanic and atmospheric currents, often over long distances. These flows, originating in or passing through sending systems, have either a direct beneficial effect in the receiving system or mitigate detrimental environmental flows in the receiving systems (see Table 1).

Characterize sending and/or receiving systems. A conceptual model of the complete ES provision process is needed in order to characterize sending and receiving systems. This includes identification of the flow type and the location of the flow system, specifying the benefits and beneficiaries of the interregional flow and deriving the system boundaries from the location of the full system and sending/receiving systems within (Fig. 2). Delineation of receiving systems is done based on the locations where benefits are received. Delineation of sending systems is done by linking the ES provision process to ecosystems when accounting for passive flows (Bagstad et al., 2013; Stürck et al., 2014).

Quantify interregional ES flows, embedded services and co-production factors. Indicators for passive biophysical flows can be assessed using a tiered approach that considers different levels of complexity, data and knowledge availability (see Table SI 1.C).

Tier 1 encompasses land cover-based approaches. Basic hydrologic and air currents are identified and within these, land cover is used as proxy for ecosystems known to potentially provide the service (e.g., Nedkov and Burkhard, 2012). This can be combined with statistical models quantifying air or water flows and other matter that they carry (e.g., soil or nutrients). Tier 2 approaches make use of various types of data and mechanistic models to quantify ES use or demand, coupled with calibrated process-based hydrological or air current models. This increased level of complexity comprises a range of possibilities using index number-type models, uncalibrated physical models that quantify ES changes and calibrated physical models to assess spatially and temporally explicit flows if suitable data are available to represent a specific ES. As an example for carbon sequestration, an approach quantifying carbon emissions relative to sequestration in a region can be considered a suitable Tier 2 indicator (Bagstad et al., 2014). Indices based on the Universal Soil Loss Equation (Renard et al., 1997) or other soil erosion and transport models can be used for sediment retention (Norman et al., 2012). For Tier 3, fate and transport models precisely quantify (i) the source of ES or the carrier of a detrimental flow and (ii) where it is received by human beneficiaries or absorbed/mitigated by the environment (Norman et al., 2013). This allows a much more precise account of interregional ES flows and dependencies, but is a data-intensive approach, which is most often applied for hydrological models of flood mitigation or air- or waterborne pollutant dispersion (Brown and Hovmøller, 2002; Raptis et al., 2016).

Embedded services are assumed not to be relevant for this type of flow. Co-production factor flows can be quantified through a review of large-scale policies or investment flows.

3.2.4. Information flows

Type of flow. Information flows refer to the transport of information from a sending to a receiving system, where this information is received through cognition (Schröter et al., 2018). They are strongly related to non-material ES, such as learning, physical experiences related to tourism or aesthetic enjoyment and spiritual or cultural experiences of certain landscapes and species (Díaz et al., 2018, see Table 1). These flows are important for individual and social well-being and are often intangible and difficult to measure, as their impact may strongly depend on the culture, beliefs and perceptions of individual beneficiaries. These flows can also contribute to raising awareness of nature's importance through learning and scientific endeavours.

Characterize sending and/or receiving systems. To assess this flow type, the species, ecological communities, landscapes or ecosystems that are providers of information flows first need to be identified. The sending system where these species, species communities or landscapes exist needs to be characterized to contextualize their importance in providing the information flows. Boundaries of protected areas or other designated sites, e.g., UNESCO natural heritage sites, Biosphere Reserves, Sacred Natural Sites or locations of webcams, that send information on wildlife to a receiving system, can help to delineate sending systems. For example, the sending system of the information flow of the existence value of the giant panda can be identified as the Wolong Nature Reserve in China (Liu et al., 2015).

Quantify interregional ES flows, embedded services and co-production. For the quantification of the interregional information flows, the importance of each location for providing the ES should be assessed. This is heavily mediated by the nature of the service and its use for outreach and public relations by organisations (e.g., zoos, conservation organizations, media). Importance can be identified using expert-based assessments, data and public surveys and/or models. For example, as a proxy for ES use, those locations of highest importance are places with the highest density of geotagged photographs and/or videos uploaded in social media representing the importance of wildlife species and their habitats. A possible indicator is the number of photos uploaded annually per square kilometre, mentions in visitor books or image use in media or nongovernmental organizations (NGO) newsletters. Another approach to quantify the importance of information flows is to consider the number of visitors or visitor days for nature-based tourism at a given site (see Table SI 1.D).

