COUPLED

OPERATIONALISING TELECOUPLINGS FOR SOLVING SUSTAINABILITY CHALLENGES FOR LAND USE

Deliverable D3.1

Operationalizing telecouplings: measuring and describing flows

Report on the outcomes of VMS 1 (flows)

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About COUPLED

Human consumption of food and agricultural products has a significant impact on the environment and the societies in the regions where they are produced. Different sectors, consumers, businesses and politicians are increasingly demanding more environmental and social sustainable land use both inside and outside Europe. Yet, there is increasing recognition of the limitations of current research approaches to adequately understand and address the increasing complexity of land system dynamics, which are often characterized by strong non-linearity, feedback mechanisms, and local contexts, and where places of production, trade, and consumption of land-based products are increasingly separated.

Coordinated by the Humboldt-Universität zu Berlin, COUPLED is a European training network in order to better integrate research, innovation and social responsibility framed around the concept of telecouplings.

COUPLED trains Early Stage Researchers capable of:

- understanding processes and actors that influence land use in an increasingly interconnected world
- considering distant, unexpected feedbacks and spillovers and to account for their social and environmental impact
- fostering new and enhanced governance measures that can shape land-use couplings to deliver more sustainable outcomes of land-use decisions

For more information see www.coupled-itn.eu

Executive Summary

Telecouplings describe the increasing coupling of human and natural systems across large distances through a range of processes, such as trade or flows of information. The telecoupling framework posits that these distal links need to be considered for comprehensively assessing the sustainability of land use. The telecoupling framework also has stimulated the scientific community to engage further with complexity and global interconnectedness when analysing the drivers, processes and consequences of land use and land-use change. Through that, the framework has emphasized the necessity of complementing place-based research with flow-based studies. It furthermore introduced the two crucial concepts of feedbacks and spillovers, which encouraged researchers to look beyond a single flow, to explore how this flow may generate responses and cascades in other human and natural systems. Despite these achievements, telecoupling studies have mainly been focussing on commodity trade, often neglecting the importance of other types of flows, and have largely fallen short of studying how these flows are influencing each other.

This deliverable reviews different types of flows and seeks to categorize them into a comprehensive typology of flows, based on the ESRs individual projects in COUPLED as well as on literature reviews. The deliverable furthermore seeks to list methods to study these flows, it provides a first attempt at an inventory of major databases for characterizing each type of flow, and it documents the development of a typology of “relations between flows” to better understand the interactions among different flows. Thus, the report aims providing a set of tools to carry out inclusive flow-based studies. Within COUPLED, this deliverable is situated within Work Package 3: PROCESSES, which seeks to understand the inter-dependencies between land and resource systems, and which flows, actors and processes produce these dependencies through forging telecouplings. The outcomes of this work package, including this deliverable, feed into synthesis efforts taking place in Work Package 6, which aim for operationalizing the telecouplings framework for sustainability research and practice.

This deliverable documents and exemplifies a typology consisting of five main categories of flows: Materials; Information; Capital; Organisms; and Energy, which we all further split into sub-categories. We illustrate all these categories with a range of examples. This typology therefore provides a comprehensive and structured overview of flows relevant for land use and thus telecoupling in land-based human-natural systems. We furthermore suggest that comprehensive telecoupling studies should consider looking simultaneously at several of these flows and their interrelations. To facilitate this, we provide an inventory of databases that may help researchers finding data for each type of flow of the typology. Finally, we list a range of methodological tools that have been used to analyse flows, which may help telecoupling researchers to extract information or metrics out of the databases, and use these data to analyse and visualize multiple flows.

This deliverable concludes by arguing that the concepts of feedbacks and spillovers, despite setting the scene for more comprehensive flow-based research, are currently limited with respect to three aspects. First, a flow in one direction might not only be coupled to a flow in the opposite direction (i.e., the feedback), but also to one or more flows in the same direction, which we here refer to as “parallel flows”. Second, the definition of feedbacks, spillovers, sending systems, and receiving system, requires the researcher or practitioner to choose a flow of main interest, which may not always be evident, especially in global studies. Finally, feedbacks and spillovers may hide a large variety of relations between flows, where each of these relations may require different analytical approaches to be analysed. We therefore suggest a concept of relations between flows, and develop a corresponding typology, composed of the following relations: medium and content, cause and consequence, complements, substitutes, exchange, and common actor (table 4). We believe that the concept of relations between flows may usefully complement the current telecoupling framework. Indeed, in cases the research objective of a study obviously underlines one main flow of interest, the concept of relations between flows will help to explicitly define the nature and origin of feedback and spillover flows. In other cases, this concept might allow researchers to apply the telecoupling framework without framing beforehand one main flow or system of main interest, but eventually afterwards. This might give interesting findings, and prove useful when looking at telecouplings from a global perspective. We hope our set of tools can help providing comprehensive answers for flow-based governance of telecoupled sustainability issues, by enhancing analyses of interactions between multiple flows.

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Abbreviations and Acronyms

CAIDA:	Center for Applied Internet Data Analysis
COMTRADE:	United Nations Commodity Trade Statistics Database
CSR:	Corporate Societal Responsibility
FAOSTAT:	FAO Statistical Databases (Food and Agriculture Organization of the United Nations)
EASIN:	European Alien Species Information Network
ESR:	Early Stage Researcher
EU:	European Union
EW-EFA:	Economy-Wide Energy Flow Analysis
EW-MFA:	Economy-Wide Material Flow Analysis
FRC:	Forest Risk Commodities
GSDR:	Global Sustainable Development Report
HANPP:	Human appropriation of net primary productivity
HS:	Harmonized System
ITU:	International Telecommunication Union
NPP:	Net Primary Productivity
OEC:	The Observatory of Economic Complexity
OLS:	Ordinary Least Squares
SETC	State Economics and Trade Commission
TRNA	Thomson Reuters News Analytics
UN:	United Nations
UNEP-IRP:	United Nations Environment Programme - International Resource Panel

Role of this deliverable in the wider COUPLED research strategy

Within its wider research strategy, COUPLED seeks to explore three overarching research questions:

1. Processes: How inter-dependent are land and resource systems in today's world, and what are new or unexpected actors and processes creating the telecouplings that produce these dependencies?
2. Distance: How is sustainability governance of land use and land-based products affected by differences in the type of linkages and telecouplings and the scale at which they operate?
3. Impacts: Which enabling conditions are required to generate opportunities for a more sustainable allocation of resources in a telecoupled world?

COUPLED addresses these three questions in three Work Packages (WPs), where the work packages relate to one research question each: WP 3 Processes, WP 4 Distance, and WP 5 Impacts. These work packages generate knowledge, via the ESRs individual PhD projects as well as various synthesis activities, that then flow into the WP Synthesis. Thus, all WPs provide a platform for collaborative, comparative and cross-sectoral research. Concretely, WP 3 will enable ESRs 1-5 to understand which kinds of processes and flows characterise telecoupled land systems and explore methods such as commodity chain analysis, material and energy flow analysis, and qualitative following techniques in order to identify and measure flows, to recognise and categorise actors, and to capture different types of spill-over flows. WP 4 focuses on the role of spatial and temporal distance in telecouplings. ESRs 6-10 will explore sending, receiving and spill-over systems by focusing on how to methodologically and conceptually define system boundaries and distance in telecoupled systems. Specifically, the ESRs will explore how to establish a unit of analysis and a workable definition of distance, how to incorporate insights from the social and natural sciences, and how to develop methodologies for measuring the strength and direction of flows across institutional, governance, social, and Euclidian distances. This will enable these ESRs to assess mismatches in flows between systems, providing entry points for policy interventions. In WP 5 ESRs 11-15 will qualify and assess systemic couplings in terms of their impacts. Using methods such as participant observation, remote sensing, supply chain analysis, and policy charting over distance these ESRs will explore causal relations, such as whether or not an observed land-use impact is the result of a particular telecoupling. Understanding actual outcomes of telecouplings will enable these ESRs to identify winners and losers of specific couplings, facilitating governance discussions regarding how to mitigate trade-offs and how to allocate resources and impacts more justly.

WP 6 will then bring together and synthesize research from the ESRs' individual projects and the cross-cutting activities in WP 3-5. Specifically, WP 6 will facilitate the operationalisation of telecoupling research via two measures. First, COUPLED will develop typologies of telecouplings and sustainability indicators for telecoupled systems based on typical combinations of actors, flows, impacts and trade-offs to identify whether more sustainable outcomes have been achieved in terms of greener, more efficient, and more socially just production, resource use, and consumption, and how and where to intervene in telecoupled systems to ensure this. Second, this will be further facilitated by the development of a Telecoupling Toolbox, where data, methods and tools to assess and model telecouplings will be organised according to the needs of different actors (e.g. companies, NGOs, governments, international organisations) and sectors (e.g. agriculture, forestry).

Virtual Meeting Series are a central tool in WPs 3 to 5 to enable discussions, knowledge consolidation and synthesis across the individual ESR projects. This deliverable 3.1 documents the outcomes of the first such Virtual Meeting Series (VMS1) within work package 3 PROCESSES which reviewed the types of flows that link land systems across large distances (e.g. biomass, information, capital). Moreover, VMS 1 identified datasets to measure and describe these flows, as well as screened methods to measure diverse flows in telecouplings (e.g. GIS, land-system models, commodity chain analyses, MEFA, network analyses). Finally, the ESRs took this VMS in the direction of thinking particularly about interrelations between flows, and the usefulness of concepts of feedbacks and spill-overs in this context.

