5-2018

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Citation

MCGRANE, Scott J.; ACUTO, Michele; ARTIOLI, Francesca; CHEN, Po-Yu; COMBER, Robert; COTTEE, Julian; FARR-WHARTON, Geremy; GREEN, Nicola; HELFGOTT, Ariella; LARCOM, Shaun; MCCANN, Julie A.; O'REILLY, Patrick; SALMORAL, Gloria; SCOTT, Marian; TODMAN, Lindsay C.; VAN GEVELT, Terry; and YAN, Xiaoyu. Scaling the nexus: Towards integrated frameworks for analysing water, energy and food. (2018). *The Geographical Journal*. 185, (4), 419-431.
Available at: https://ink.library.smu.edu.sg/cis_research/50

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Accepted: 5 March 2018

DOI: 10.1111/geoj.12256

WILEY THE GJ Royal Geographical Society with IBG

THEMED SECTION

GEOGRAPHY AND THE WATER–ENERGY–FOOD NEXUS

Scaling the nexus: Towards integrated frameworks for analysing water, energy and food

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Funding information
Engineering and Physical Sciences Research Council, Grant/Award Number: EP/N005600/1; Biotechnology and Biological Research Council of the UK

The emergence of the water–energy–food (WEF) nexus has resulted in changes to the way we perceive our natural resources. Stressors such as climate change and population growth have highlighted the fragility of our WEF systems, necessitating integrated solutions across multiple scales. While a number of frameworks and analytical tools have been developed since 2011, a comprehensive WEF nexus tool remains elusive, hindered in part by our limited data and understanding of the interdependencies and connections across the WEF systems. To achieve this, the community of academics, practitioners and policy-makers invested in WEF nexus research are addressing several critical areas that currently remain as barriers. First, the plurality of scales (e.g., spatial, temporal, institutional, jurisdictional) necessitates a more comprehensive effort to assess interdependencies between water, energy and food, from household to institutional and national levels. Second, and closely related to scale, a lack of available data often hinders our ability to quantify physical stocks and flows of resources. Overcoming these barriers necessitates engaging multiple stakeholders, and using experiences and local insights to better understand nexus dynamics in particular locations or scenarios, and we exemplify this with the inclusion of a UK-based case study on exploring the nexus in a particular geographical area. We elucidate many challenges that have arisen across nexus research, including the impact of multiple scales in operation, and concomitantly, what impact these scales have on data accessibility. We assess some of the critical frameworks and tools that are applied by nexus researchers and articulate some of the steps required to develop from nexus thinking to an operationalisable concept, with a consistent focus on scale and data availability.

KEYWORDS
data availability, nexus drivers, scales and levels, uncertainty, water–energy–food nexus, water-energy-food webs

1 | INTRODUCTION

The emergence of the water–energy–food (WEF) nexus in response to major global challenges has led to significant changes in the way academics and policy-makers think about our natural resources (Smajgl et al., 2016). WEF resources are inextricably linked: water and energy are used in the production and manufacture of food, while energy is required to extract, treat and distribute water from source to supply, while also being used in the cooking, manufacture and storage of food produce. Food waste is increasingly being used as a means of generating energy, and water is a critical resource in the energy production process. In 2009, former UK Chief Scientific Advisor, Sir John Beddington, addressed the interlinked nature of resource issues in his "perfect storm" speech (Sample, 2009), indicating that a growing population and success in reducing poverty in developing countries will place considerable strain on our WEF resources by 2030. In a 2014 report, the InterAction Council identified challenges within the nexus posing a critical threat to global society alongside sectarian conflict and nuclear proliferation (Mohtar & Daher, 2016).

Currently, the global population sits at 7.5 billion, expected to reach 9 billion by the year 2040 (United Nations Department of Economic and Social Affairs, 2016a). Around 795 million people are undernourished, 1.4 billion have no access to electricity and 2.4 billion having no access to basic sanitation services, with a further 665 million having no access to clean drinking water (United Nations Department of Economic and Social Affairs, 2016b). Concomitantly, the developed world experiences a world of "plenty," often resulting in diet-related health conditions and poor conservation practices, with large volumes of waste. The diversification of demand patterns from a growing middle-class culture has resulted in an expectation for year-round access to a variety of produce, including fruit and vegetables, creating high, displaced water and energy footprints.

Water, food and energy are often overseen by different governmental departments, and researchers from particular disciplines carry out analyses in an isolated manner (Leck et al., 2015). The nexus aims to break down silo mentality and assess the interdependencies and management of these areas as an integrated process that considers how (1) actions in one area may influence the coordination of institutions and policies for resource management, (2) unintended and unexpected consequences can be avoided, and (3) synergies in the collective management of the WEF systems can deliver enhanced security. A principal aim of nexus studies is to promote sustainable and increasingly efficient resource use, making existing resources go further to meet the needs of more people, while simultaneously protecting ecosystems (Stockholm Environment Institute, 2014).

