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

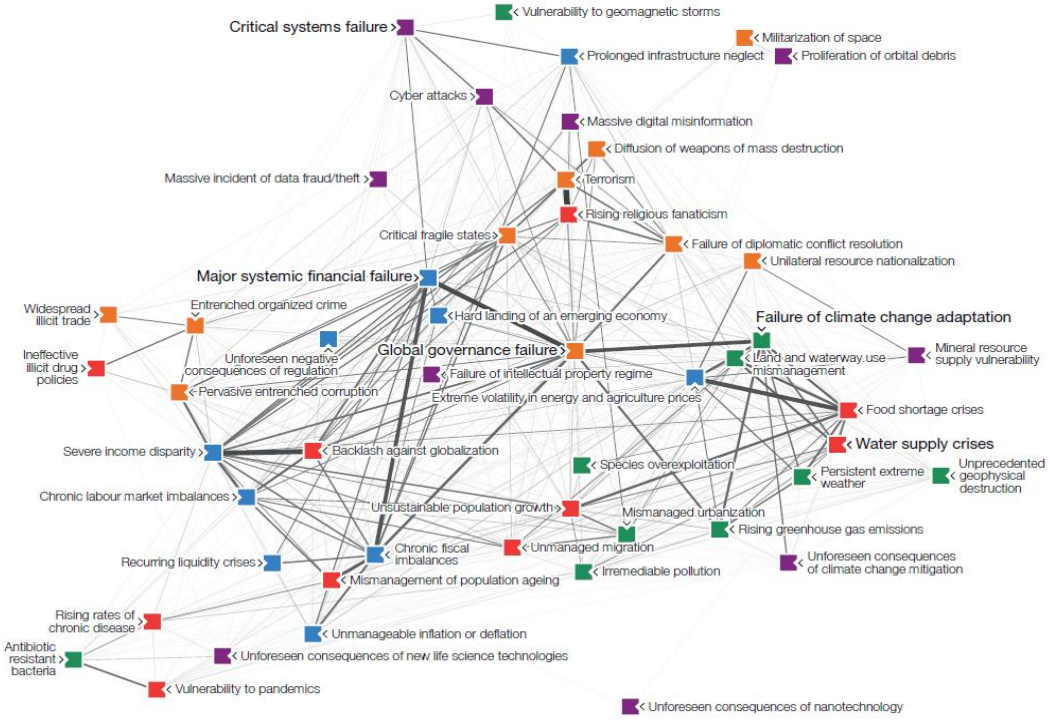
Dr. Janez Sušnik

Senior Lecturer
IHE Delft Institute for Water Education

j.susnik@un-ihe.org

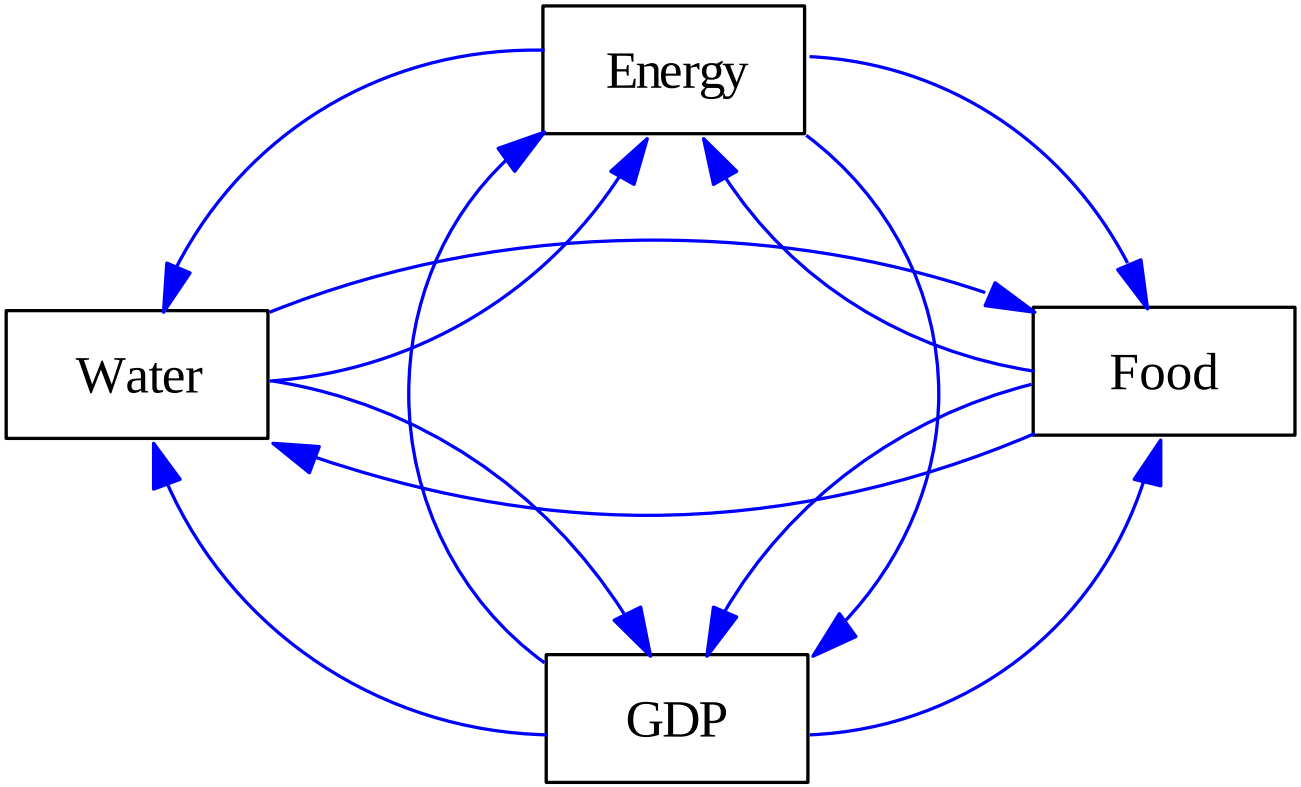
INTRODUCTION

- Water, energy, food, GDP tightly connected – a global system
- Increasing concern over resource exploitation and sustainability
- Greater calls for ‘nexus’ thinking → reconcile with huge growth and demand?