1 Introduction

In a globalized and interconnected world, tangible and intangible items flow from one area of the planet to the other. From goods, people, and capital to ideas, information, memes, and energy, flows traverse the globe connecting individuals, corporations, and governments across space and time. Making sense of and analysing the implications of globalization and of an interconnected planet, and working towards ensuring the sustainable utilization of resources is central to the academic work within land system science. This report reflects on the telecoupling approach (Liu et al. 2013; Challies et al. 2014; Friis et al. 2016; Friis & Nielsen 2017), which has in recent years been used to describe, understand, and analyse the interrelation and interconnectedness of human-natural systems. Within the telecoupling framework, as described by Liu et al. (2013), five interconnected components are presented: Systems, Agents, Flows, Causes, and Effects. The focus on the present paper is on one of these components: flows.

The need for flow-based to complement place-based research and governance, had already been acknowledged in land use sciences by Seto et al. (2012) with the term teleconnection. Teleconnections build on flows which link physically or culturally areas and systems that might be separated in space. The initial telecoupling framework already integrated the teleconnection concept by introducing the two major concepts of feedbacks and spillovers (Friis et al. 2016). These feedbacks and spillover processes can be observed between different flow types. Ideally all these processes should be considered simultaneously at global scale, to carry out comprehensive telecoupling studies and polycentric governance strategies (Oberlack et al. 2018). While the importance of addressing teleconnections is already acknowledge since almost a decade, actual mapping and quantification of these processes lags behind. This report aims to further involve the teleconnection concept in telecoupling research, by providing a set of tools to carry out inclusive flow-based studies: a comprehensive typology that structures different types of flows and aids further exploration by pointing users to a list of methods to study these flows, as well as an inventory of major databases for each type of flow, and a second typology of relations to understand the interactions between various flows.

Kapsar et al. (2019) already identified a list of flows analysed in the telecoupling literature. We attempt to generalize this first list of flows into a more comprehensive and structured typology. We aim for a classification that collectively encompass all types of relevant flows for land use science, while mutually excluding each other (see discussion for caveats concerning this claim). We therefore include “energy flows” as an independent category, but encompass for instance “investment” to the broader category of “capital flows”. For each of the five broad categories, we structured further as for instance the category "flows of organisms" which encompasses “animal migration”, “species dispersal”, “human migration” and “tourism” listed by Kapsar et al. (2019). Our typology attempts to complement and further conceptualize existing lists. It comes with inventories of relevant and available data sources for each type of flow, and methods currently used to reveal, analyse and visualize these flows, in order to guide researchers to make full use of our typology.

Finally, this report argues that the concepts of feedbacks and spillovers, despite setting the scene for more comprehensive flow-based research, offer limited potential to reveal processes in telecouplings with respect to three aspects. First, a flow is not always coupled to flow in the opposite direction (the feedback), but as well to flows in the same direction, which we refer to as “parallel flow”. Second, the definitions of feedbacks and spillovers, as well as sending and receiving systems, suggest that the researcher must choose a flow of main interest, which may not be obvious especially for global-scale studies. Third, the concepts of feedbacks and spillovers may hide a wide range of relations between flows, each being revealed by adapted analytical approaches, and coming with specific implications. We therefore suggest a concept of relations between flows and a corresponding typology. We argue that this concept can complement the current telecoupling framework, or sometimes even be more adequate for pragmatic and comprehensive flow-based research, especially when looking at telecouplings from a global perspective.

2 Definitions

This section seeks to define key terminology as it is used in this deliverable.

- A **flow** is defined as the movement of an entity, which we refer to as content, between two systems.
- A flow is moving between two **stocks**, which are in practice defined based on the system boundaries chosen by the researcher, and expressed according to the indicators used to track the flow (e.g. number of individuals, kg, kW).
- A **coupling** is the combination of several flows, between the same two systems. The telecoupling framework assumes that the researcher picks one flow of main interest, and defines all other flows, as well as the names of all involved systems, relatively to this flow of main interest.
- In the initial framework, origin and destination of the main flow are respectively defined as the sending and receiving system of the coupling. We acknowledge that it may not be always straightforward to identify a main flow, so we suggest to talk about content flowing from an **origin system** to a **destination system**[1 2] to qualify all flows.
- Consequently, in the initial framework, a flow whose direction is opposite to the one of major interest is called a **feedback** (Liu et al. 2018a).
- We suggest to add the notion of **parallel flow,** for a flow moving in the same direction as the flow of major interest.
- Flows that are linked to the main flow of interest, but involve other systems than the sending and receiving systems are called **spillover flows** (Liu et al. 2018a). For instance, conservation efforts to protect the Amazon rainforest (flows of information and/or funds) may lead to shift/increase commodities sourcing (material flows) from surrounding areas with unprotected native vegetation.

<u>Attributes of Flows</u>

- A flow can be **intended or unintended**, depending on the willingness of an agent / a group of agents to send and receive it. Intended flows of materials mostly correspond to trade relations between systems, while unintended flows of materials can range from transboundary pollutants to wind and water streams.
- The content can be non-reproducible, freely reproducible, or costly reproducible. In the case of **non-reproducible content** (i.e. content that is prompt to the laws of mass and energy conservation), the total differential of the stock has to equal the sum of inflows minus outflows (e.g. materials, energy). One unit of content flowing to the destination is hence not available anymore in the stock of the origin system. On the other hand, stocks of **freely reproducible content** can instantly grow, so that content can be instantly duplicated in the moment it flows out. The obtainment of one unit of content by the destination system does not prevent the origin system from possessing it as well. Such flows (e.g. information) thus do not reduce the stock in the sending system. In between, outflows of **costly reproducible content** do not per se prevent the origin system of possessing it again, but the latter faces a production cost (accounted in time, money, education…) to rebuild its stock (e.g. organisms).

[1] We encountered several terms to qualify the **origin** of flows in telecoupling literature, meaning the system from which the considered content "flows" or "move outward" (Liu et al. 2013) (e.g."provisioning area" (Serna-Chavez et al. 2014), "service provision hotspot" (Palomo et al. 2013), "area of service supply" (Nedkov & Burkhard 2012), "area where the content that flows is sourced" (Schröter et al. 2018), or "original production countries (Kastner et al. 2011)).
To qualify the **destination** of flows, we found the notions of "benefiting area" (SBA) (Lautenbach et al. 2012; Serna-Chavez et al. 2014), "area of service demand" (Nedkov & Burkhard 2012), "importing country", or "country of consumption" (Kastner et al. 2011). In Material and Energy Flow Analysis (MEFA), the destination can either be the "socio-economic stock in the national territory", or the "extra-national territory" (Haberl et al. 2016). Finally, research about international funds would rather talk about the "recipient" of the fund.

[2] In practice, sending and receiving systems are commutable, according to the scope of the research question that is addressed. For instance, trade-based analyses traditionally meant to define the producing countries as sending systems, and the consuming countries as receiving (benefits) systems. However, in a study about lifestyle aiming to assess the impacts of changing demand for agricultural commodities, the consuming country takes on the role of system sending the demand (request) to the global food system, and countries involving in the production and exportation of these commodities to the consumption basin are the receiving systems. The coupled human-natural systems are the same but their roles in the telecoupling swap because the scope of the study differs.

- Stocks and flows of freely reproducible content are however often limited by their **medium**. For instance, the knowledge of a given community is a stock of information that can theoretically be reproduced freely, and spread and share to members of this, or other communities. In practice, flows of information face mediums depletion: the knowledgeable humans themselves, and the communication technologies (talking, paper, radio waves, internet, etc).
- The literature often qualifies additional flows directly related to the telecoupling process analysed as “embodied flows”. We suggest that the term “embodied flow” actually endorse three different meanings, which are worth distinguishing: “upstream requirements”, “embodied impacts” and “medium-content relations”. **“Upstream requirements”** refer to all the anthropogenic inputs (e.g. knowledge, investments), and ecological processes (e.g. pollination, photosynthesis, precipitation) required along the value chain to produce the content flowing. Upstream inputs do not reach the final destination, but are essential to major flows. **“Embodied impacts”,** sometimes referred to as “flows of impacts”, are the positive or negative outcomes occurring along the value chain. Impacts from flows are benefits (e.g. ecosystem services), but also burdens (e.g. pollution, deforestation). Assessing impacts often requires considering people's valuation of flows’ outcomes through adapted metrics (e.g. kcal available per capita). Outcomes may be regulated through a market or not, thus being externalities. Although assessing “upstream requirements” (e.g. virtual water flows) and “embodied impacts” (embodied deforestation) are essential for assessing sustainability or justice issues in telecouplings, these do not inform about the processes which link two systems. Thus in this paper, we qualify the process of several contents flowing along with the same medium[3] by the title **"medium-content relation”** (see section on relations between flows).

Attributes of systems

- The two systems delimiting the flow can be defined **ontologically** (i.e. based on geographical, often national or administrative, boundaries), or **epistemologically** (i.e. based on social, economic, cultural, institutional or environmental distance) (see report of Coupled Work Package 4 – Distances) (Friis & Nielsen 2017).
- Flows are likely to run through **intermediate systems** before reaching the final destination. Theory about networks underlines that each intermediate may enhance, diminish, modify or even stop the flow (Newman 2010). Acknowledging the existence of intermediate systems is essential to understand the functioning of the flow, and how do benefits and burdens distribute along the flow chain (Drakou et al. 2018). In land system science, it is often useful to trace back to the first origin of the flow, for example in order to link primary producers to final consumers of land-based commodities. Nonetheless, completely ignoring the existence of intermediate systems would oversimplify the picture, and hide some processes in the telecoupling since spillover effects may originate from intermediate systems as well.