Despite arising as a consequence of major global pressures, the need to understand the interactions within the nexus, and associated policy interventions, involves multiple scales. There remains a disconnect between the spatial scale at which decisions are made, and both WEF production and consumption. Under the auspices of an EPSRC-funded project WEF-WEBs[1] (Water-Energy-Food Webs), the authors of this paper seek to identify WEF interdependencies, across multiple scales and sectors in the UK, by identifying existing data and potential new sources and thereby identifying entry points for improved management and governance of these resources. This paper provides a comprehensive assessment of frameworks and approaches for assessing the nexus, focusing on two key issues, namely frameworks and tools that have been applied across nexus problems, and an assessment of the contrasting scales of these problems. Challenges relating to variations in the availability and quality of data in nexus assessments are then discussed along with the resulting uncertainties. Finally, these challenges are illustrated using a UK case study.

2 | DRIVERS AND DEVELOPMENT OF THE NEXUS

The nexus seeks to challenge boundaries and connect discourse between academics, experts and policy-makers, who possess different forms of technical knowledge and disciplinary perspectives. In the UK, energy governance and policy are overseen by the Department for Business, Energy and Industrial Strategy (BEIS), whereas food and water are the remit of the Department of Food and Rural Affairs (DEFRA, 2016). Similar patterns can be observed in other national government organisations, and also within cross-national organisations such as the United Nations and the European Union. Supranational targets such as the sustainable development goals (Table S1) have been integral in the emergence of nexus thinking (Sachs, 2012). Importantly, there is recognition that, in order to achieve all goals simultaneously, the interconnectivity of the actions taken to advance individual goals must be considered (United Nations Environment Programme et al., 2015). Practically, however, this presents a huge challenge. As part of the shift towards "nexus thinking," dialogue has emerged that seeks to bridge these divides, resulting in the emergence of transdisciplinary research groups and cross-agency working groups, such as the authors, currently involved in the WEFWEBs project.

Key criticisms of the nexus are often a lack of originality and novelty, lack of clarity and lack of practical applicability, being viewed as a framework that facilitates discussion, but yields no action (Cairns & Krzywoszynska, 2016). Many have come to view the nexus as a repackaging of existing integrated frameworks such as Integrated Water Resource Management (IWRM), which is an oft-cited example of a framework the nexus seeks to build upon, with debated success (Benson et al., 2015). The nexus attempts to differentiate itself by considering the WEF sectors concomitantly, soliciting cross-sectoral cooperation rather than assessing the impacts of changes through one particular lens. However, the nexus has not yet managed to free itself from the same pitfalls, with conscious and unconscious bias often impacting how assessments are undertaken. For example, nexus assessments of food production consider energy and water as inputs, whereas through a water lens, food and energy production are both primary users (Bazilian et al., 2011).

3 | METHODOLOGIES FOR ASSESSING THE NEXUS

3.1 | Existing nexus frameworks

Since the 2011 Bonn Conference (Hoff, 2011), several nexus frameworks have evolved (Andrews-Speed et al., 2012; Bizikova et al., 2013; European Report Development, 2012; ICIMOD, 2015; UNECE, 2014). Here, we identify some key conceptual nexus frameworks (Table S2). These different purposes have resulted in different boundaries for frameworks, with some simultaneously considering constraints on additional resources such as land and minerals. The frameworks have also been developed at different scales, from regional (e.g., Bizikova et al., 2013; ICIMOD, 2015) to global (e.g., WBCSD, 2014; World Economic Forum, 2011). This range of frameworks stems from the complexity of the nexus and points to a need for a hierarchical framework that integrates across scales. Such a framework, however, is lacking, and would rely on a variety of tools to represent the nexus from different perspectives and scales.

3.2 | Existing modelling systems

A number of models have also been developed to assess the nexus quantitatively (Table S3). MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) (Giampietro & Food and Agriculture Association of the United Nations, 2013) is a framework for defining systems (e.g., water, land, energy, food) under different levels of analysis (e.g., society wide or by socio-economic compartments). MuSIASEM distinguishes between funds (they have to be maintained and reproduced in the metabolic process) and flows (elements that change during analysis). Labour (hours of human activity), capital, land and available water (rivers, groundwater, soil water) are considered funds, while food, energy and water (abstractions) comprise the flows. Several tools (e.g., hydrological modelling, footprint analysis, mass balance) and approaches (top down and bottom up) are applied to quantify funds and resources flows. Multi-level analysis is the basis of the quantitative assessment of the FAO Nexus Approach (FAO, 2014). Taking similar approaches and applying them at local levels to identify emerging dynamics may prove challenging, as data confidentiality and commercial confidence issues rapidly become apparent with regard to individuals and companies.