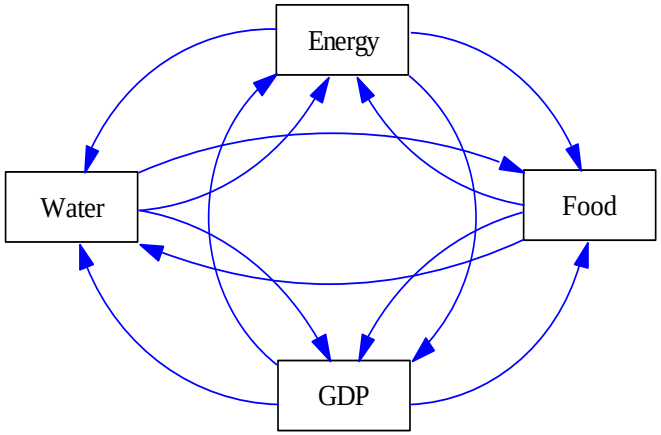
Source: World Economic Forum

INTRODUCTION



INTRODUCTION

- **Qualitative description** of the WEF-GDP system
  - What form do relationships take?
  - How can change in one sector impact others?
  - How can uncertainty be accounted for?
  - What are key causal influences?
  - How strong are relationships?
  - What are the system trends?



INTRODUCTION

- Many cross-sector studies, but usually limited in:
  - Space (localised case studies)
  - Sectors (e.g. one or two, not interacting)
- Few are global *and* comprehensive
- A classic example (nearly 50 years old!) → Limits to Growth
- One main issue: the 'nexus' means anything and everything (or nothing…)→ lack of cohesion/tools/focus
- **WEF-GDP not coherently modelled at the global scale**

AIMS

- To address some of those questions pertaining to the WEF-GDP system

- Quantitatively assess and model:
  - Correlation between sectors
  - Uncertainty in the data
  - Causal relationships (direction, strength)
  - System *trajectories* to 2100

DATA AND METHODS

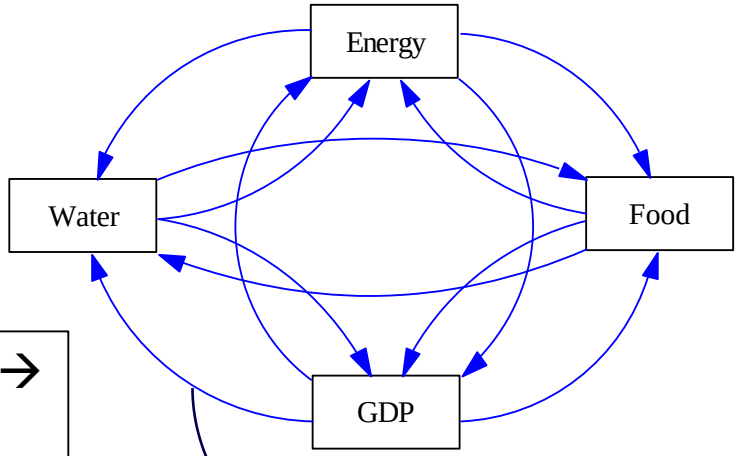
Table 1: Summary statistics of the data used in this study

Metric	Total number of countries used in analysis[1]	Temporal coverage [min range; maximum range; completeness]	Data source
Total GDP	203	1960-2013 [1 year; 54 years; variable completeness from totally complete 1960-2013 to patchy or single entry]	World Bank (August 2014; http://data.worldbank.org)
Total national water withdrawal	183	1962-2012. Data are reported in approximately five-year intervals, although the reporting period varies between countries. Data are more complete after the 1980's. [1 entry; 9 entries; variable from complete records to only one value entered]	UN FAO AQUASTAT database (August 2014)
Total national crop production[2]	176	1961-2013. Data are reported at annual intervals for each country. [8 years; complete coverage; where data are available, coverage is good.]	UN FAOSTAT database (August 2014)
Total national net electricity consumption	184	1980-2011. Data are reported at annual intervals for each country. [6 years; complete coverage; where data are recorded, coverage is good]	US Energy Information Administration (www.eia.gov; August 2014)

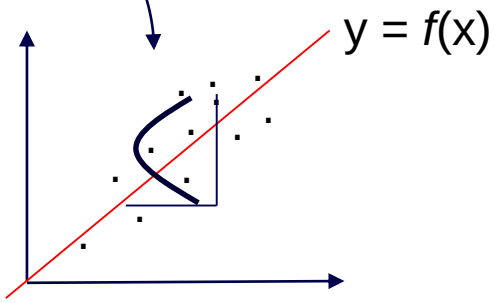
[1]This is the total number of countries with at least one data entry in the timeseries. These countries are not all necessarily used in the relationship analyses, which depends on there being corresponding data available in both of the variables. Only when data for a given value and year are available in both parameters is that country used. See text for details.