Temporality

- While a flow is often observed among two systems over a period of time, a stock is observed in a specific system at a given point in time (Haberl et al. 2017). Stocks and flows are related to each other through the **turnover rate** (Erb et al. 2016). In the previous example, the turnover rate relates to the time a given piece of information gets forgotten within this community, either because of lacking storage capacities, or because all mediums (people, books, etc.) have left the given community. The turnover rate can inform about the resilience capacity of the systems of origin.
- Flows are **dynamic** as their intensity and direction change over time (e.g. trade relations, migration patterns, CO_2 fluxes). Temporal dynamics should be tracked in telecoupling studies as they are likely to explain part of existing land systems, and give rise to non-linear system changes and spillover effects in distant areas.

However, some flows may be more or less **sticky**, meaning that their intensity and/or direction may stay constant over time. The stickiness of a flow relates to its origin and destination systems, which may not

[3] For instance, in the case of nitrogen in soybean exports from Brazil to Germany, the upstream requirement would be the total nitrogen fertilization of Brazilian fields; the embodied impact would refer to both the deforestation associated to soya production in Brazil, and eutrophication in Germany due to excessive manure release; finally, the medium-content relation would correspond to the amount of nitrogen actually contained in the soybeans being transported.

remain in the same location. In fact, if companies trade goods with one another, the flow might be sticky to the companies, but not to a specific place if the company delocalizes its production sites.

3 Methodology

We first began our development of a comprehensive typology of flows during a meeting at the Institute of Social Ecology, Vienna, in September 2018. We have been attempting to develop a typology where all types of flows would be mutually exclusive but overall exhaustive. Despite practical difficulties with this approach, we agreed upon a preliminary typology to characterize the main flows relevant to land system science. We refined this framework through a literature review and several follow-up discussions, in the context of physical meetings and via the virtual meetings series, within our group. Through this iterative process, we agreed upon a final typology, supported by examples from the literature on land system science and proximate fields, provided by 15 COUPLED PhD students (ESRs). In addition, we identified key challenges to analyse the different types of flows and maintained a table of methods that can be used to address some of these methodological challenges. We also compiled an inventory of flow databases that can be consulted to analyse the different types of flows. Finally, we developed a second typology characterizing the interrelations between the different types of flows. When combined, our two typologies provide guidelines on how flows in land system science can be analysed and hence, and on how telecoupling research can be operationalized.

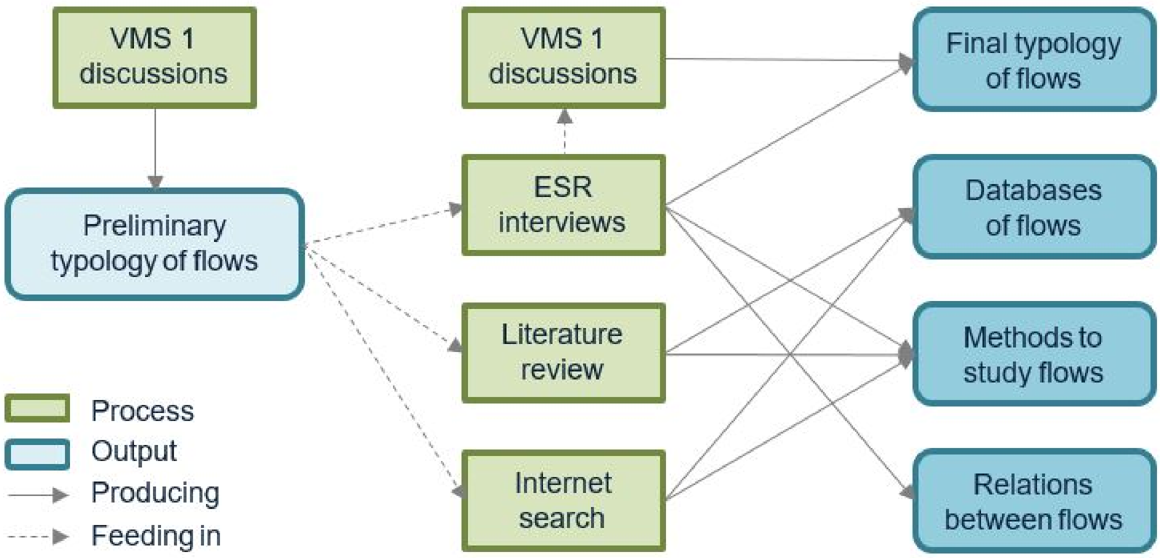

Figure 1. Methodology and key steps to develop the typology of flows, associated data, and this report

4 Results

In the following sections, we present the tools we developed for comprehensive flow-based telecoupling research. We begin by presenting a typology of flows and include examples to illustrate the different type of flows. We then show which methods can be used to identify, analyse, reveal, and visualize the different type of flow. We also provide an overview of the databases containing data useful for studying flows, and we lastly delve into an analysis of the relations between different types of flows.

4.1 Typology of flows for telecoupling

To understand the complex, multidirectional interactions and spillovers within a telecoupled system, one needs to be able to distinguish between different types of flows and their corresponding attributes. Taking the example of Chinese pork consumption, one can easily recognize that many different types of flows are a play. For example, migration from rural to urban areas in China may induce dietary shifts towards meat intensive diets. Following intensive marketing campaigns promoting European pork, this could lead to an increase in Chinese demand for European pork leading to an increase in the production of European pork, which, in turn, leads to an increase in the demand for pig feed. As this is a combination of barley produced in Europe and soybeans produced mostly in Argentina, Brazil and Paraguay, the demand for soya can lead to increased production of soybean in these regions, thus leading to expansions of crop fields places like the Argentinian Chaco. The logistics of transporting the soybeans or the pork to their respective locations requires an extensive exchange of information to make sure that both commodities arrive at the right place and at the right time. In addition, the physical act of transporting both commodities require a substantial amount of energy. Moreover, there are several legal and financial issues that need to be sorted, such as transferring ownership of the pork and transferring the money, either in physical or digital form. It is as well noteworthy that these flows are linked to various social and ecological impacts all along the way, such as increased rates of deforestation, associated carbon emissions, and biodiversity loss in the Argentinian Chaco, eutrophication in Europe, or health outcomes in China due to increased meat consumption.

Although merely an example used to illustrate the plethora of flows involved in the trade of pork, it shows how global demand for products and trade cause a variety of different flows. Here, we propose a typology to differentiate between different types of flows, consisting of five main categories: Materials (e.g., pork meat, soybeans); Information (e.g., logistics); Capital (e.g., monetary compensation); Organisms (e.g., rural-urban migration of people); and Energy (e.g., transport), each containing a number of sub-categories (Table 1).

This typology is intended to cover all flows relevant to telecoupling research and we have strived to make our categories mutually exclusive and collectively exhaustive, but are aware of potential overlaps. The distinction between material and energy is particularly problematic, as all materials (as well as organisms which are in fact living material) contain as well energy by the law of relativity. To have fully exclusive categories, we should have looked at non-material energy separately (electricity, waves, heat, etc.). However, because they are often considered together in land system science, we decided to keep material and immaterial energy in the larger category of energy flows, despite the physical overlap with material flows. Therefore, our claim about the exclusiveness of the various types should not be understood at the physical level, but rather at the functional and analytical levels. We prioritize the functional level, because although human migration actually “contains” a flow of organisms (people), a flow of material (the human bodies and artefacts), a flow of information (the knowledge brought along by migrants), and a flow of capital (human capital), all of these contained flows serve a different function for human and natural systems. How the researcher classifies the flow hence depends on the importance that is given to either of these contained flows in the functioning of the studied system. We second focus on the analytical level, because these categories typically correspond to different fields of the academic literature, are inventoried in different databases, and analysed with different methods. Table 1 reports our typology of flows with a couple of examples for each flow. We describe each of the individual types of flows below. A list of studies from the literature illustrating each type can as well be found in the appendix.

Table 1: Typology of flows

Flow	Sub-flows	Examples
Materials	Biomass	Agricultural (soy, palm oil, cereals, meat…), forestry (timber, wood pellets, …)
	Fossil fuels	Oil, gas, coal (Material content)
	Minerals and metals	Au, Ag, Fe, Si, stones, rock, soil, sediment
	Nutrients and pollutants	Nitrogen, phosphorus, potassium, Particulate Matter, chemical compounds (NOx, SOx)
	Water	Groundwater, surface water, rainwater, seawater
	Air and gas	Wind, oxygen, CO_2
Capital	Currency	Remittances, monetary payments

	Stocks and bonds	Stocks, bonds, futures, options
	Property rights	Titles, deeds, tenure
	Digital	Cryptocurrency, software, user profiles, big data, servers, clouds
	Licenses	Patents, copyrights, permits, charters, trademarks, franchise
Information	Written	Books, articles, newspapers, journals
	Verbal	Conversations, groups
	Knowledge	Tacit, indigenous, scientific, explicit
	Digital	Internet, Social Media, blogs, wikis
	Non-verbal	Culture, discourses
Organisms (Living-beings)	Humans	Migration, tourism, labour, refugees, professional movement
	Non-human Animals	Migration, species trade
	Plants	Migration, species trade
	Fungi	Migration, species trade
	Bacteria and viruses	Pathogenic bacteria
Energy	Material energy	Fossil fuels, biomass (biofuels, fuel wood, food, etc.),
	Non material energy	Electricity, electro-magnetic waves (light, radio, internet, etc.), heat

Material flows

Material flows refer to flows that involve physical matter or chemical substances. Material flows can be observed at different levels, from the object or commodity level (e.g. Soybeans) up to its chemical content (Nitrogen, Carbon, etc.). Examples of material flows include flows of biomass, metals, minerals, water, air, as well as various substances including pollutants or nutrients. Material flows are typically described in mass units (e.g. tons of biomass) or in absolute numbers (e.g. number of tractors). Strictly speaking, material flows are non-reproducible, because they follow the law of mass conservation.[4] Intended flows of materials mostly correspond to trade relations between systems. Trade relations tend to be relatively sticky over time, because of particular affinities, cultural similarities, colonial relations, etc. (Infante-Amate & Krausmann 2019) that are sometimes institutionalised in trade agreements. Unintended flows of materials can range from transboundary pollutants to wind and water streams. Economics have traditionally looked at material flows at the commodity level. More recently, new academic fields such as social ecology (Haberl et al. 2016) and industrial ecology (Pauliuk et al. 2019) have started analysing societal material flows at the biophysical level.