The CLEWS (climate, land, energy and water systems) framework has been applied in a number of studies (e.g., Howells et al., 2013; Welsch et al., 2014), providing a robust and integrated framework for assessing nexus interlinkages and future scenarios, incorporating stakeholder involvement in scenario development and testing. The CLEWS framework is composed of three sub-models: Water Environment and Planning (WEAP), Long-term Energy and Planning (LEAP) and a land-use model derived from the Agro-Ecological Zones (AEZ) model, developed to form the central tool of other nexus frameworks. Existing applications of CLEWS have been national level, although some of these have been in small geographies (e.g., Mauritius). Furthermore, CLEWS does not explicitly consider food, instead focusing on land use and agricultural landscapes.

Some analytical frameworks provide interactive tools, which are appropriate for visualisation of nexus connections (Table S3). For example, the WEF Nexus Tool 2.0 (Mohtar & Daher, 2014) assesses the flows between WEF in Qatar. It incorporates user-driven scenarios of WEF sourcing and production, including measures of self-sufficiency and imports, and transportation methods. Applications are limited to agricultural crop production, and in the current version, fail to assess wider food production such as livestock, dairy production and processed foods. Similarly, CSIRO's National Outlook Model (NOM) of Australia (Hatfield-Dodds et al., 2015) provides tools that incorporate data and stakeholder inputs at the national scale of Australia (Table S3). The NOM framework relies on a series of interconnected proprietary (CSIRO) models, imposing significant computational and input data requirements. As a result, implementation of the NOM is geographically restricted to Australia, but serves as an excellent template for assessing the nexus at a national scale.

In the UK, the Foreseer tool is another interactive tool that generates scenarios of natural resource supply, transformation, and use, as well as the effects on water, energy and food resources. The tool links physical models plus the technologies that transform the resources into final services (Curmi et al., 2013). To date, the Foreseer tool has been developed for California, China and the UK, using nationally available databases. No efforts have been made to date to assess more local levels, and this may prove challenging owing to the limited corresponding data at sub-national scales.

3.3 | Other useful tools and approaches

As part of the WEFWEBs project, we are exploring ways in which the nexus emerges at different scales, considering national scale dynamics and interactions down to local, catchment-specific dynamics. This has involved appraising a number of tools that encompass national-level data down to individual stakeholder data, to elucidate resource availability and consumption, flow of materials, governance and associated impacts. The following section highlights some of these tools and approaches.

3.3.1 | Environmental extended input–output analysis

A starting point for nexus assessments is often a robust set of environmental data that can provide insight based on a top-down (national → local) approach. Environmental accounting enables global agencies and national governments to take stock of economic and environmental resources and provide a detailed overview of stocks and flows of natural resources. The System of Environmental-Economic Accounting (SEEA) was introduced in 2012 (United Nations et al., 2014) to provide practitioners with a tool to track trends, uses and availability of environmental stocks. The SEEA Central Framework (UN, 2014) is the most recent statistical framework consisting of a comprehensive set of tables and accounts, which guides the compilation of consistent and comparable statistics and indicators for policy-making, analysis and research. The SEEA adopts the input–output principle, and applies an environmental extended input–output (EEIO) analysis. The relevance of using EEIO for the nexus is that this attempts to analyse structures of production and consumption and their material flows, rather than assuming a societal black-box (Schaffartzik et al., 2014). EEIO is a powerful method to assess relationships between economic sectors and the downstream environmental impacts, as well as embodied environmental impacts from trade activities. As limitations, there are known issues of homogeneity of grouped products, low resolution of categories under analysis, homogeneity of prices, omission of some activities (e.g., unpaid work), no data availability for every nation, and large time lags between publications (Kitzes, 2013; Schaffartzik et al., 2014). Furthermore, many assumptions are made in the comparison of national datasets that often fail to consider diversity within parameters. For example, comparisons of energy intensity averages are often constructed for national comparisons, but fail to account for differences in national energy systems. While environmental accounts provide a useful collation of national annual data, they often fail to assess data and processes at smaller spatial and temporal scales. Moreover, the information is often fragmented and for specific domains, which makes it difficult to provide insights of cross-sectoral dependencies.