[2] The total crop production is the sum of many different crop types from the UN FAOSTAT database. See Table 1 in Sušnik (2015) for all the crop types included in this calculation. Production is measured in kg yr^{-1}.

DATA AND METHODS



Correlation analysis between WEF-GDP pairs → Best-fit regression relations



Best-fit distribution assessment of WEF-GDP sectors

Causal analysis between WEF-GDP pairs using multispatial convergence cross mapping

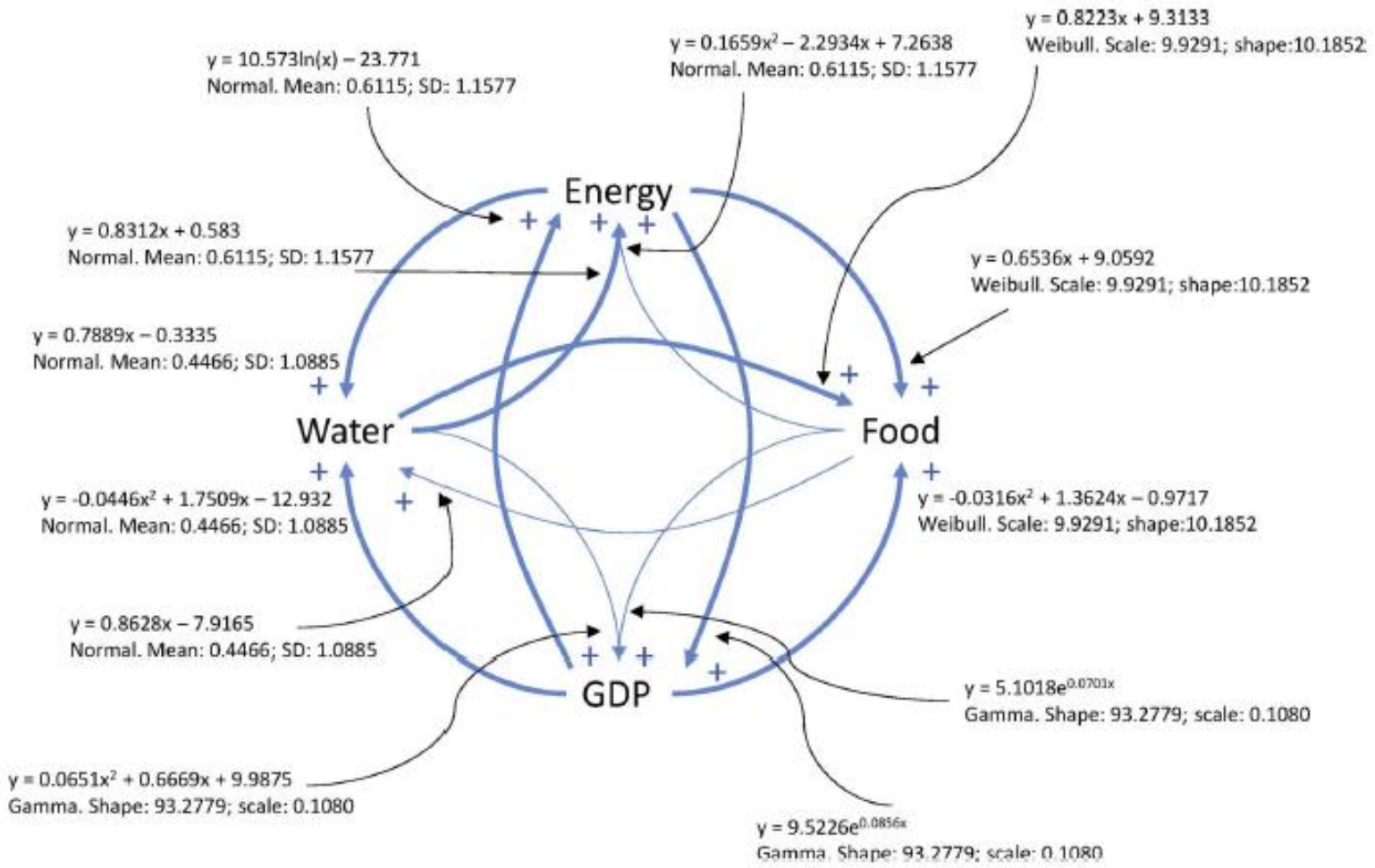
DATA AND METHODS

Table 3
Best-fit regressions relationships between the four sectors (WEF and GDP), and best-fit statistical distribution of each sector. All regressions have a *p*-statistic < 0.01.

Sectoral pairing	Best-fit regression[b]	Adjusted R^2[b]	Number of correlated points (n)
GDP → total national water withdrawal[a]	$y = -0.0446 \times^{b} + 1.7509x - 12.932$	0.57	243
GDP → total national food production[a]	$y = -0.0316 \times^{b} + 1.3624x - 0.9717$	0.51	3704
GDP → total national net electricity consumption[a]	$y = 10.573\ln(x) - 23.771$	0.9	2555
Total national water withdrawal → GDP	$y = 0.0651 \times^{b} + 0.6669x + 9.9875$	0.58	243
Total national food production → GDP	$y = 5.1018e^{0.0701x}$	0.51	3704
Total national net electricity consumption → GDP	$y = 9.5226e^{0.0856x}$	0.9	2555
Total national water withdrawal → total national food production	$y = 0.8223x + 9.3133$	0.71	472
Total national water withdrawal → total national net electricity consumption	$y = 0.8312x + 0.583$	0.65	453
Total national net electricity consumption → total national food production	$y = 0.6536x + 9.0592$	0.5	4964
Total national food production → total national water withdrawal	$y = 0.8628x - 7.9165$	0.71	472
Total national net electricity consumption → total national water withdrawal	$y = 0.7889x - 0.3335$	0.65	453
Total national food production → total national net electricity consumption	$y = 0.1659 \times^{b} - 2.2934x + 7.2638$	0.55	4964
Sector	**Best fit statistical distribution**		
GDP	Gamma. Shape: 93.2779; scale: 0.1080		
Water withdrawals[a]	Normal. Mean: from regression equation; SD: 1.0885		
Food production[a]	Weibull. Scale: 9.9291; shape: 10.1852		
Electricity consumption	Normal. Mean: from regression equation; SD: 1.1577		