The report of the International Resource Panel on international trade in resources provides a comprehensive overview of global material flows contained and embodied in international trade. It shows how material trade increased from 4 billion tonnes in 1980 to more than 10 billion tonnes in 2010. This represents a share of 15% of the global material use. This ratio reaches 40% when including resources indirectly associated with trade. These material resource typically flow from low income and sparsely populated countries to high income and densely populated countries (International Resources Panel 2015). A review of methods used to analyse material flows can be found in (Huang et al. 2012). Among these, a well-known analytical scope to study material flows is Economy-Wide Material Flow Analysis (EW-MFA) (Eurostat 2013).

Capital flows

Capital usually refers to a stock of accumulated assets. These assets can be composed of material (physical capital), information (human capital), organisms (natural capital), etc. However, the term capital as well often refers to the ownership of these assets, rather than to the assets themselves. This is

[4] However, the object composed of these materials is reproducible to some extent. For example, one can regrow soybeans even if the system runs out of it. However, if a system runs out of phosphorus or water, both needed to grow soybean, it needs to obtain it from another system to rebuild its stock.

particularly true when dealing with capital flows. For example, the transfer of land property rights corresponds to a change of the ownership of the land, rather than the land itself. Similarly, monetary transfers correspond to a change in ownership over commodities and assets purchased in the future. We therefore, for the scope of this study, define capital as the right on current or future property over economic or productive value. This right can be transferred or traded, and is enforced by law, mutual agreement or power. In that sense, it is a specific type of information, which emphasizes the role of ownership. Common forms of capital are property rights, which guarantees current property, and currency, which ensures future property. Other forms of capital as physical, human, natural capital and patents reflect the ownership on productive materials, labour skills, natural resources and ideas respectively. Capital is hence in a sense freely reproducible, but its value is most of the time highly dependent on its physical counterpart. Indeed, one can always infinitely expand the amount of currency in an economy, but the value of this currency is likely to drop as a consequence if the economy is not growing at the same time. Nonetheless, financial speculation 'bubbles' have shown that capital flows are not only dependent on their physical counterpart, but as well on various expectations (i.e. on information flows). Although capital flows have originally mostly been analysed in finance, its study has been extended to various other scientific fields.

In certain cases (e.g. donation, foreign aid, transfer payment), however, capital flows do not expect physical counterparts (goods or services), but rather support certain groups, purposes or actions. Capital flows may even be used in exchange of no action, as in the case of payments to ensure conservation of forest (Harstad 2016). Flows of conservation funding are very important capital flows in land-use science and telecoupling research. Existing work mostly relies on compiled database on publicly accessible records (e.g., donor reports, expenditure records) (Miller 2013; de Oliveira & Bernard 2017) and sometimes from surveys or individual organizations (Holmes 2013; Larson et al. 2016). Because of the data collection process, information is often more complete on the donor (sending system) side rather than the recipients/implementers (receiving system) side, and are often only available at national level. Such research also often sees the process as a two-way game - either between funders and local implementers, between buyers and sellers, or between donors and recipients. However, in reality, funding transaction between distal systems are enabled through multiple layers (steps) of actors (donors – funding distributors – implementing agencies – recipients – local actors). The preferences and roles of each type of actors could be further explored.

Information flows

We define information flows as the communication or reception of knowledge or intelligence between human beings. Although information flows between non-human beings may be just as common as between humans (Conradt & Roper 2005), they are less likely to occur over long distances. Information flows between humans, facilitated by the Internet, social media, and the capacities of communication that enable action are hence arguably more important for land system science and telecoupled research (Eakin et al. 2014), justifying the anthropogenic perspective we adopt here. Although the role of social media and communication technology in shaping information spread and related telecoupling processes is increasingly being recognized, the mechanisms through which they operate are poorly understood (Liu et al. 2018b). Recent studies on the influence of information flows on environmental outcomes include Cahan et al. (2015) (Cahan et al. 2015), who use panel data econometrics to examine whether favourable media coverage drives firms to act more socially responsible; (Schmuck et al. 2018) who compare the effects of three types of green print ads on perceptions of environmental brand benefits, and (Zhang et al. 2019) who use the Chinese Social Survey 2013 to investigate how internet use affects resident satisfaction with governmental environmental protection.

However, these studies tend to focus on specific types of flow that often encompasses a range of sub flows (Liu et al. 2018b). Liberti and Peterson (2018) make a distinction between hard information, i.e. information that is easily reduced to numbers, and soft information, i.e. information that is difficult to completely summarize in a numeric score (Liberti & Petersen 2018). Examples of hard information in land system science are easy to find and relatively easy to analyse; an example would be the annual rate of tree cover loss within a certain region as measured by a satellite. Examples of soft information in land system science include discourses of land policy (Hananel 2013), narratives of land use degradation (Boateng 2017) or landscape values (van Zanten et al. 2016). Although soft information is likely to play a crucial role in land-use decisions, the literature on information flows in system fields is a small but emerging field. To distinguish between and assess the impacts of different flows at play, a better understanding is needed on what information flows exist and how they drive land-use change and sustainability outcomes (Cahan et al. 2015; Schmuck et al. 2018; Zhang et al. 2019).

Flows of organisms (living-beings)

We define organisms as the living counterpart of material flows, i.e. such flows involve physical matter under the form of living beings/organisms. Any movement of a species under its alive form may be acknowledged in this category. Typical examples include migrating humans and animals, as well as plants invasion and bacteria spread. Frequency (numbers of individuals flowing) is the most common metric to account for flows of organisms. An organism leaves the stock of one system to furnish the stock of another. However, due to their capacity to reproduce, they do not prevent the initial stock to rebuild, unless the species is extinct in the system of origin since reproduction involves a production cost. Flows of organisms are likely to impact stocks in the origin and destination systems, because they compete with other organisms relying on the same biotic and abiotic resources (e.g. invasive species). Most of the flows of organisms that telecoupling research considered so far deals with human migration, probably because humans have agency on their spatial movements. Flows of people can be voluntary (migration) or involuntary (refugee), and relate to permanent (migration) or temporary (seasonal/circular migration, leisure, tourism, business) relocation. Understanding people's agency and motivations for mobility, and how these influence connections among land systems is likely to offer opportunities to operationalize sustainability in telecouplings.

Flows of organisms can be at the core of telecoupling research, or investigated as a parallel, spillover, or feedback flows. For instance, the spread of malaria through human migration would qualify as a parallel flow, while the displacement of wild animals from deforested areas in reaction to the Chinese demand for pork fed with soy produced on these areas in Latin America would qualify as spillover. Flow of European tourists to the Wolong reserve in reaction to the promotion on social medias of a newborn Panda in the reserve would qualify as a feedback. Moreover, human flows are often researched for their capacity to respond to, drive, or mediate other flows. If causal and consequential processes around flows of people happen locally, one should consider them as upstream requirements, and impacts. For instance, human migration may happen in response to environmental pollution (Boas et al. 2018), or changes in contextual assets (e.g. landscapes, infrastructures, politics) (Prideaux 2005). Former flows of humans (e.g. previous touristic experience, former colonization) may be drivers of current ones (Balli et al. 2016), or carriers of capitals and ideas (Balli et al. 2016). Finally, bilateral flows of tourists have been used to allocate global carbon emissions responsibilities due to air travel, but also on-site demand for goods and services (Lenzen et al. 2018). Seasonal animal migration or anthropogenic species reintroduction are also investigated for their effects on telecoupling dynamics. For instance, reintroducing pandas in the Wolong reserve in China, causes multiple outbound flows of information which led to corresponding flows of funding and tourists (Liu et al. 2015), while the migration of the northern pintail between Canada and the United States impacts human-natural systems in the visited locations by providing ecosystem services such as wild food, and leisure activities (Schröter et al. 2018). Flows of plants and micro-organisms (e.g. bacteria) are more likely to qualify as impacts of telecoupling, because their spread and distribution rely on ecological conditions in the places they colonize. Finally, investigating the spatial stickiness of flows of organisms, in time, may be insightful to advance research on telecoupling. For instance, anomalies in seasonal animal migrations can inform about ecosystems change in the system of origin.