In a tiered approach, Tier 1 would include a review of publications (like newspaper articles and reports) related to information flows between receiving and sending systems with regard to species, ecological communities, landscapes or ecosystems. In Tier 2, data on the actual use and value of such non-material ES can be collected and analysed. For example, the importance of a sending system for recreational experiences can be quantified through the number of people who upload photographs and videos in social media platforms, such as Flickr, Panoramio or Instagram, in a particular place (Willemen et al., 2015; Martínez Pastur et al., 2016; Hausmann et al., 2017; Oteros-Rozas et al., 2017). The origin and number of visitors and time spent in the sending system provides information on tourism and recreational experiences. National visitor statistics, provided by World Tourism Organization (UNWTO), Global Biodiversity Information Facility (GBIF) and Community Research and Development Information Service (CORDIS) could serve as data sources. For learning and inspiration, the number of contributors to citizen science recording schemes (e.g., eBird, i-Naturalist etc., Roy et al., 2012; Di Minin et al., 2015; Biodiversity Indicators Partnership, 2017; Chandler et al., 2017) and the origin of school curriculums studying issues related to the sending system could be quantified, e.g., the number of hours dedicated to nature-related topics about the sending system at different education levels.

Further, the number of users and quantity of keywords in digital search engines (Wikipedia, Google, etc., Proulx et al., 2014; Nghiem et al., 2016; Correia et al., 2017) in the receiving system with an interest in the sending system could serve as an indicator. Other media-based indicators like the analysis of the number of newspaper articles, magazine covers and articles, novels, logos, songs (Coscieme, 2015) or documentaries that report about the sending system in the receiving system could provide information on the ES flow (Liu et al., 2015; Carlson et al., 2018).

A comprehensive Tier 3 quantitative assessment does not exist for this ES flow type, but combined social media/photo analyses and discourse/content analyses could be suitable tools to identify physical and psychological experiences (e.g., Stepchenkova and Zhan, 2013). Kozinets (2002) describes netnography–the use of ethnographic methods for the analysis of online communities. Tussyadiah and Fesenmaier (2009) used these methods to analyse travel videos as mediators of tourist experiences. In order to identify ES flows related to learning, inspiration and supporting identities, but also for physical and psychological experiences, analyses with language processing software (computational linguistic analysis, semantic network analysis; e.g., Thelwall et al., 2010; Michel et al., 2011; Ladle et al., 2016), content analyses, surveys, focus group discussions with representatives could be used (Norton et al., 2012; Thiagarajah et al., 2015). Further, spatial autocorrelation could uncover patterns in information distribution between sending and receiving systems (Casalegno et al., 2013; Plieninger et al., 2013).

An assessment of embedded ES, such as habitat creation and maintenance is important for target species, and can be done through its spatial analysis in the sending system. Co-production is inherent to the information flow as this necessarily involves non-natural capital, such as people's knowledge and skills (human capital), social networks and structures that facilitate social interactions (social capital) and technological (in case the information flows are mediated by e.g. social media).

3.3. Conduct interpretation

The final step in interregional ES flows analysis is the interpretation of results in light of the study goal and scope (section 3.1). Specifically, the interpretation should provide an evidence-based assessment of current interregional ES dependencies and an evaluation of the assessment's uncertainty. Based on this, it should identify potential for improvement and facilitation towards more sustainable use of ES.

3.3.1. Uncertainty and data gaps

Uncertainty analysis should include an evaluation of the quality of the input data, propagation of uncertainties through the flow quantification approach and the consequences for validity of the output in the light of the purpose of the study (Hamel and Bryant, 2017).

While approaches for mapping or quantifying ES supply or demand *in situ* are already data intensive, the assessment of interregional ES flows requires even greater data availability. Additionally, *in situ* mapping or quantification of ES supply (sending systems) is often accompanied by high uncertainties (Bryant et al., 2018). Uncertainties in ES demand and within receiving systems are largely unexplored (Wolff et al., 2017). The larger array of data linkages and thematic and spatiotemporal resolution in analysing interregional flow will introduce uncertainties due to lack of data compatibility, and impact error propagation in subsequent analyses. For example, assessing interregional flows of pollination embedded in trade combines the mapping and quantification of pollination supply, demand for traded products dependent on pollination and trade flows. While supply and demand for pollination can be clearly linked to locations at high resolution (see e.g., Zulian et al., 2013), trade data are typically country specific. This hampers the linking of receiving systems to sending systems and consequently limits the potential of co-production analyses. Specific uncertainty aspects apply to the four flow types.