[a] Results originally from Sušnik (2015).
[b] x is always the independent variable (the first of the variables in the left-hand column), y is the metric of interest on the right of the metric pairs. SD = standard deviation.

TOWARDS A QUANTIFIED WEF-GDP SYSTEM

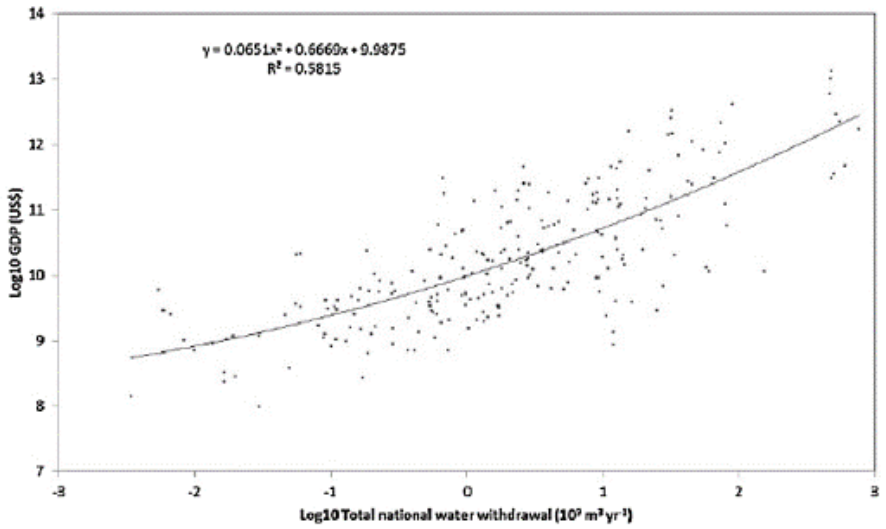


DATA AND METHODS

- Creation of seven GDP growth scenarios to 2100
  - Ranging from 5% yr^{-1} increase to 4% yr^{-1} decrease
- All information and conceptual model used to develop a quantitative system dynamics model
- Monte-Carlo sampling of the best-fit distributions. 100x model runs.
- Initialised with WEF-GDP values in 1961. GDP growth implemented from 2020. Annual timestep
- Historical data used to validate model results

RESULTS – CORRELATION AND CAUSALITY

a)



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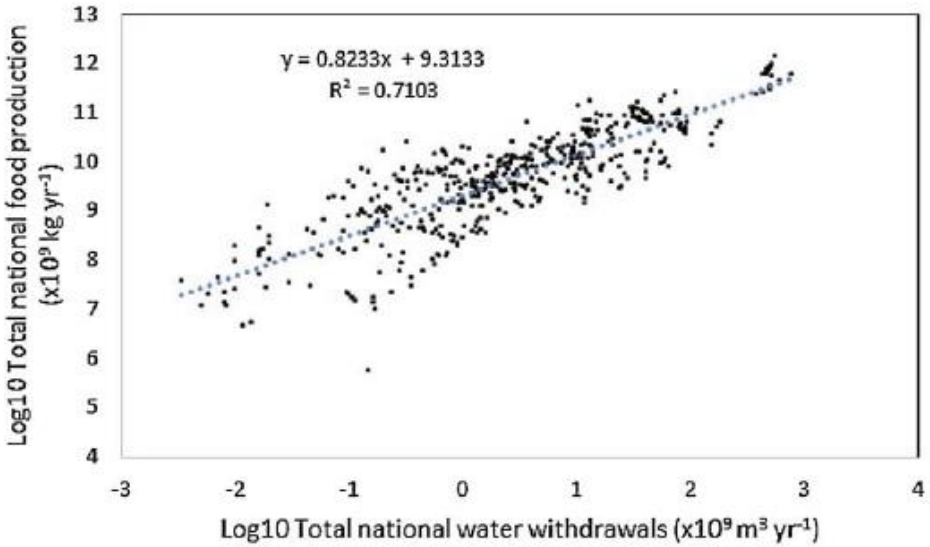

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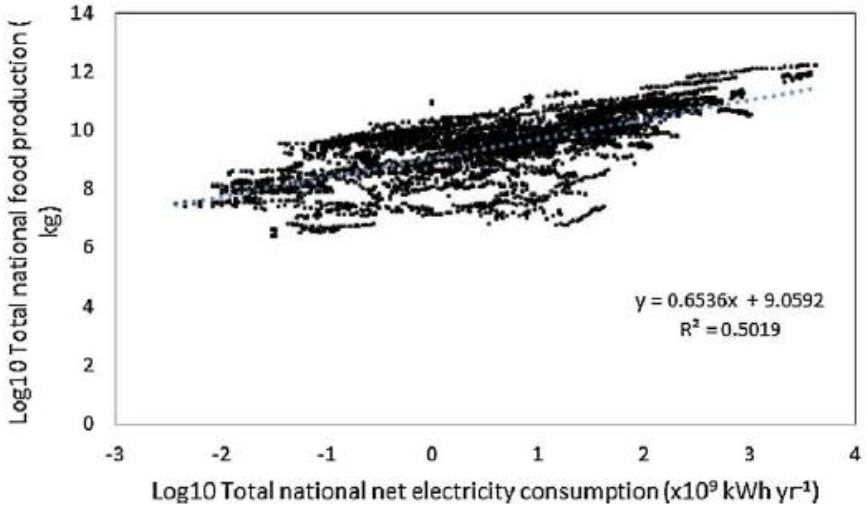