Energy flows

We define energy as the capacity or power to do work or provide heat. Energy sources are typically divided into four categories: fossil fuels, nuclear heat, biomass, and other renewable energies. Energy flows are non-reproducible because they follow the law of energy conservation. Energy can take various forms, as electrical, mechanical, chemical, thermal, nuclear, etc. and can be transformed from one form to another. However, each of these transformations inevitably induces a drop in the work of the energy from the source to final use, given the second law of thermodynamics. This is why exergy measures are sometimes preferred to energy, as they reveal the maximum useful work a fuel can provide (Cullen & Allwood 2010).

We illustrate the flows of energy using two examples. Similar to the Economy-Wide Material Flow Analysis, the Economy-Wide Energy Flow Analysis (EW-EFA), describes the flows of energy at the national level. It includes all flows of energy-rich materials, and immaterial flows of energy such as electricity or heat. EFA differs from classical energy balance sheets, as it encompasses all biomass products, including all food and feed products. Haberl et al. applied the EW-EFA methodology to study the energetic metabolism of the EU15 and the USA (Haberl et al. 2006). They found that in 2001, energy imports represented around 40% of domestic energy consumption in the EU, and 20% in the USA. Furthermore, in the EU-15, domestic energy consumption was found to be higher than total terrestrial NPP, meaning that using all European biomass for energy purposes would not be sufficient to satisfy all energy needs of Europeans. (Cullen & Allwood 2010) took a different approach, by mapping the global flows of energy from energy sources to final services. Their methodology, which relies on an engineering approach, describes the energy flows between the different devices that convert the inflowing energy into a more useful energy, and eventually into a service provided for end users.

4.2 Inventory of flow databases

Based on our proposed typology of flows, we have compiled a list of relevant data sources that can be used to analyse the different types of flows. For each type of flow, we have provided a definition and three indicators that are examples of the flow, including three data sources with their units of measurements. For example, information flows can be defined as ways of communication or as the reception of knowledge or intelligence. Relevant indicators of information flows include internet behaviour, telephone behaviour and news items; data on these indicators is provided by CAIDA (global interconnection facilities), ITU (fixed-telephone subscriptions per country) and the ITU (sentiment scores of news articles), respectively. A more comprehensive table per flow-type can be found in the Appendix.

Table 2: Examples of data sources for analysing flows

Type of flow	Data source	Indicators	Unit of measurement
Materials	**COMTRADE**	Global trade flows	Volumes of trade
	Eurostat	Trade flows with the EU	Volumes of trade
	FAOstat	Global agriculture and forestry trade flows	Volumes of trade
Capital	**AidData**	Foreign aid transactions	Currency units
	Datamarket	Stock exchanges	Currency units
	Foundation Center	Private philanthropy grants	Currency units
Information	**CAIDA**	Internet behaviour	Global interconnection facilities
	ITU	Telephone behaviour	Fixed-telephone subscriptions per country
	TRNA	News items	Sentiment scores
Organisms	**EASIN**	Invasive Species census and location	Indice (0 – 1) expressing the relative yields obtained in absence of pollinators
	Immigration (UN)	Bilateral flows of migrants.	Number of migrants to and from countries

	IOM	Global human migration	Preferences archetypical recreation users
Energy	**Enerdata**	Global yearly energy production, trade, consumption	Tonnes oil equivalent
	Eurostat	Energy balance sheets of the EU, Sankey diagrams	Tonnes oil equivalent
	Global material and energy flows 2000	Global EFA	Joules

4.3 Methods to analyse, reveal, and visualize flows

Through literature review, we summarized methods commonly used to make sense of the above inventoried data. Tracking flows may indeed be difficult as they travel through multiple actors and systems. Meanwhile, the metrics of flows are often embedded in existing research and statistics collected in one system rather than transactions between two systems. Therefore, additional data collection/cleaning/construction is often needed to subtract the flows between the subset of systems of interest, to combine the data collected by the sending and receiving systems, and to collect extra information that are not measured in existing databases. Here we listed commonly used methods that will help researchers interested in telecoupling to extract information or metrics on flows between systems, and use them to analyse and visualize telecouplings.

Table 3: Methods to reveal, analyse, and visualize flows

Step	**Method**	**Examples**	**References**
Data collection	Sending system-based approach	Collecting funding data from donor's databases Collecting tourism data from countries of origin Value chain analysis	Miller 2013 Lenzen et al. 2018
	Receiving system-based approach	Collecting funding source and expenditure data from conservation landscape; Collecting tourism data from destinations; Life cycle analysis	Lenzen et al. 2018 Yang & Wong 2012
	Combined	Combining data from both the sending and receiving system, and cross-validate; Global trade flow	TRASE
	Qualitative	Interviews Structured Unstructured Focus groups Workshop Participant Observation	Bernard 2017
Database	Harmonization	Converting amount of $ in different year and different currencies to	Miller 2013

construction		single currency	Nakamura Lam 2017
	Conversion of metrics	eHANPP factors by land-use type Conventions of Material Flow Accounting (MFA) as described by Eurostat (2007) (+adaptations) EFA indicators (accounts for all biomass)	Haberl et al. 2006 Schaffartzik et al. 2014 Kastner et al. 2015
Analysis	Qualitative – understating the role of actors, the perception and reasoning, the discourses, etc. (can also be data collection methods)	Case studies Location-based Actor-based Process-based Other Historical research (Analysis of documents, artefacts, and historical items) Phenomenological Philosophical	Bernard 2017
	Quantitative – analysing the correlation between the size of the flows and other variables, the impact of flows, and the structure/impact of the actor networks, etc.	Econometrics Synthetic control Simple OLS regression Panel regression Matching Social-economic network analysis Ecological network analyses	Sills et al. 2015 Miller 2013 Balli et al. 2016 Bruggeman et al. 2018
Visualization	Mapping	Connection map Flow map Route map	
	Network visualization	Network diagrams Segmented Arc/Chord diagrams Sankey diagram Parallel sets Sankey arcs Box and arrow graphs	Ribecca, 2019

4.4 Relations between flows

Foundational papers about telecoupling research (Liu et al. 2013; Friis et al. 2016) underscore that a telecoupling system involves several flows (or processes). If the initial framework acknowledges that the decisions and actions of agents in a system may be the causes and consequences of telecoupling processes, it does not include, in an obvious way, the idea that flows could be linked to one another. However, paying attention to the relations among flows may be of great help in understanding parallel, feedback and spillover processes happening in telecoupling systems, which may not always be driven by agents' decisions.

Below, we propose a typology of relations between flows, supported by examples that we collected from our own research and papers reviewed by COUPLED ESRs. Our typology does not claim to be exhaustive nor mutually exclusive, but is intended to provide a structured way of thinking about interactions among flows. We provide a graph with symbols to represent our six relations, and exemplify their position in the initial telecoupling framework (Liu et al. 2013). We expect this exercise to help telecoupling researchers to capture unintended feedbacks or spillovers, and to take them into account when suggesting operationalized solutions to telecoupling issues. Further work would investigate useful methods to reveal the type of relations between flows, as well as the key features to be aware of when dealing with a certain type of relations.

Table 4: Typology of relations between flows (to be continued)

Relations	Description	Examples from literature
1. Medium and content	One flow of interest is contained in the other one (e.g. energy contained in palm oil imports).	A common example of the medium-content relation is the amount of nutrients (N,P,K) contained in international trade of agricultural products (Grote et al. 2005). Shi et al. as well made the distinction between the amount of nitrogen actually contained in the imported products, and the amount of nitrogen used and lost to the environment along the production chain (Shi et al. 2016).[5] From a socioeconomic perspective, agricultural products also contain a nutritional value. In addition to bilateral trade flows expressed in tonnes, FAOstat provides bilateral flows data in kcal. Cruise boats crossing the ocean may also act as a carrier of toxic components (Boas et al. 2018).[6]
2. Cause and consequence	One flow is the cause of another (e.g. information about deforestation linked to imports causes conservation funds flowing in return).	Flows of people causes additional flows. For instance, flows of money may be the consequence of tourism flow (Lenzen et al. 2018), flows of goods may be initiated following a trip, or a migration, and additional human flows (e.g. tourism) may be the consequence of previous ones (e.g. migration) (Balli et al. 2016). Environmental migration flows may cause emerging flows of warning information about potential disasters. Cruise tourism causes flows of sewage, bilge, and ballast water in the environment (Boas et al. 2018). Information flows may cause various flows. Spreading the information about the companies which perform well in Corporate Societal Responsibility (CSR) is likely to generate a flow of positive promotion of these companies by the medias (Cahan et al. 2015). The consequence of the diffusion of cultural content (e.g. "An Inconvenient Truth", documentary about climate change) is an increase in the purchase of voluntary carbon offsets (Jacobsen 2011), granting property rights to indigenous communities reduces forest clearing by more than three-quarters (Blackman et al. 2018) and sustainable development discourses (e.g. in global conferences) lead to voluntary private agreements and to more efficient governmental Forest policies (Arts & Buizer 2009).

[5] As explained in the definitions, this paper does not deal with embodied impacts (nitrogen lost leading to eutrophication) and upstream requirements (total nitrogen fertilization or fixation): embodied impacts indeed rather correspond to a relation between a flow and an impact (see COUPLED Work Package 5 on impacts), while upstream requirements may have been extracted or produced locally or within the origin system. Therefore, both of them where considered as out of scope for this paper.

[6] Relations can be “intended or unintended” from an anthropogenic point of view. For instance, the information (information flow) written on a letter (material flow) is an intended relation, while the pathogens (flow of organisms) carried by migrating human or animal population (flow of organisms), or invasive species (flow of organisms) transported through the trade of physical goods (material flow) are unintended flows. However, unintended flows can bring along positive consequences for populations, such as the diffusion of know-hows and technologies coming along human migration. Accounting for the intention behind flows may be crucial when seeking for the most relevant type of governance to regulate this flow.

