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Data-driven quantification of the global water-energy-food system

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ABSTRACT

There is increasing interest in the global water-energy-food (WEF) system and potential system trajectories, especially considering growing concerns over resource exploitation and sustainability. Previous studies investigating different aspects of this system have a number of shortcomings, meaning it is difficult to identify system-wide tradeoffs, and makes comparison difficult. A global analysis of the WEF system linked to gross domestic product (GDP) growth is presented, integrating the four sectors into a coherent analysis and modelling framework. GDP was included as previous related work demonstrates a link between GDP and each WEF sector. A system dynamics modelling approach quantifies previously qualitative descriptions of the global WEF-GDP system, while a Monte-Carlo sampling approach is adopted to characterise national-level variability in resource use. Correlative and causal analysis show links of varying strength between sectors. For example, the GDP-electricity consumption sectors are strongly correlated while food production and electricity consumption are weakly correlated. Causal analysis reveals that ‘correlation does not imply causation’. There are noticeable asymmetries in causality between certain sectors. Historical WEF-GDP values are well recreated. Future scenarios were assessed using seven GDP growth estimates to 2100. Water withdrawals in 2100 and food production in 2050 are close to other estimations. Results suggest that humanity risks exceeding the ‘safe operating space’ for water withdrawal. Reducing water withdrawal while maintaining or increasing food production is critical, and should be decoupled from economic growth. This work provides a quantitative modelling framework to previously qualitative descriptions of the WEF-GDP system, offering a platform on which to build.

1. Introduction

It is becoming increasingly clear that we live in a ‘hyperconnected’ world (World Economic Forum, 2016) in which natural resource exploitation and human development are bound together in an extraordinarily complex system. An important event to make explicit this system and to bring it to the wider consciousness was the Bonn Nexus Conference in 2011 (Hoff, 2011), which focussed particularly on the water-energy-food (WEF) nexus. Since then, the ‘classical’ WEF nexus has evolved to include land use, the environment, climate change, and/or the economy (e.g. WWF and SABMiller, 2014; Sušnik, 2015; WWAP, 2015; Fasel et al., 2016; Feng et al., 2016; World Bank, 2016; World Economic Forum, 2016). It has been expanded to cover human development and mental health (Biggs et al., 2015; Fabiola and De Rosa, 2016; Hernandez, 2016; Sušnik and van der Zaag, 2017), and in some cases has been ‘shrunk’ to become more focussed, for example in detailed investigations on (urban) water-energy relationships (e.g. Kenway et al., 2011; Davies et al., 2013; Holland et al., 2015; Hussein et al., 2017; Valek et al., 2017). Steffen et al. (2015) alluded to this complex system when the idea of planetary limits was put forward. It is increasingly clear that which of these planetary limits are exceeded, when, and by how much, are related to each other (e.g. the volume of water required for all uses will change as energy demand changes, as the energy mix changes, and as diets change globally). Others have used different terms to mean a complex system connected at the global scale, and in which actions to one sector can have significant impacts on other sectors, sometimes without prior knowledge of these connections even existing (e.g. the idea of ‘teleconnections’, especially in the climate system; Najibi et al., 2017). Global think-tanks and multinational corporations are showing increased interest in the nexus and its potential implications to business (e.g. IMechE, 2013; WWF and SABMiller, 2014; EEA, 2015; World Bank, 2016; World Economic Forum, 2016). Some major European Union research projects focussing on the nexus have recently begun, of which two merit particular attention: SIM4NEXUS (Sustainable Integrated Management FOR the NEXUS of water-land-food-energy-climate for a resource-efficient Europe; www.sim4nexus.eu), which assesses policies and pathways in the water, food, energy, land and climate sectors that will help enable a resource efficient Europe and which will develop a policy-maker interfacing serious game based on state-of-the-art science. MAGIC (http://magic-nexus.eu/) is focussed on policy and integration, and is testing how changes to policy can contribute to a more efficient nexus in Europe.

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Despite the increased interest, and the considerable increase in ‘nexus’ literature, there is a distinct lack of quantification as to how this system behaves. This is unsurprising given that ‘nexus’ means different things to different groups. At present, many studies qualitatively describe various nexus relationships (e.g. Cai et al., 2017), explaining how (in principle) changes to one nexus system sector (e.g. water) may impact on other system sectors (e.g. electricity generation). Where quantitative studies have been carried out, they usually either:

i) focus on a small part of a wider system, for example water and energy interactions only (e.g. Valek et al., 2017);
ii) focus on specific case studies that are detailed quantitatively, but can lack the generality to enable wider application (e.g. Hussein et al., 2017);
iii) some combination of (i) and (ii).

There are a few example of studies that are detailed and that cover a wider area or many sectors. Arguably the earliest global study on a nexus (in this case the relationships between population, human capital, agriculture and pollution) was that of Meadows et al. (1972). While initially this study was denounced and its conclusions dismissed, 40 years of subsequent data have revealed that some of the major global system sector *trajectories* were predicted reasonably well (Turner, 2008; Hall and Day, 2009; Turner, 2009), with hindsight allowing numbers to be placed on the y-axes of the Meadows et al. charts, which originally were without a scale (contributing to some of the early dismissal).