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RESULTS – CORRELATION AND CAUSALITY

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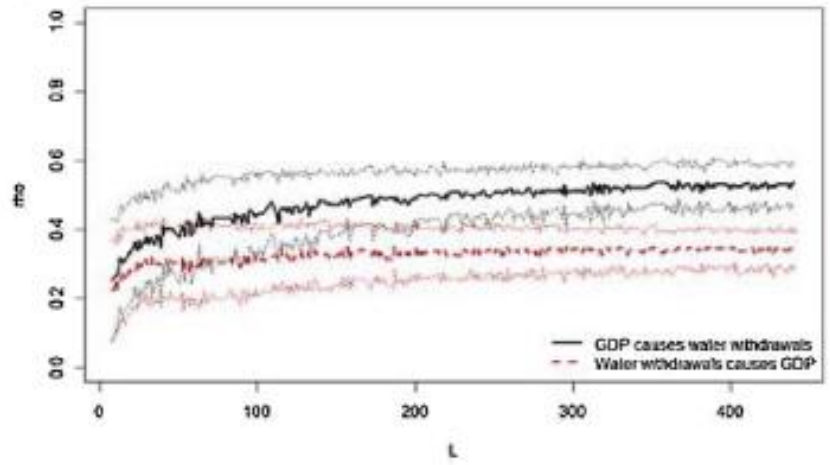

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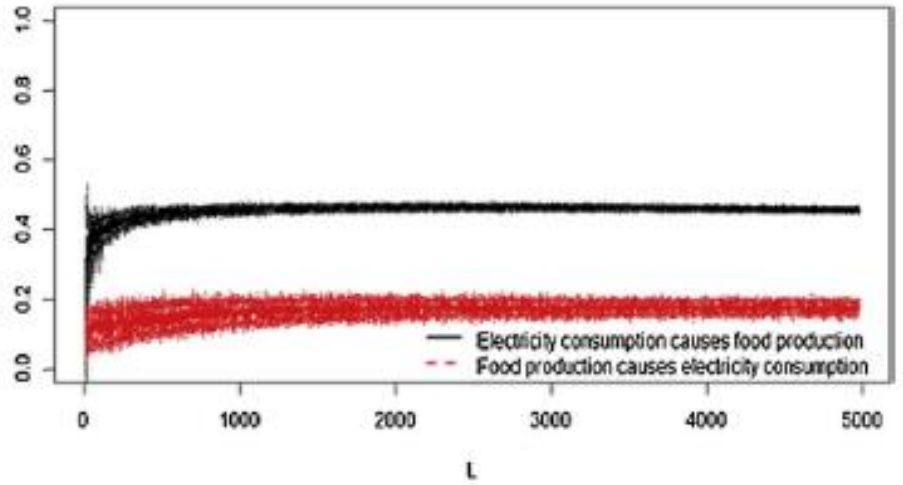
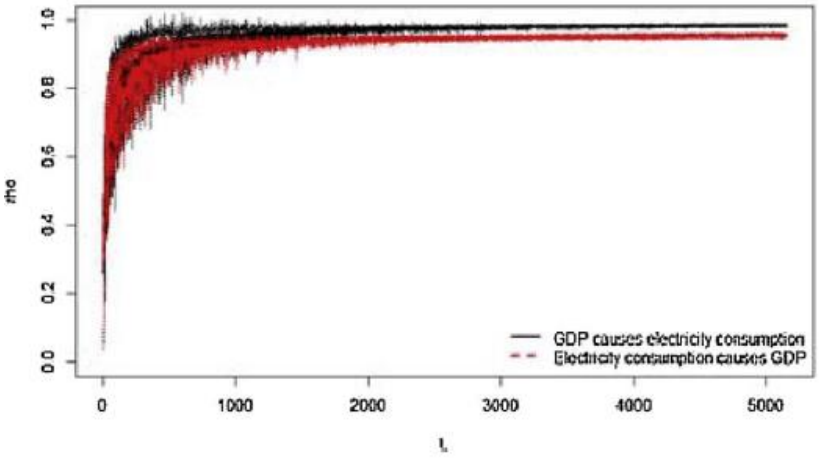
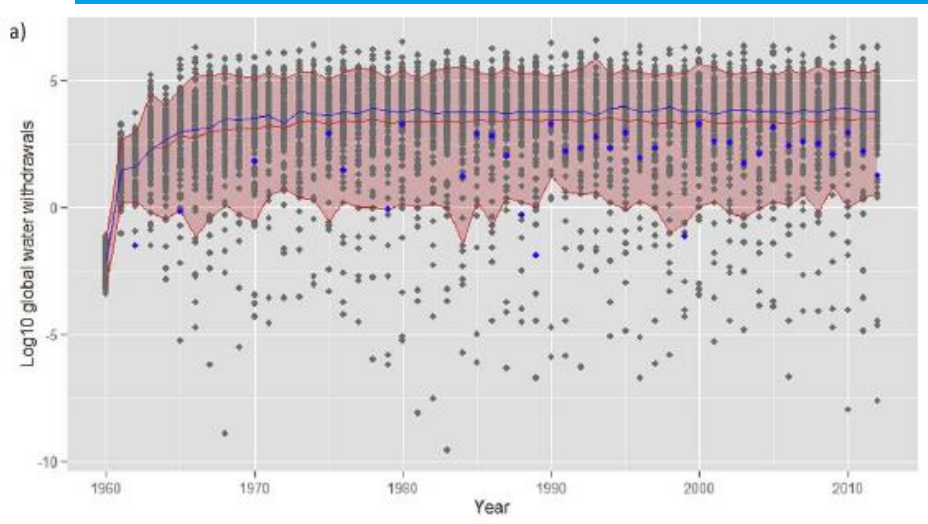
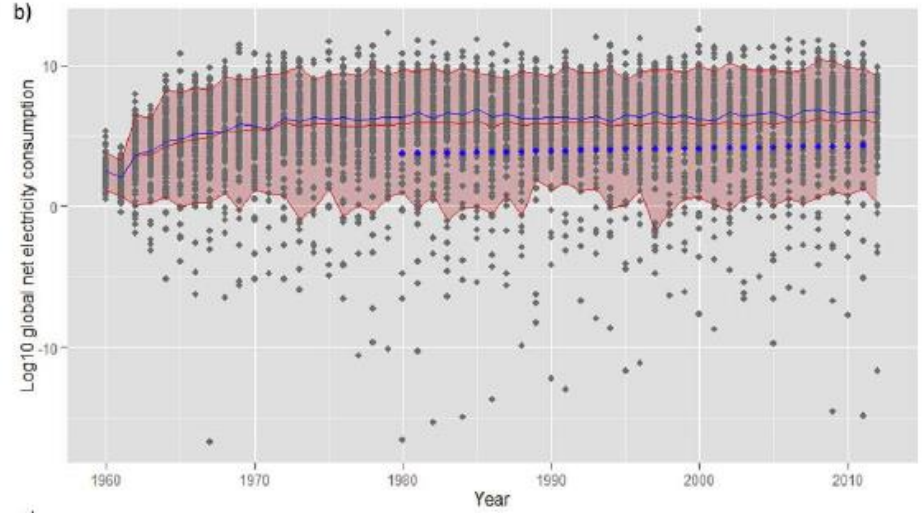


