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Unpacking the nexus: Different spatial scales for water, food and energy

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ABSTRACT

Recent years have shown increased awareness that the use of the basic resources water, food, and energy are highly interconnected (referred to as a 'nexus'). Spatial scales are an important but complicating factor in nexus analyses, and should receive more attention – especially in the policy-oriented literature. In this paper, we 'unpack' the nexus concept, aiming to understand the differences between water, food and energy resources, especially in terms of spatial scales. We use physical indicators to show the differences in terms of absolute magnitude of production and the distance and volume of physical trade, for seven resource categories: water withdrawal, crops, animal products, bio-energy, coal, oil, and natural gas. We hypothesize that the differences in trade extent are related to physical characteristics of these resources: we expect high priced, high density, geographically concentrated resources to be traded more and over longer distances. We found that these factors, taken together, can explain some of the differences in trade extent (and thus spatial scale involved), although for each individual factor there are exceptions. We further explore the spatial scales by showing the bidirectional physical trade flows at the continental scale for crops, animal products, bio-energy and fossil fuels. We also visualize how nexus resources are directly dependent on each other, using a Sankey diagram. Since both direct dependencies and physical trade are present, we investigate the role of resource-saving imports, which is a form of virtual trade. The resource-saving imports highlight the importance of continental and global scales for nexus analyses.

1. Introduction

In examining the sustainability of natural resource use, the concept of the 'resource nexus' has emerged in recent years, expressing the idea that the production and consumption of resources such as food, water, energy and land are all intricately related (Bizikova et al., 2013; Finley and Seiber, 2014; Hellegers et al., 2008; Ringler et al., 2013, 2016; World Economic Forum, 2011a). For example, food production requires land and water, but also energy (to power machines and produce fertilizer). Energy production uses water in extraction and refinement of fossil fuels and for cooling thermo-electric power plants. Electricity production via hydropower reservoirs can be conceived of as both consuming water (due to additional evaporation) and conserving water. Fossil fuel extraction "consumes" land and water by polluting it. Land and water are also used in the production of bio-energy (both liquid biofuels and fuel wood or charcoal). Some food crops may be converted to biofuels – although separate crop varieties are often developed for food and for biofuels. Energy is necessary for desalination of water, but also for pumping groundwater, transportation to and from end users, and wastewater treatment. Finally, land itself is also intimately involved in the water cycle, by collecting precipitation and acting as buffer for water availability, and because irrigation rights are often tied to land ownership (Bos and Wolters, 1990). Note that these are only a subset of the possible interactions. Although natural ecosystems also require land and water, and support farming, forestry and water collection, we take an anthropocentric perspective and treat water, food and energy as commodities in this paper.

There is an awareness in research and policy communities that spatial scales are an important, but also complicating factor in any nexus analysis. Policy-related documents typically argue that management of the resource nexus should be organized at several policy levels simultaneously, each of which operates at a different spatial scale, such as local, watershed, national, and global scales (Bazilian et al., 2011; Biggs et al., 2015; World Economic Forum, 2011b). We get the impression that 'the' resource nexus is often seen as a monolithic thing, especially in policy communities, and that the role of spatial scales receives insufficient attention to date. To some extent, the role of spatial scales has been addressed in the scientific literature. For example,

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Table 1
Main data sources used in this study.

Dataset	Reference	Description
Comtrade	Comtrade (2016)	Bidirectional imports between countries (in kg and US$) for detailed commodities (SITCv1), for 1962–2015.
CEPII	Mayer and Zignago (2011)	Distances between and within countries (in km) based on locations and population sizes of major cities, for 2004.
FAOFBS	FAOSTAT (2014)	Food Balance Sheets per country and commodity, for 1961–2011.
FAOLAND	FAOSTAT (2016)	Land area per end use and country (the Land Inputs database), for 1961–2013.
FAOPOP	FAOSTAT (2016)	Population per country, for 1950–2100.
FAOPROD	FAOSTAT (2016)	Production (in kg) for detailed commodities per country (the PRODSTAT database), for 1961–2013.
IEAHED	IEA (2016a)	Headline Energy Data. Import and production of energy commodities (in J), for large energy producing or consuming countries and some regional aggregates, for 1971–2015.
IMAGE	Bijl et al. (2016); Bondeau et al. (2007); Stehfest et al. (2014)	Water withdrawal (model output) and population size per IMAGE region, for 1971–2100.

Garcia and You (2016) explain that each of the links between water, food, energy and land occurs at a particular spatial scale, while in Hejazi et al. (2015) the importance of interdependencies between nexus resources varies with the spatial scale. We take a different approach and 'unpack' the nexus concept by starting with the differences between the resources themselves, especially in terms of spatial scales.