The World3 model of Simonovic (2002) is based on the system dynamics modelling (SDM) paradigm (Ford, 1999; Capra and Luisi, 2014). It analyses the consumption of global water resources. Despite its narrow focus, the model includes interaction with the agricultural and industrial sectors, as well as consideration of pollution and population. While the model is broadly applicable at the global scale, and acknowledges the close relationship between these sectors and the economy, it uses data that are now quite old (> 20 years). World3 makes some useful projections of the global water inventory based on gross-scale global system dynamics.

As more recent examples, Feng et al. (2016) use SDM to explore the water-power-environment nexus in Hehuang Region, China. Although spatially very limited, with restricted ability to scale up the conclusions, the study uses comprehensive data across a number of sectors to project water, power and environmental parameter trajectories into the near and far futures, attempting to quantify the system on a local scale and understand its long-term dynamics and evolution. Chen et al. (2018) use a multi-region input-output (MRIO) analysis to show the connection between agricultural production, freshwater use and international trade. It is shown that in general, resource-rich, less-developed countries transfer resources to resource-poor, well-developed countries, and that land productivity and water productivity generally show an inverse relationship.

While there is increasing interest in describing the ‘nexus’, and while there are more efforts going to better understand different systems, robust quantification of the WEF system, interaction between these sectors and their relationship to the economy through the proxy of gross domestic product (GDP) is lacking on a global level. Fig. 1 shows a familiar schematic of the WEF system linked to GDP. Boxes show the WEF-GDP sectors, and arrowed lines denote connections between the sectors. What form do these relationships take? How can change in one sector be used to estimate change in another? How can the inherent uncertainty involved when making global-scale observations be accounted for? In which way do causal relationships operate? Are the connections of a reinforcing mechanism (c.f. runaway greenhouse warming), or of a balancing mechanism (c.f. birth-death dynamics in classical population models)? How strong, relatively, are these relationships between sectors? These are questions that, so far, have not been well answered, and Fig. 1 remains largely a qualitative description of this globally critical system rather than a quantitative tool.

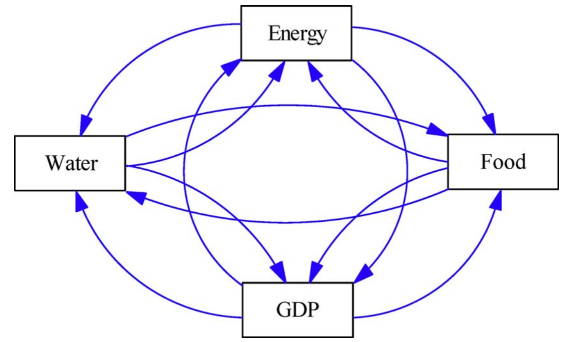

Fig. 1. Schematic representation of the water-energy-food-economy system. Every sector interacts with every other sector in the system.

Using global level data at national resolution over the past c. 50 years, the aim of this work is to quantify, at the global level based on national-scale data, the WEF-GDP system in terms of:

a) acorrelation between system sectors;
b) the uncertainty and scatter between these sectors;
c) causal relationships between the sectors, and;
d) system trajectories to 2100 under several economic growth scenarios.

This work aims to add quantification to the currently qualitative Fig. 1, and to start to address some of the main gaps in current understanding described above. In this paper, the focus is the water-energy-food nexus and the link to national economies (GDP). The link to GDP was made explicit by Sušnik (2015) who shows that water, energy and food metrics correlate closely with GDP. In this paper, the word ‘system’ is used in place of ‘nexus’ to make explicit the point that this system is in essence observable, quantifiable and able to be modelled robustly in order to i) determine underlying dynamics and; ii) create scenarios of potential system development under global change.

2. Data and methods

2.1. Data

This study uses data from many sources to form relationships between WEF and GDP metrics. All data are at national resolution, and cover over 175 countries representing almost all socio-demographic-economic conditions since the 1960′s. Table 1 summarises the data. Some of the data and results presented in this paper are based on the analysis presented in Sušnik (2015). In such cases, details will not be repeated here, and the reader is referred to Sušnik (2015). The most relevant and important results from the previous work are summarised when required. The three analyses that are used here from Sušnik (2015) are: GDP → total national water withdrawals; GDP → total national food production and; GDP → total national net electricity consumption.

Total water withdrawal is a measure of all the water *withdrawn* in a nation from all sources. Water withdrawn is not the same as water consumed (i.e. water ‘lost’ from a system, through evaporation for example), which is generally lower. However, data on water withdrawn can be more reliable than for water consumed, and was used here as a measure of the pressure on available water resources. It is likely that substituting water withdrawals for water consumption would affect the results, however predicting how the results might change is difficult. For example, some energy-generating processes withdraw a lot of water, but consume relatively little, and vice-versa. It is probable that increases in energy generation will lead to increases in water consumption generally. It is likely that relationships would remain, but