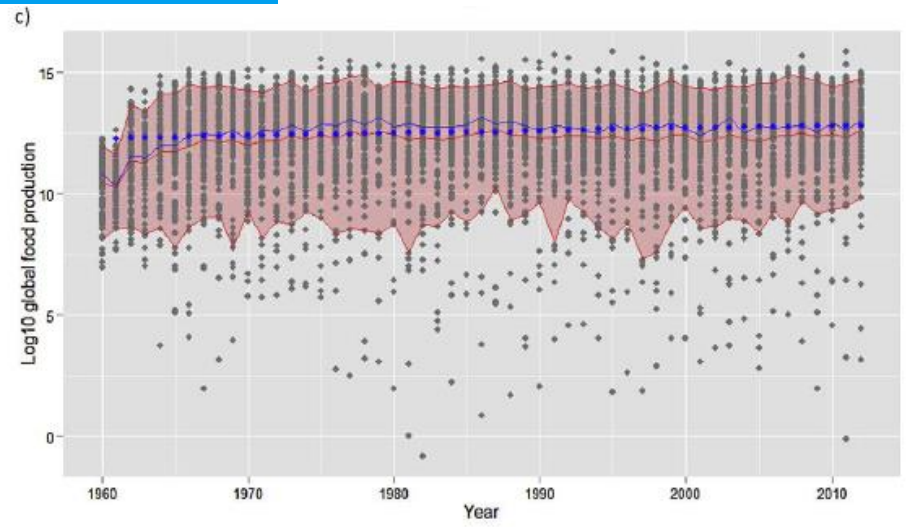


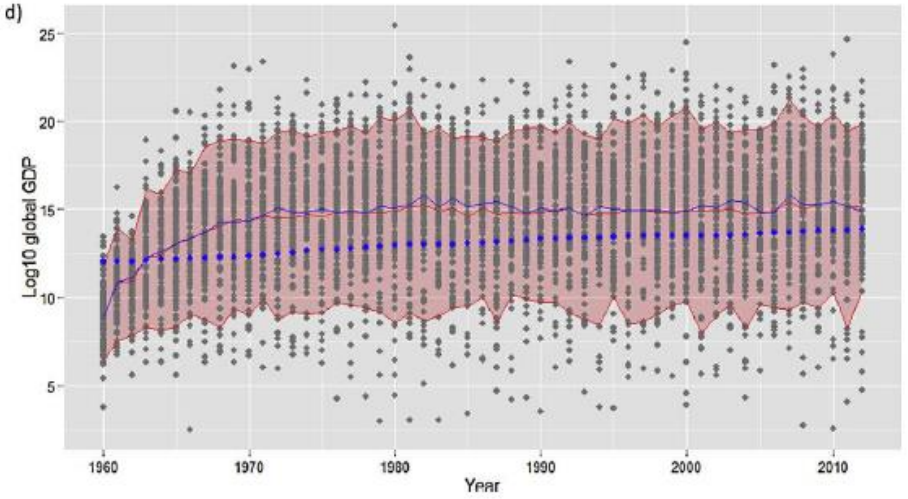
Correlation (strength) does not imply causality