- Regarding ES flowing via international trade, we encourage the tracing of bilateral trade data back to the sending regions. Uncertainties in this process arise from the underlying assumption that used biomass products are assumed to be proportionally sourced from domestic production and foreign supply (Kastner et al., 2011b). This assumption propagates further when the flows of co-production factors, embedded services and impacts are quantified. Another major uncertainty arises when attempting to represent ES flows using high-resolution maps. Here, downscaling country specific crop trade data to high-resolution maps requires assumptions on crop coverage that inherently introduce uncertainties.
- Data gaps and uncertainties exist for the species migration and dispersal flow type regarding species' spatio-temporal distribution, population sizes, habitat dependence and legal and illegal harvest. Quantification approaches are uncertain in terms of the conceptual limitations of social media or citizen science approaches, the relative dependence of species on different habitats in their range, uncertainties with monetary valuation and benefit transfer if applicable and uncertainties in species distribution models.
- For passive biophysical flows, uncertainties depend on the service and Tier level; reasonably established datasets often exist though with limitations and uncertainties. For Tier 1 analyses building on land use/cover data, parameterization might be the largest source of uncertainty. Analysing water flows based on measured data (Turpie et al., 2008) means that measurement errors and the availability of calibration data have to be considered. For all Tier levels, model parameterization introduces additional uncertainties due to simplification of the process as well as ambiguous or limited process understanding (Schulp et al., 2014).
- For all analyses of information flows, care should be taken in data interpretation to provide inclusivity of different viewpoints. Analysis of any information medium, such as social media postings, newspaper articles or focus groups discussions, will only reflect the views of the respective users or participants. This is unavoidable and a balance should be sought between interest groups while potential biases should be clearly described, and, if possible, addressed.

A generic uncertainty issue concerns whether the scale of the data and models used matches the scale of analysis and the consequences of scale mismatches. The uncertainty analysis should at minimum qualitatively identify the sources of uncertainty and their potential size and