In this paper, we explore the role of spatial scales in the water-food-energy (WFE) nexus. We first show how water, food and energy are very different resources in terms of overall magnitude of flows and the extent of trade. Each resource involves different spatial scales, since the distance and volume of physical trade differs per resource. We then hypothesize that the extent of trade is related to the physical characteristics of the resources. We expect more trade over longer distances for resources with (1) a high price since transportation costs are then relatively small, (2) a high density since these should be easier to transport, and (3) little geographic overlap between supply and demand locations (i.e. the resource is hard to source locally). Next, we visualize physical transportation of nexus resources between continents, to further specify the average trade distances mentioned previously, to highlight the bi-directionality of trade flows, and to show that 'long distance' does not necessarily equate to 'global'. This also shows that the continental scale is important as an intermediate scale of analysis between the national and global scale, since continents have different climates and natural resource endowments, and most continents are separated by oceans which restrict the modes of transport. Besides physical trade, resource-saving imports (virtual trade) are another important mechanism through which nexus resource uses at local and national scales are tied together over long distances (i.e. involving continental- or global-scale systems) (Chapagain et al., 2006; Hoekstra and Hung, 2002). When the production of resource A (e.g. crops) is directly dependent on resource B (e.g. water), and resource A is traded physically, then resource B is said to be traded virtually via resource A (e.g. virtual water trade). We therefore also show how the production of some of the nexus resources is directly dependent on other nexus resources, using a Sankey diagram at the global scale. Besides the well-known resource-saving concept of water saved by importing crops, we also estimate the volume of water saved by importing animal products, the water saved by saving feed crops by importing animal products, and the land area saved via the same mechanisms. Finally, the understanding of scale dependencies of nexus resources is not only interesting for the current situation, but also for the future. Our integrated quantitative approach may serve as a starting point for analysing how the relevant spatial scales for particular resources may change in the future due to socio-economic trends, climate change impacts and climate change mitigation.

The paper is organised as follows. After explaining our data sources and calculations (Section 2), we examine the differences between water, food and energy resources, especially in terms of spatial scales, by comparing physical characteristics (Section 3.1). Next, we show production and trade flows of the nexus resources at the continental scale (Section 3.2). In Section 3.3, we visually display and further investigate the direct dependencies between the resources, now also including land as an input. Section 3.4 combines direct dependencies and physical trade to estimate resource-saving imports and discuss the implications for spatial scales. In Section 4 we provide suggestions for further research, and the main findings are summarized in Section 5. The Supplementary information contains equations, additional physical indicators, a discussion of potential future changes and an overview of the relevant spatial scales for each resource.

2. Methods

Our approach is to analyse the spatial scales involved in the resource nexus in its current state, using openly available databases as much as possible, and filling the gaps with output from existing model simulations. We present the data requirements and calculations for the physical characteristics (2.1), the direct dependencies between resources (2.2), resource-saving imports (2.3) and the continental scale analysis (2.4). The main data sources with references are listed in Table 1.

2.1. Physical characteristics

We calculate the physical characteristics of the nexus resources for the following three reasons: (1) to explore the differences and similarities between the resources, (2) to explore how the differences relate to spatial scales (using trade distance and volume), and (3) to explore potential explanatory factors for the extent of trade. Regarding the third point, we expect more trade over longer distances for resources with a high price (since transportation costs are then relatively small), high density (since these should be easier to transport), and little geographic overlap between supply and demand locations (i.e. the resource is hard to source locally).

For water, we only focus on withdrawal, for food we distinguish crops and animal products and for energy we distinguish bio-energy, coal, oil and gas. We hereby have seven different nexus resources in total. The flow size of these seven resources is estimated by (i) the global total production. The trade extent is represented by (ii) the percentage of production traded internationally and (iii) the average trade distance. To explain the trade extent in terms of characteristics of the resources themselves, we calculated the (iv) average price of imports, (v) the densities of the resources and the (vi) geographic concentration of supply/demand. Note that bidirectional trade data are needed, since net trade data may obscure the actual physical transportation. The physical characteristics are calculated as follows (see the equations in the Supplementary information).

Total production of the seven resources is calculated in terms of mass (Gt) and energy (EJ). For water, we define "production" to be withdrawal, which is the amount abstracted from freshwater sources, based on the integrated assessment model IMAGE (Bijl et al., 2016; Bondeau et al., 2007; Stehfest et al., 2014). Production of food commodities in mass is aggregated from FAO Food Balance Sheets