3. Complements	One flow comes to complement another, because you need the second one to make use of the first one (e.g. rubber and metals imports to build airplanes; flows of goods or money follow a population flow). Both flows end up in the same "system" but can originate from different ones.	Infrastructures requires a wide range of inputs (e.g. raw materials and labour forces). Metals, minerals, energy, flow simultaneously towards the location of the construction. Often, a construction comes along with investment (capital flows), and sometimes labour from abroad (flows of organisms). A process such as cruise tourism drives two complementary flows: water and fuel which are needed on board (Boas et al. 2018). Similar complementarity dynamics happen in the supply chains of objects, especially when a wide range of primary materials are involved.
4. Substitutes	One flow substitutes the other, because they can serve the same purpose (e.g. palm oil imports replace rapeseed oil imports). This replacement flow can be either from the same system, or from other systems.	In various economic sectors, several inputs may have substitutes, i.e. alternative inputs that are able to assume the same function, but are less costly or more valuable (renewable energies). When one input substitutes another, related flows also substitute. For instance, minerals may replace wood for construction (Schaffartzik et al. 2014; Saikku & Mattila 2017). Domestic flows of palm oil are likely to be substituted by imports from a cheaper source in case of trade tariffs change (Marin-Burgos & Clancy 2017). Also, vegetal-based proteins substitute animal-based proteins in diets (Clarys et al. 2014) and the same dynamic could be observed for the ingredients included in fish meal (Newton & Little 2018). Substitution dynamics also happen with flows of people. For instance, inbound tourism flows to destinations are substituting to one another according to changes in landscapes features, touristic infrastructures (Prideaux 2005) or according to the relative level of freedom and security in the destinations (Balli et al. 2016).
5. Exchange	Two flows which are exchanged against each other (e.g. currency and goods). The exchange often implies an exchange value, determined through bargaining and power relations. The exchange can involve a compensation (trade of benefits against costs). However, this compensation does not need to be in monetary terms.	The most common illustration of an exchange relationship between flows is the trade interactions, when commodities flow in exchange of a monetary flow (Dorninger 2016). However, if considering currency as an intermediary solely facilitating the trade, the exchange can be considered to involve two or more flows of commodities (e.g. fossil fuel exchanged against food products in the middle east, Haberl et al. 2006). In the case of certified products, more detailed information flowing from the food system towards consumers is exchanged against additional means (good working conditions, fair remuneration, farming technics) (Schröter et al. 2018).
6. Common actor	Two flows are linked to each other by the fact that they are governed by the same actor (e.g. investments into a multinational company and imports of palm oil through the supply chain of this company).	The relationship common actor relates widely to governance dynamics. Indeed, one private company may invest in the lands of one country (e.g. land grabbing) and then bring labour and materials to construct the infrastructures required to extract energy from this land. These flows relate to each other due to the presence of this common actor in the country. Public actors may also be the backbone of a wide variety of flows by releasing policies which influence patterns of flows inside their area of governance (e.g. Europe), or towards external systems (Cuypers et al. 2013). For instance, flows of information through the edition of the National Policy for Climate Change, and of the Forest Code by the Brazilian government led to various incentives flows to ensure the adoption of environmental measures (Gebara & Agrawal 2017).

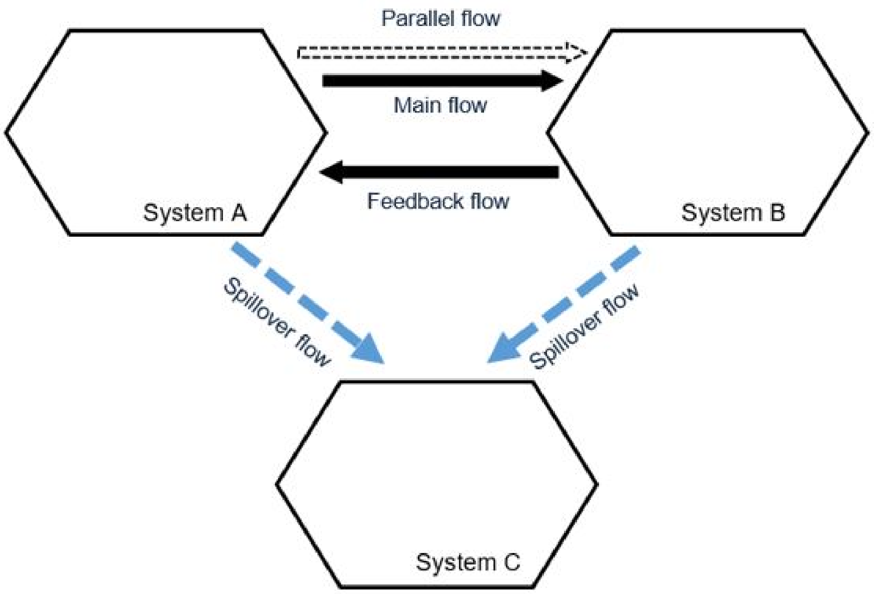

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Figure 2: Original types of flows in the telecoupling framework from Liu et al. (2013). In telecoupling literature, flows are often categorized the "main flow" (from the sending system, depends on the main flow/system of interest), "feedback flows" (as a response from the receiving system, to the main flow), and the "spillover flows" (from the two coupled systems to another system, triggered by the telecoupling relations). We suggest to add the notion of "parallel flow" which flows in the same direction between the same two systems than the main flow.

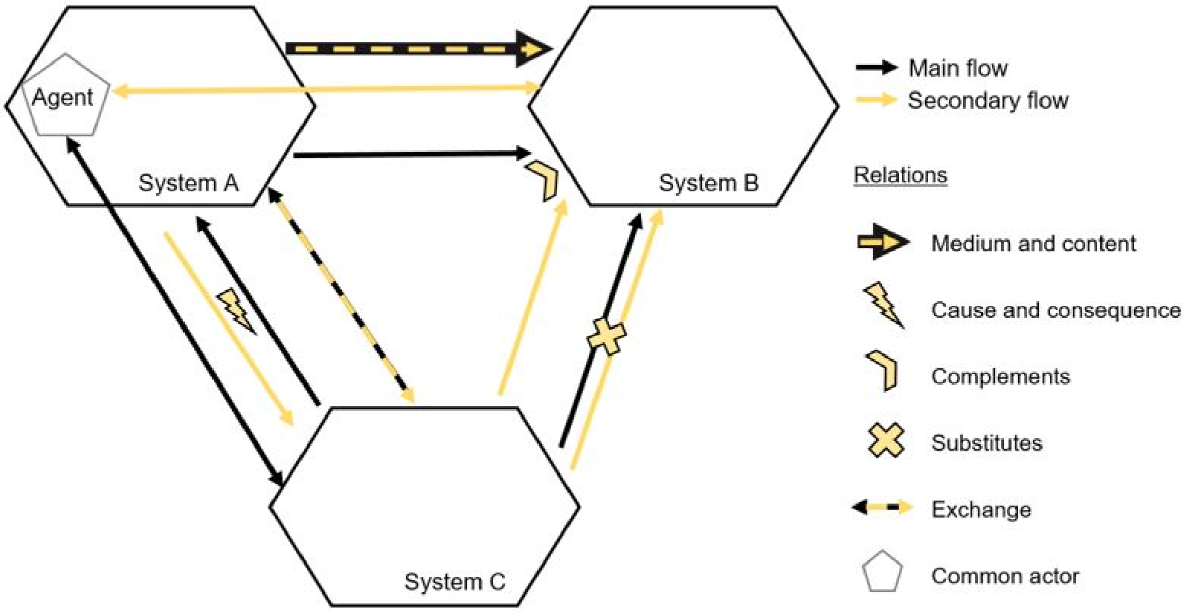

Figure 3: Our typology of relations among flows illustrated on the telecoupling framework from Liu et al. (2013). Only the relations "medium and content", and "exchange" necessarily happen among the two same systems. There is no rule for other relations. For instance, a "cause and consequence" relation could characterize two flows happening between different systems, while a "complement" relation could qualify two flows between the same two systems. The direction of arrows however matters, as it indicates in which relation, the related flows share destination. In the case of the "common actor" relation, two flows share either the destination and/or the origin, according to the location and role of the common actor. Symbols of legend we propose on this graph are meant to guide the illustration of relation among flows in further telecoupling studies.

5 Exemplifying the typologies: flows in COUPLED ESRs' research

In table 5, we summarize which flows the ESRs from COUPLED are studying, as well as which data sources and methods they are using. It also reveals that several ESRs are attempting to study the relations between various flows, which supports the elaboration of systematic methods to analyse how flows are influencing each other.