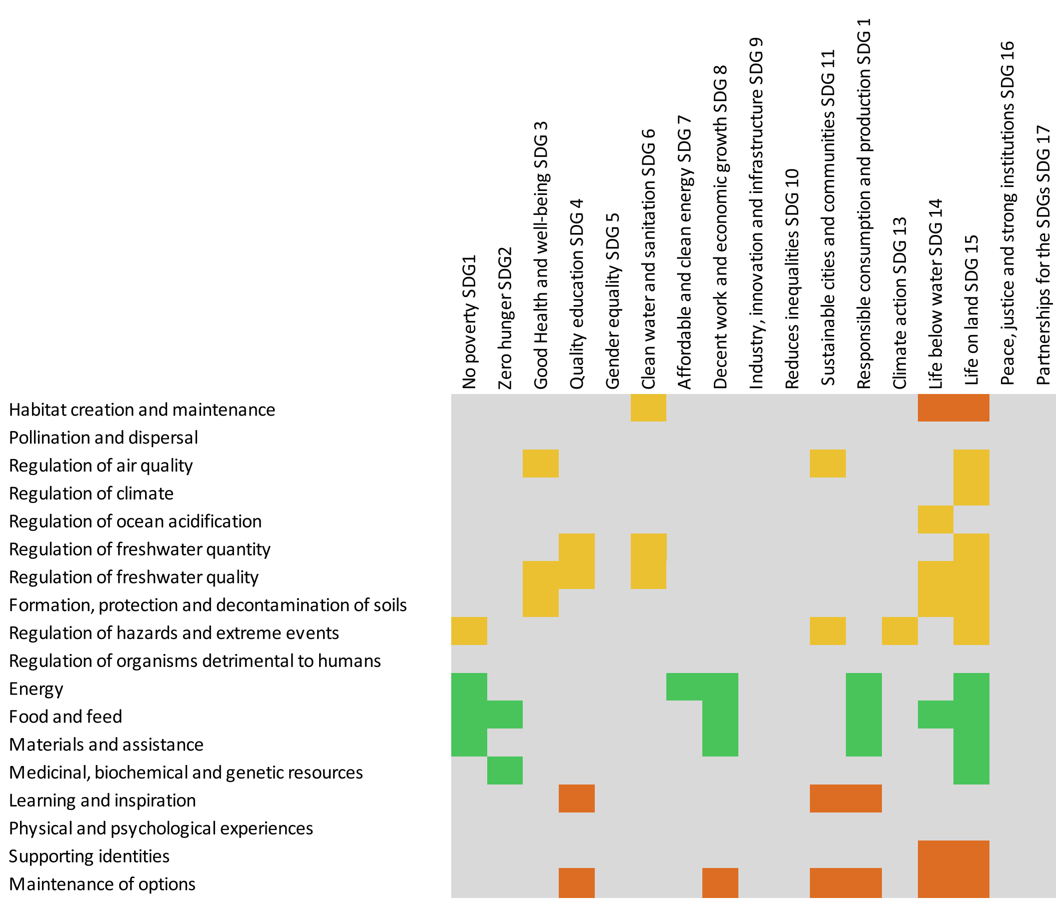

Fig. 3. Link between ecosystem services through three types of interregional ecosystem services flows (green: traded goods, yellow: passive biophysical flows and orange: information flows) and UN Sustainable Development Goals (SDG) indicators. Only links between ecosystem services and existing SDG indicators are mentioned (none found for migratory species).

location effects on modelled outputs. For model-based approaches, established techniques for uncertainty quantification exist, such as Monte Carlo analysis or quantifying a range of outputs (Hamel and Bryant, 2017).

A common data gap is associated with temporal aspects of ES change (Rau et al., 2018). Temporal patterns of ES supply are often unknown, may be complex and non-linear and affected by both abiotic physical changes (e.g., in hydrology or climate) and indirect socio-political drivers that determine land-use change. ES demand and flow are affected by a complex set of social, economic and political drivers; together these make interactions between sending and receiving regions volatile. Time lags between changes in the sending system and effects in the receiving system are common, such as in heat transfer through the Pacific Decadal Oscillation. Responses are therefore likely to face time lags and often occur in response to events (Rau et al., 2018). Data on temporal dynamics of ES supply, demand, and flow are rarely available, with the exception of trade data. While the lack of data hampers monitoring and empirical evaluation of changes in interregional flows, scenario analysis could contribute to the quantification of uncertainties in potential future changes.

3.3.2. Interpret consequences of interregional ES flows

A central aim in the analysis of interregional ES flows is to assess the linked socioeconomic and environmental consequences of such flows on both sending and receiving systems. These relate to the positive or negative consequences of such flows for national economies, dependency, equity and ultimately security in each system.

The Sustainable Development Goals and their indicators provide a useful frame to link ES flow types and different aspects of development and human well-being that might be affected by ES flows in sending and receiving systems. For example, we found a potential link between interregional ES flows and 12 of the 17 Sustainable Development Goals for at least one type of flow (Fig. 3). For SDG goals 14 (Life below water) and 15 (Life on land) we found links with most types of flows (traded goods, passive biophysical flows, information flows) and with the highest number of ES categories (SDG 6 and 13, respectively, see Table 2 for examples). Individual ES categories most often found to have a link with SDGs were food and feed, maintenance of options (six times each), regulation of freshwater and coastal water quality and energy (five times each) (counted only once per SDG-flow type combination). Traded goods and passive biophysical flows were found to potentially influence seven SDGs and information flows six SDGs. Species migration flows was the only flow type without a direct relationship with the proposed indicators to measure progress towards the SDGs. This does not mean that species migration is not essential to achieve the SDGs, but that the identification of this link is missing at the policy level. For example, SDG goals 14 (Life below water) and 15 (Life on land) comprise broad biodiversity conservation goals, which also affect migratory species.

Generally, when an interregional ES flow affects a SDG, it does so by influencing both sending and receiving systems. For instance, traded goods of food and feed, materials and energy have effects on both the importing and the exporting country. Interregional ES flow assessments should therefore take into account this in particular affect poverty, hunger and health SDGs. Fair and equitable benefit sharing of genetic information – a process that inherently involves interregional ES flows – is directly mentioned in SDGs 2 and 15.