RESULTS – HISTORICAL VALIDATION









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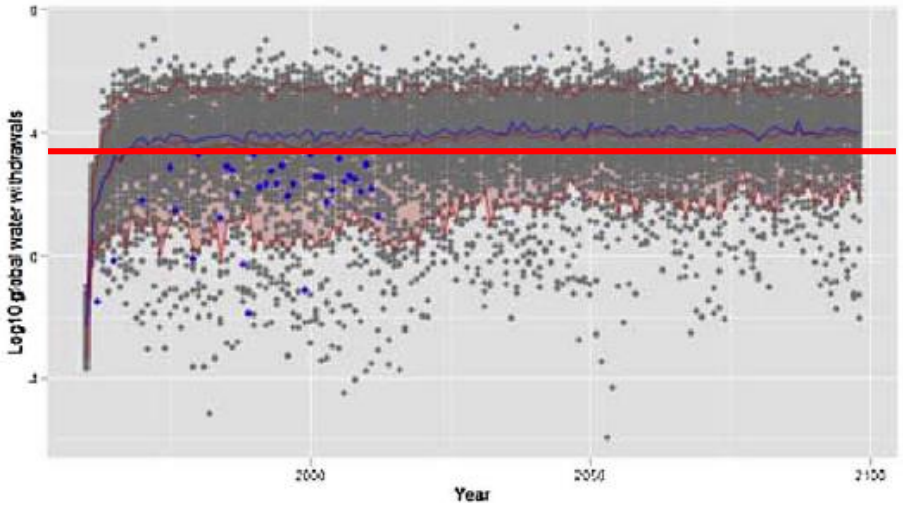
RESULTS – FUTURE PATHWAYS

a)



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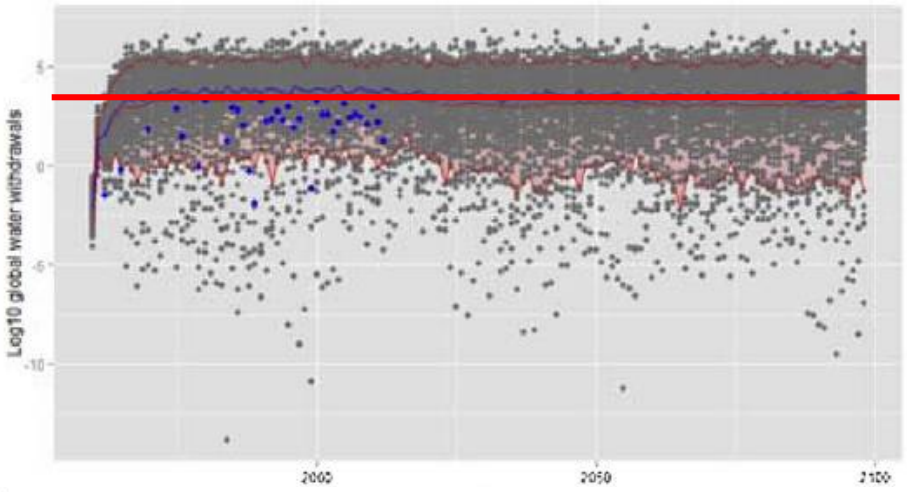

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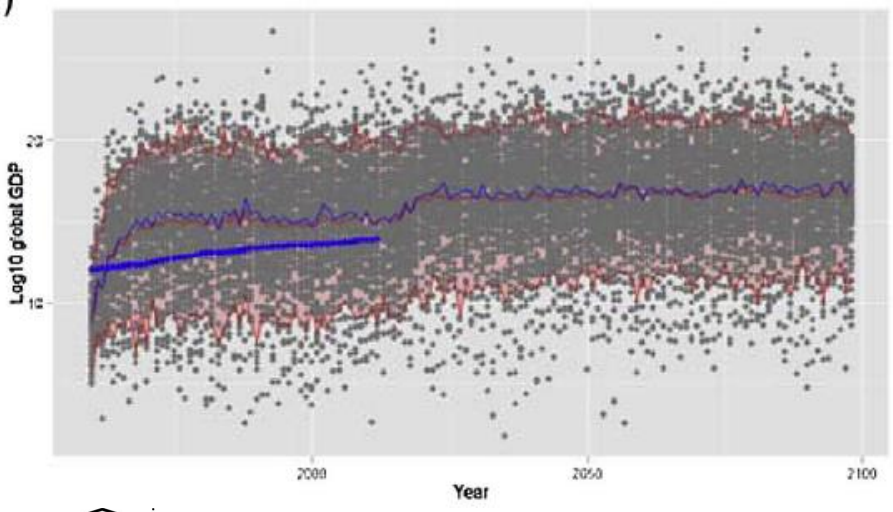

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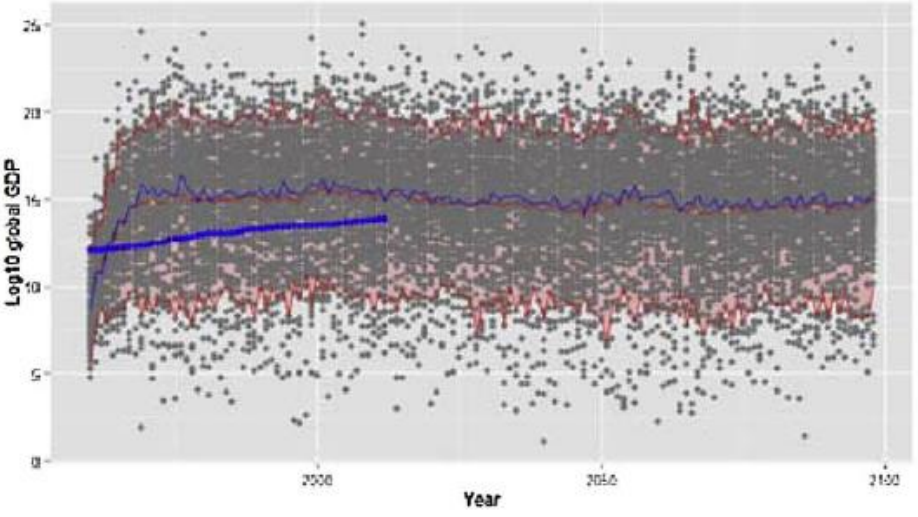

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DISCUSSION: WATER

- Steffan et al. put ‘safe planetary limit’ for water withdrawals at 4000 km3/yr.