Table 5: Flows in COUPLED ESR's research (to be completed)

ESR	Flows Type	Flow Content	Data source	Methods used to analyse, visualize, or reveal flows	Related flows (type of relation)
Simon Bager	Material	Coffee	Stakeholders, provincial level production and land use data if available	Stakeholder interviews, questionnaire surveys, fuzzy maps,	Financial flows (exchange) Information flows, certificates (complement) Digital flows, blockchain technology
	Information	ZDC commitments	Forest500 data, Literature	Stakeholder interviews, Focus groups	Agricultural goods (cause and consequence)
Louise Marie Busck-Lumholt	Information	Policy, project information, management plans, project deliverables, training, etc.	Project participants, project affiliated GOs / NGOs	Individual interviews, Q-method, questionnaire surveys, information flow diagrams, (project) document review	Discursive flows, financial flows (cause consequence, complements)
Johanna Coenen	Capital	Loans/infrastructure investments	Descriptive statistical data	n/a (flows will not be the core of the research)	Infrastructure development might create spillovers because new markets and areas along the way are more easily accessible (cause and consequence); infrastructure can impede other flows such as animal migration (cause and consequence)
	Information	Knowledge (on technology)		n/a (flows will not be the core of the research)	
	Organism	Labour migration	Descriptive statistical data	n/a (flows will not be the core of the research)	Remittances (cause and consequence)
Anna Frohn Pedersen	Information	Discourses of empowerment, sustainability and transparency in the small-scale gold mining	Qualitative data: semi-structured interviews with various stakeholders and participant observation from stakeholder	Ethnographic fieldwork; qualitative data coding and analysis	Capital flows, commodity flows and information flows in the gold value chain and in Tanzania in general. I expect these types of flows to influence the ways in which sustainability,

		sector	meetings, mining explorations, etc.		transparency and empowerment are understood and discussed by stakeholders, across different scales. (Cause and consequence)
	Information	Transparency in the value chain of small-scale gold production	Qualitative data: semi-structured interviews with various stakeholders and participant observation from stakeholder meetings, mining explorations, etc.	Ethnographic fieldwork; qualitative data coding and analysis	Capital flows and commodity flows in the gold value chain
Perrine Laroche	Material	Agricultural commodities	FAOSTAT, Kastner et al. 2011, Kastner et al. 2015	physical trade matrices	Flows of information about the environmental footprint of diets lead to dietary guidelines influencing flows of agricultural commodities (cause-consequence)
	Organism	Airline passengers	UNWTO, Tourism Satellite Account (TSA)	Passengers' origin and destination records	Airline travels contain natural rubber (in the aircraft wheels) (medium and content), however it is needed to trace back the production place to allocate the land use impacts
Floris Leijten	Information	Displacement of deforestation due to corporate zero-deforestation commitments	Crop suitability indices, data on market accessibility and land use projections from integrated assessment models	Spatial analysis and GIS	Material flows Capital flows (Cause and consequence)
	Capital	Price responsiveness of agricultural production	Data on agricultural yield and production (MapSPAM) and agricultural prci	Statistical analysis	Material flows Information flows (Cause and Consequence)
Sahar Malik	Material	Palm oil	TRASE		Information flows (Cause and consequence)
Finn Mempel	Information	Narratives, discourses	News media, social media, interviews	Natural Language Processing, Discourse Social Networks	n/a
	Material	Nutrients	FAOSTAT, USDA	Physical trade matrices	n/a

				(corrected for reexports)	
Claudia Parra Paitan	Material	Cocoa	Land cover data from multiple sources: (ESA, Forestry Commission Ghana, Satelligence, CERGIS Ghana, Hansen et al 2013, Hackman et al 2017). Cocoa trade data from ICCO (International Cocoa Organization) LCA impact factors from multiple sources	Spatial analysis with GIS tools Land use model CLUMondo Life cycle assessment methods	Material flows (Complements, Substitutes, Cause and consequence)
Joel Persson	Information	Environmental Discourses	Qualitative: Interview transcripts & organisational documents	Discourse Analysis	Agency constraints due to capacity to engage in discourse (cause and consequence); Human capital embodying expertise (medium and content)
	Information	Policy models for protected area management	Qualitative: Interview transcripts; Household surveys; Participant observation	Institutional analysis; Social Network Analysis (descriptive)	Monetary flows accompanying policies (complements); Accountability structures between network participants
Pin Pravalprukskul	Commodity	Maize	FAOSTAT, and national production, land use and trade data, provincial level production and land use data if available	To be determined	To be determined
Siyu Qin	Capital	Conservation funding commitment	AidData, FoundationCenter	To be determined	Information flow (cause and consequence, exchange)
Tiago Reis	Material	Soybeans	TRASE	Network analysis	n/a
	Material	Maize	FAOSTAT, and national production, land use and trade data, provincial	To be determined	To be determined

			level production and land use data if available		
Nicolas Roux	Material	All biomass	FAOSTAT, Kastner et al. 2011, Kastner et al. 2015	Physical trade matrices, embodied HANPP	Monetary compensation (exchange), Bioenergy (medium and content), Fossil fuels (substitutes) Human migration (cause-consequence), Information flows (Cause-consequence, common actor)
Gabi Sonderegger	All	All	All telecoupling literature	Systematic review to reveal how flows are visualized in telecoupling research	n/a

6 Discussion & Conclusions

The telecoupling framework has served as an encouragement for the scientific community to engage further with complexity and global interconnectedness when analysing the drivers, processes and consequences of land use. Is has indeed been effective in conveying the necessity of moving from place-based to flow-based research. However, it has been shown that the literature has until now been largely biased towards the analysis of trade flows (Kapsar et al. 2019), often focussing solely on single or a few commodities, such as soy (Silva et al. 2017) or palm oil (Marin-Burgos & Clancy 2017; Rulli et al. 2019). Moreover, telecoupling studies have until now fallen short of integrating flows of various types, and systematically analysing how these flows are influencing each other. The typology we suggested hence opens the path towards more comprehensive telecoupling studies that looks simultaneously at different types of flows and how they relate to one another.

A few studies already attempted to look at various types of flows (Liu et al. 2015). Among these, the (forthcoming) Global Sustainable Development Report quantifies the increase in flows of information, goods, capital and humans over the last century (GSDR 2019). We believe that our typology can contribute to such work, by formalizing a more comprehensive but still tractable categorization of most socio-ecological flows, which are relevant for land use science and telecoupling. However, although attempting to reach overall exhaustiveness and mutual exclusiveness across the different types of flows we identified, this typology should not be seen as a rigid and universal classification of all possible sub-flows. One should indeed be aware that the different flows can often not be physically separated, especially between materials and energy. As already underlined, the mutual exclusiveness of the different types of flows should therefore be understood at the functional or analytical level, rather than at the physical level. Furthermore, the boundary between the types of flows, as well as the inclusion of a sub-flow into one of the categories, may to some extent depend on the researcher's goal. Our typology should therefore rather be seen as a heuristic guide, providing a graspable overview of the different types of flows, and as an encouragement to combine these different flows into more comprehensive flow-based research.

We did not include services as a type of flows, but we acknowledge that each of the flow types we inventoried in this report are likely to reflect the exchange of services among distal systems. For instance, Schröter et al. (2018) already suggested that interregional flows of ecosystem services happen through four processes which relate to flows of materials, information and organisms. We suggest that capturing flows of services requires additional metrics, able to reveal the benefits that people derive from various flows. For instance, trade of agricultural products in terms of macronutrients (e.g. vitamins, protein, iron) can be used as a proxy for flows of nutrition, considered as an ecosystem service. The occurrence of specific terms in international discourses can be used as metric to trace flows of political ideas from one system to another. This is an example of a socio-economic service that is reflected in information flows.

The databases and the various methods for analysing flows that we list can as well serve as a good starting point to analyse various types of flows. There, however, exist several other databases and methods that we may not have registered here, but might better serve specific purposes. It should nonetheless be noted, that not all the databases reveal flows at the bilateral level. Indeed, many are restricted to the national level, describing only the contents flowing in and out of the system. Although this has sometimes been simplified to a flow between the given country and “the rest of the world” (Liu et al. 2015), this remains a major limitation for in depth telecoupling studies.

We believe that the concept of relations between flows we introduced can significantly contribute to the telecoupling framework. The idea that several flows are affecting each other has indeed until now solely been touched upon by the concepts of feedbacks and spillovers. As we have seen, this notion of feedback does not account for flows moving between the same two systems, and in the same direction as the flow of major interest, which we have called parallel flows. This is indeed by definition the case for a medium and its content, but may as well occur for two complements or substitutes flowing between the same systems. Furthermore, feedbacks and spillovers tend to be perceived as homogeneous concepts, hiding the variety of relations that can link different flows. A feedback could hide either an exchange, or a consequence of the original flow. Similarly, spillovers can conceal a substitutability, or complementarity between two flows, which would have drastically different implications for the analysis or the governance of this telecoupling. Finally, the concepts of feedbacks and spillovers assume that the researcher defines a single flow of main interest between a sending and a receiving system, which may sometimes not be possible, especially for global studies. We therefore argue that the notion of relations between flows provides a more general and applicable concept to analyse the linkages between numerous flows.

Adopting the concept of relations between flows has the potential to significantly improve the applicability and usefulness of the telecoupling framework for research in the land system science community. Indeed, when defining one flow of major interest does make sense, one could move beyond the initial terminology of feedbacks, parallel flows and spillovers, by defining the relation linking the various flows. On the other hand, when choosing a main flow of interest is not relevant, as it is often the case for global flow studies, one could still analyse the interconnectedness between various types of flows, by applying our typology of relations between flows. Nevertheless, our suggestions of possible major types of relations between flows should not be understood as an exhaustive list, but rather as illustrations of the concept. Various other relations could in fact be thought of, and still need to be analysed. The next steps will therefore consist of determining a set of qualitative and quantitative methods to reveal the kind of relation linking two flows, and to analyse the scale, impact and volatility of these relations.

Finally, incorporating several types of flows within a single study requires thorough transdisciplinary collaboration. This may however often be challenging, given the expertise and specialization of the researcher, as well as data or time limitations. In this case, our typology could offer a broader perspective to frame a given study within the bigger spectrum of all types of flows. The typology and the relations between the flows could be used to link and identify patterns across several studies dealing with different types of flows. A further step could hence be a systematic review of the literature dealing with flows that would disclose how often a given type of flow has been studied within and outside the telecoupling literature, and identify the relations between the flows analysed in various fields.