While some aspects of interregional ES flows are can be interpreted using the SDGs (in particular, those addressing basic needs and health), there are other societal concerns that are important to consider, such as economic impacts, social cohesion and cultural identity. One way to interpret the consequences of interregional ES flows is economic impact evaluation. Impacts of flows in the receiving region can use multiple valuation methods, e.g., replacement costs for pest control (López-Hoffman et al., 2014) or harvested meat (Goldstein et al., 2014), visitor expenditures and consumer surplus (e.g., recreational use, such as hunting & fishing, Mattsson et al., 2018) or non-use values (Semmens et al., 2018). If implemented, spatial subsidy-based conservation payments would thus typically flow from the Global North to the South. Impact assessment in the sending system is related to the state of and pressure on habitat types, land cover or ecosystems of the sending system, e.g., their protected status, carrying capacity and vulnerability. The impact assessment in the receiving system could inform policymakers about potential consequences of their decisions.

Furthermore, interregional ES flows can also be interpreted in terms of social cohesion and cultural identity. For example, the rising demand for biofuels in Europe (Lamers et al., 2012; Blaber-Wegg et al., 2015) has entailed negative economic, social and cultural impacts in the Global South (Overbeek et al., 2012). The increasing demand for land in the South for biofuels, particularly oil palm and soy, has resulted in increasing trends of land grabbing (Rulli et al., 2013; GRAIN et al., 2014), threatening the rights of land access and tenure of indigenous peoples and local communities (e.g., Obidzinski et al., 2012; Overbeek et al., 2012; Mingorría et al., 2014). Competition for land access has in many cases created social conflicts and jeopardized social cohesion between communities (Rist et al., 2010; Overbeek et al., 2012; Mingorría et al., 2014; Brad et al., 2015). Cultural identity can be compromised even by the substitution of croplands with cultural meaning (e.g., maize in Central America) by oil palm (Mingorría et al., 2014) or acquisition of ancestral lands with spiritual and cultural meaning by agricultural companies (Abbink, 2011; Grant and Das, 2015).

As the above examples illustrate, strong interlinkages of distant locations result in an unequal distribution of benefits and costs of ES

Table 2
Examples of Sustainable Development Goal indicators potentially being affected by interregional ecosystem service flows.

Flow type	SDG Indicator	Discussion/Explanation
Physical flows of traded goods	8.4.1 Material footprint, material footprint per capita and material footprint per GDP	Flows of traded goods influence the total material footprint of a country, derived from both inside and outside ecosystems
	15.6.1 Number of countries that have adopted legislative, administrative and policy frameworks to ensure fair and equitable sharing of benefits	Flows of ecological entities bearing genetic information from sending to receiving systems
Passive biophysical flows	6.5.2 Proportion of transboundary basin area with an operational arrangement for water cooperation	Flows of water used for drinking water and prevention of detrimental flows (flooding)
	13.1.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population	Regulation of hazards, like floods, across long distances, for instance in an international watershed
Information flows	12.8.1 Extent to which (i) global citizenship education and (ii) education for sustainable development (including climate change education) are mainstreamed in (a) national education policies; (b) curricula; (c) teacher education; and (d) student assessment	Information flows on species and ecosystems supporting learning and inspiration in the context of education for sustainable development
	15.1.2 Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type	Knowledge on existence of protected areas contributes to the service category supporting identities, which includes the satisfaction derived from knowing that a particular ecosystem, habitat or species exists

consumption. While many societies can mutually benefit from telecoupling, e.g. for ensuring food security (Wood et al., 2018a) they can also undermine human well-being and security of communities worldwide, particularly in the Global South. For example, consumption and trade patterns of coffee or palm oil in the Global North can trigger unsustainable exploitation and degradation of ecosystems in the sending countries (Jha et al., 2014; Mingorría et al., 2014) and impact on land degradation and the security of affected communities.

In the context of telecoupling, the idea of human security is vital, since it follows a people- and actor-centred approach and addresses the needs, rights and values of those living in regions providing ES to other regions and potentially facing risks in doing so (O'Brien et al., 2013). Some aspects of human security can be easily incorporated in national-scale assessments through objective indicators for access to food, water or shelter or life expectancy among others. Here, the SDG indicators can be employed or the Human Security Index (Hastings, 2011) can serve as an umbrella indicator. Less tangible and subjective aspects of human security referring to cultural norms and values or socio-psychological attitudes and impacts are less easy to take into account. Indirect outcomes of land degradation through overexploitation, such as violent conflicts or migration, can be significant, but are less easily measured and also depend on interactions with other socio-political factors (IPBES, 2018b).