Model means 2017	Literature values	Reference
2900-3700 km3	2600-4000 km3	Steffan et al. 2015; Hanasaki et al. 2013; Wada and Bierkens, 2014.
Model means 2100	**Literature values**	**Reference**
2700-6700 km3	6000-13300	Wada and Bierkens, 2014; Hanasaki et al. 2013; Hejazi et al. 2014

DISCUSSION: ENERGY AND FOOD

- **ENERGY**
  - 2017 *model*: 570000-1900000 x 10^9 kWh; *EIA*: 37100 x 10^9 kWh
  - 2050 *model*: 237000-6400000 x 10^9 kWh; *EIA*: 45000 x 10^9 kWh
- **FOOD**
  - 2013 *model*: 1450-4158 x 10^9 kg; *FAO*: 5080 x 10^9 kg
  - 2050 *model*: 1680-7120 x 10^9 kg; *FAO*: 7147-7548 x 10^9 kg

DISCUSSION

- Correlation *does not* imply equal levels of causality (e.g. GDP-water; GDP-food → similar R^2, different causal results).
- Asymmetry common in causal relations
- Historical results replicated reasonably well.
- **Future trajectories depend strongly on GDP growth → implications for resource exploitation**

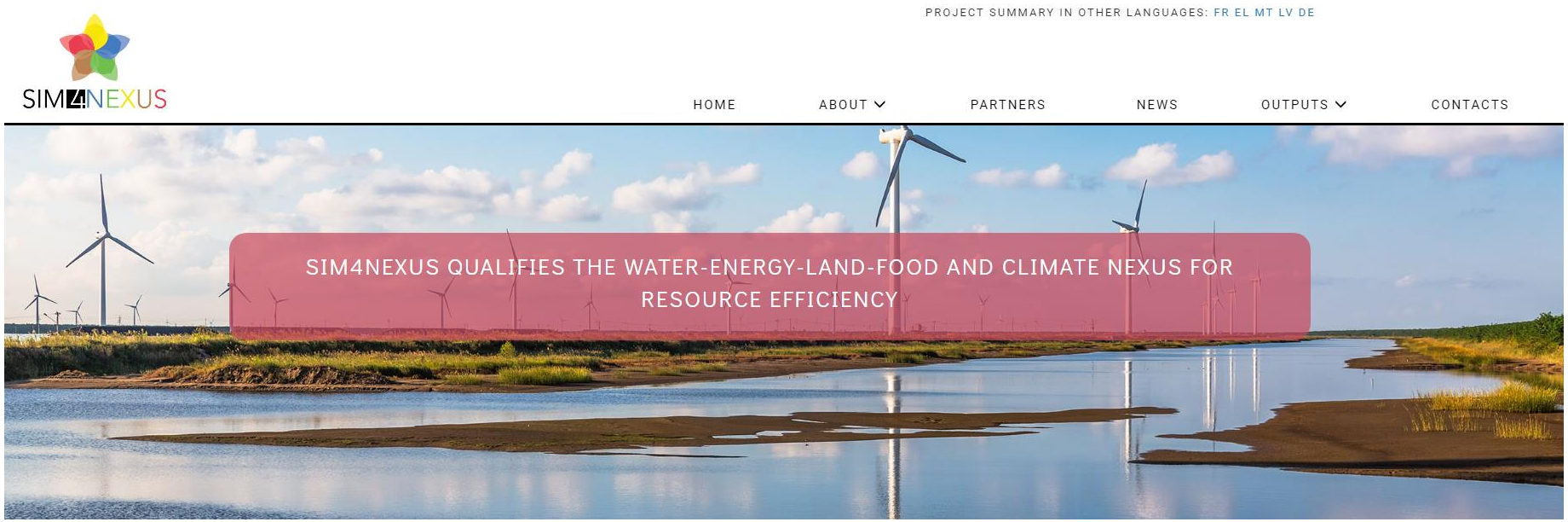
CONCLUSIONS

- Previously qualitative WEF-GDP ‘models’ quantified
- Correlation between sectors does not correspond to causality
- Quantitative SDM model reproduced historical values reasonably well
- Trajectories to 2100 suggest possibility of exceeding ‘safe operating space’
- **Link of WEF sector growth to GDP performance must be weakened/decoupled**
- Next: do this at national resolution

ACKNOWLEDGEMENT

- This work is feeding into a major EC Horizon2020 project

- SIM4NEXUS (www.sim4nexus.eu)



REFERENCE

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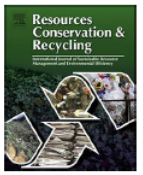

Full length article

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Janez Sušnik

Integrated Water Systems and Governance Department, IHE Delft Institute for Water Education, PO Box 3015, 2601DA Delft, The Netherlands

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Nexus
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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.


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