Flow-based research is essential to understand how distant processes are affecting local sustainability outcomes. Researchers have tended to focus mainly on the flows they are most familiar with, while a large range of flows are occurring simultaneously in telecoupled systems. Neglecting flows interrelations can confuse causal mechanisms, and mist assessing repercussions on other flows. We here provided a set of tools that should facilitate the collective analyses of flows. We hope that these will contribute to more inclusive flow-based studies, in order to provide comprehensive answers for the governance of telecoupled systems.

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Annex 1 – Surveyed literature by flow type

Table S1: Literature for material flows

	Biomass	Fossil energy carriers	Metals	Industrial minerals	Constructio n minerals	Nutrients	Water	Air	Gas
Andriamihaja et al. 2019	Clove, vanilla, silk			Quartz crystal					
Andris et al. 2018							Stream		
Boas et al. 2018				Plastic in the Ocean				Water used to service passenger of cruise tourism	
Boillat et al. 2018	Timber, sea products								
Carr et al. 2012							Virtual water		
Drakou et al. 2018	Tuna								
Franz et al. 2018		Biofuels							Biogas
Grote et al. 2005						N,P,K global			
Huang et al. 2012	Total Biomass (MFA)	Total Fossil energy carriers (MFA)	Total Metals (MFA)	Total industrial minerals (MFA)	Total construction minerals (MFA)				
Kastner et al. 2015	Embodied HANPP								
Krausmann et al. 2016	Total Biomass (MFA)	Total Fossil energy carriers (MFA)	Total Metals (MFA)	Total industrial minerals (MFA)	Total construction minerals (MFA)				
Le Noë et al. 2018						Nitrogen, phosphorus (France)			
Lenzen et al. 2018	Consumer								CO_2

	goods								
Newton 2018	Ingredients for fish meal								
Rautner et al. 2013	Palm oil, soy, pulp and paper, timber, beef	Fossil fuels, minerals							
Schaffartzik et al. 2014	Total Biomass (MFA)	Total Fossil energy carriers (MFA)	Total Metals (MFA)	Total industrial minerals (MFA)	Total construction minerals (MFA)				
Schröter et al. 2018	Certified coffee								
Wood et al. 2018						Protein, energy, zinc, calcium, iron, vitamin B12, folate and vitamin A			
Xu et al. 2018						Virtual nitrogen	Virtual water		Virtual CO_2

Table S2: Literature for information flows

	Verbal	**Written**	**Non-verbal**	**Digital**	**Knowledge**
Agrawal 2005			Socially integrated environmental Norms		
Andris et al. 2018	Tele-communications		Proclivities, thoughts	Stated relationships	
Arts & Buizer 2009		Voluntary and private agreements; Public Forest Policies	Sustainable Development discourses in global conferences		
Balli et al. 2016			Institutional quality; Level of freedom; Civil liberty		
Bellmann et al. 2016		Public Food Safety Standards; Private sustainability standards on trade and production patterns			
Boas et al. 2018	Cyclone warning messages through telecision, and radio	Cyclone warning messages through text messages			
Borgatti 2005	Gossip, emails		Attitudes		
Cahan et al. 2015		Corporate social responsibility and media coverage			
Elgert, 2012	Roundtable on Responsible Soy				
Gebara & Agrawal 2017		(Brazil) Action Plan to Prevent and Control Deforestation in the Amazon (PPCDAm), Action Plan to Prevent and Control Deforestation and Fire in the Brazilian Cerrado (PPCerrado), Plan for Low Carbon Agriculture (ABC)	National Policy for Climate Change (Brazil), the Forest Code (Brazil)		

Jacobsen 2011	Al Gore's documentary An Inconvenient Truth and environmental awareness		Al Gore's documentary An Inconvenient Truth and environmental awareness		
Marin-Burgos & Clancy 2017			Market liberalization		
Marin-Burgos & Clancy 2017			Import tariffs and import licenses		
Oberlack et al. 2018	Global conservation priorities, global coordination of conservation actions				
Prideaux 2005		Tourism infrastructures in Chinese cities: Number of star rated hotels	Global referencing of World Heritage Sites in Chinese cities		
Schmuck et al. 2017			Effects of three types of green print ads		
Tang et al. 2010	Telephone calls, documents and emails				
Zhang et al. 2015		Internet use and the satisfaction with governmental environmental protection			

Table S3: Literature for capital flows

	Money transfer	Stocks and bonds	Property Rights	Digital	Licenses
Alix-Garcia & Gibbs 2017			The acquisition of slaughterhouses in the Amazon		
Andriamihaja et al. 2019	Carbon credits for conservation project in Madagascar Funding of biodiversity conservation projects Money exchanged for trade of vanilla, clove,silk and quartz				
Bellmann et al. 2016	Subsidies (to fisheries)				
Blackman et al. 2018			Titling indigenous communities in Peru		
Boillat et al. 2018	Biodiversity aid money				
Borgatti 2005	Money				(REDD+ commitments)
Carneiro de Oliveira & Bernard 2017	Expenditure on protected areas in Caatinga				
Dorninger, January 2016	Monetary compensation for eHANPP flows				
Halimanjaya 2014	Aid for climate change mitigation				
Lenzen et al. 2018	Expenditures				
Marin-Burgos & Clancy 2017	Subsidies to oil palm production for biofuels		Tax exemptions credit facilities, fiscal incentives, price regulation for the oil palm production to the biofuel sector		
Miller et al. 2013	International aid for biodiversity conservation				
Nonthakot & Villano	Remittances				

2008					
Schröter et al. 2018	Financial and technical support to certified coffee production				
Schröter et al. 2018	Donations for the conservation of pandas in the Wolong Nature Reserve (e.g. WWF)				
Strelneck & Vilela 2017	International aid for conservation in the Amazon				
Weiler et al. 2018	Aid for climate change adaptation				

Table S4: Literature for organisms flows

	Humans	**Animal migration**	**Plant migration**	**Bacteria / vira**
Andris et al. 2018	Travel/transportation			
Balli et al. 2016	Immigration			
Balli et al. 2016	Former colonisation			
Balli et al. 2016	Tourism			
Boas et al. 2018	Cruise tourism			
Boas et al. 2018	Environmental migration (migration driven by environmental danger)			
Boillat et al. 2018	Tourism, migration			
Borgatti 2005				Infection
Lenzen et al. 2018	Global tourism			
Liu et al. 2013	Tourists	Pandas		
Nonthakot & Villano 2008	Labor migration			
Prideaux 2005	Inbound tourism			
Schröter et al. 2018		Northern pintails migration		

Table S5: Literature for energy flows

	Biomass	**Fossil fuels**	**Nuclear heat**	**(other) Renewable energies**	
Andris et al. 2018.					Electricity
Boas et al. 2018		Fuel used as input for cruise tourism			
Chen et al. 2018	IEA data (embodied energy flows)	IEA data (embodied energy flows)	IEA data (embodied energy flows)	IEA data (embodied energy flows)	
Cullen & Allwood, January 2010	Does not include food (IEA data)	IEA data	IEA data	IEA data	
Haberl et al. 2006	Total biomass (EFA), EU and USA	Total Fossil fuels (EFA), EU and USA	Total Nuclear (EFA), EU and USA	Total RE (EFA), EU and USA	
Kastner et al. 2015	Embodied HANPP				

Annex 2 – Extended inventory of databases

Table S6: Extended inventory of databases

Type of flow	Data source	Indicators	Unit of measurement
Capital	AidData	Top of Form Foreign aid transactions Bottom of Form	Top of Form Currency units Bottom of Form
	Datamarket		
	Foundation Center	Private philanthropy grants	Currency units
	IIF		
	IMF		
	Trading Economies		
	TSA		
Material	COMTRADE	Global trade flows	Absolute quantities, masse units, monetary value
	Eurostat	Trade flows with the EU	
	FAOstat	Global agriculture and forestry trade flows	
	Global Trade Atlas	Commodity trade flow for HS and SETC classes	
	GTAP		
	OECD		
	OEC	Commodity trade flow for HS and SETC classes	USD
	TRASE	Commodity trade flows for select agricultural commodities	Tonnes of materials
	Fineprint	Total global material flows	Tonnes of materials
	Materialflows	Visualisations of global material flows	Tonnes of materials
	Resource Watch	Global use and flows in primary resources	Tonnes of materials
	Steinberger et al. (2010)		

	UN-IRP	Total global material flows	Tonnes of materials
Organisms	EASIN	Invasive Species census and location	Indice (0 – 1) expressing the relative yields obtained in absence of pollinators
	Immigration (UN)	Bilateral flows of migrants.	Species richness
	IOM	Global human migration	Preferences archetypical recreation users Bottom of Form
	Migration Data Portal		
	Movebank (animal migration)		
	NOAA fisheries		
	Outbound tourism (UNWTO)		
	WHO		
Energy	Enerdata	Global yearly energy production, trade, consumption	
	Eurostat	Energy balance sheets of the EU, Sankey diagrams	
	Global material and energy flows 2000	Global EFA	
	IEA		
	WorldBank		
Information	CAIDA	Internet behaviour	Global interconnection facilities
	Statista	Telephone behaviour	Fixed-telephone subscriptions per country
	ITU	News items	Sentiment scores
	SEDAC		
	TRNA		
	WorldBank		