3.3.3. Formulate options for governance

The interpretation of interregional flow assessments should provide a baseline for considering ES governance, development and overall sustainability (Schröter et al., 2018). Most importantly, a more comprehensive view of how interregional flows and associated policies affect ES provision and allocation can inform policy, showing how a region's social well-being is affected by environmental conditions abroad and how consumption impacts ecosystems elsewhere. In many cases, interactions are nested and non-linear feedbacks exist, making assessments highly complex. This points to the importance of developing robust indicators that can raise awareness about the distant effects of consumer choices and dependencies on distant regions. Ultimately, such analyses can inform certification schemes and bilateral agreements and treaties to support responsible consumer and policy decisions. To sustainably manage resources, externalities of environmental and social costs incurred elsewhere would need to be internalised in the costs of traded goods or payments for ES as well as subsidy payments to sending regions of migratory species (e.g., Bagstad et al., 2018). Additionally, cross-boundary catchment management plans, clean air acts, designation of conservation areas or access and benefit-sharing agreements could consider such interregional ES flows. Overall, the potential for improved equity and economic efficiency (i.e., increasing benefits, reducing damages) or even approaches towards interregional optimization (Kreidenweis et al., 2016) could be elaborated. This deliberation should be conducted with experts from NGOs, policy, science and the private sector.

To formulate and finally to decide for policy options requires also to make different ES flow types commensurable (i.e., to measure them on the same scale in order to compare losses and gains). A unit of measure is required which allows a comparison between the different ES flow types and which would facilitate an analysis of their trade-offs. A common standardized unit is in monetary terms (Abson et al., 2014). Traded goods have a market value and other ES flow types could be identified by socio-cultural values translated into monetary values by, e.g. willingness to pay or the travel cost method. However, the critique on monetization is related to transfer the pricing mechanism to ecosystems and their services which are not for sale (i.e., limits to "commodification", Gómez-Baggethun and Ruiz-Pérez, 2011). ES with intrinsic or bequest values are hardly covered by economic analyses. In addition, socio-cultural values are context and scale dependent as they are rooted in perceptions (Hauck et al., 2013). In order to recognize plurality in values of nature, approaches that consider multiple values and attributes should be preferred (Martín-López et al., 2014; Arias-Arévalo et al., 2018). Decision-making can be facilitated by multi-criteria valuation methods, e.g. by ranking and weighting of semi-quantitative values on a Likert-scale (Koschke et al., 2012) or by multi attribute utility functions (Würtenberger et al., 2006). Quantitative values from the different ES flow types of one Tier level could be standardized and weighted based on preferences, e.g. by experts or stakeholders.

4. Conclusions

This guidance provides a blueprint for assessing interregional flows of ES flows, their potential connections to the SDGs, as well as related aspects of governance, trade and resource management. Our structured, systematic approach considers four different ES flow types (Table 1), and synthesizes relevant scientific work on appropriate methodological approaches for each type. Our intention is to support ecosystem assessments such as national ecosystem assessments and ecosystem accounts which should consider externalities implied by interregional ES flows.

As discussed above, analyses of complex interregional ES flows are likely to have high data demands. Given that data is often scarce, we present a tiered approach of three levels of analysis, starting at Tier 1 with basic evaluation that can be conducted with sparse data, to more complex analyse (Tiers 2 and 3) as data and resources become available. We recognize that it is important to communicate associated uncertainty in an accessible way, so that analyses can be improved when further evidence becomes available. We note that while our guidance cannot provide in-depth technical description of all quantification approaches, because the four ES flow types cover wide fields of research, it presents a starting point for researchers interested in assessing interregional flows. Most importantly, these approaches require collaboration across different disciplines, as well as practitioners, to generate meaningful and policy-relevant assessments.

The next step in the study of interregional flows of ES is to apply this guidance to case studies. Such efforts will naturally be limited by data gaps and resources available. As a starting point, it will be important to quantify the impact of interregional ES flows between nations. This will provide evidence to develop metrics and national indicators, inform certification schemes, trade and natural resource management. This is needed to address root causes of global biodiversity and ES losses, and to inform institutional responses and governance models to reach the SDGs and goals of the Convention on Biological Diversity. Developing the evidence base for understanding interregional ES flows and working towards national and global-scale solutions can support the goal of ensuring long-term and sustainable ES provision. In sum, information on interregional ES flows will inform efforts to halt and reverse land degradation, increase food and water security, contribute to climate mitigation and adaptation and avoid conflict and migration for a sustainable future.

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Appendix A. Supplementary data

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