3.3.2 | Indicators

Increasingly, there has been a growing interest in the role of indicators to represent aspects of the nexus. Ecological, water, land, carbon, energy and material footprints (or indicators) comprise what is known as family footprints, which can be used to measure natural resource sustainability boundaries (e.g., Vanham, 2015). National environmental footprints are used to show the differences between individual countries regarding the global environmental burdens they impose (e.g., Environmental Performance Index), assigning environmental burdens to final consumers of products and services (Weinzettel et al., 2014). A main difference of footprints in comparison to traditional environmental accounting is that they can account for direct and indirect consumption of resources (i.e., upstream consumption). Moreover, footprint studies apply several approaches depending on the object and level of analysis (e.g., from a product to national scale) (Fang et al., 2014). The success of a given indicator depends on the availability of data and the motivation for its development. Many successful indicators have a large number of sub-indices, necessitating significant input data from a diverse range of sources. Furthermore, many indicators are based on national-level data, where data are most readily available to researchers. The application of indicators to nexus research has been slow to progress, though limited examples are beginning to emerge (Willis et al., 2016).

3.3.3 | Life cycle assessment

Life cycle assessment (LCA) is a widely accepted and applied environmental management tool for quantifying present day emissions, resource consumption, and assessing environmental and health impacts associated with processes, products or activities over their entire life cycle. The LCA methodology comprises four main stages (ISO, 2014): (1) goal and scope definition, (2) life cycle inventory analysis, (3) life cycle impact assessment, and (4) interpretation of results. LCA has been applied extensively in evaluating energy technologies (Ou et al., 2012), food products (de Vries & de Boer, 2010; Roy et al., 2009) and water systems (Lundie et al., 2004; Stokes & Horvath, 2006). LCA is a valuable and convenient tool in exploring the nexus from a physical perspective as existing software (e.g., SimaPro[2]) and inventory databases (e.g., Ecoinvent[3]) can be used to identify physical connections and flows, as well as environmental impacts for a defined system. LCA is widely used in food production and consumption assessments (Green et al., 2015; Van Der Werf et al., 2014), and water–energy nexus studies (Feng et al., 2014; Pacetti et al., 2015), while applications of LCA in the context of the WEF nexus are slowly appearing, often from a food perspective (Al-Ansari et al., 2015; De Laurentiis et al., 2016). It remains unclear how LCA can be used to analyse the nexus without focusing on any individual sectoral perspective. Furthermore, LCA is not sufficient to address the nexus for a full geographical area, since all sectors and activities within the area need to be accounted for. The emerging spatio-temporal dynamic LCA methods (e.g., Maier et al., 2017; Raschio et al., 2017) have the potential to be more useful in exploring the nexus in a geographical context and when coupled with future scenarios in contrast to existing conventional LCA methods, which are static and non-spatial. However, significantly more data on the locations and times of the processes and elementary flows, as well as background environmental characteristics, are needed to establish the spatially and temporally explicit inventory databases required.

3.3.4 | Participatory workshop engagement

Building on a rich conceptual foundation (Ulrich, 1993), participatory modelling activities bring together key stakeholders and provide a set of tools that allow synthesis of knowledge and views to occur, generating both qualitative and quantitative data. By bringing in grounded knowledge, often not captured in scientific knowledge bases, participants provide insights which support more innovative and appropriate design of policies and actions (Midgley & Richardson, 2007). Participatory modelling develops system representations and models that are capable of integrating knowledge from multiple actors, disciplines and sectors, including the public (Jones et al., 2009). Participatory modelling of nexus issues results in not only new outputs in the form of qualitative data and conceptual models that better capture interdependencies and trade-offs, but also changed viewpoints, improved knowledge and new insights, and connections among participants. This anecdotal evidence provides a rich insight into many of the interconnections across the nexus that would otherwise be masked via undertaking a purely quantitative data-based analysis.

4 | SCALE AND DATA

4.1 | Transcending scales in the nexus

In their review, Cash et al. (2006) highlight the disparity of scales across the nexus. While nexus thinking is driven by the quest to address global problems (e.g., climate change, finite resource base, growing population and migration), it is often local scales (e.g., household > regional > national) where nexus practice emerges. Closely linked to spatial scale is jurisdictional scale, whereby political units such as cities, regional councils/states or national governments are charged with implementing policy and governance (Bhaduri et al., 2015). Temporal scale is also key for the nexus, with scenario planning often implemented as a tool for future interpretations of climate change or population projections. These three scales also then define the scales at which data are required. With a multiplicity of scales, a number of problems and challenges emerge across nexus research (Cash et al., 2006). Continuing the adoption of their terminology, Cash et al. (2006) also identify three problems, of ignorance, mismatch and plurality. Mismatches in scale and level of the nexus are readily exemplified by the disparity between human actions and the environment within which physical processes operate. For example, our knowledge of global climate change has advanced to allow us understand better the uncertainty surrounding the security of our global resources into the future, yet resolutions are often not useful to more regional requirements for management of river basins or farms. Pluralism often (incorrectly) assumes that there exists one perfect solution for a given problem, negating the different needs of all actors involved in the process and the nonlinear relationships that can lead to a multitude of different outcomes.

4.2 | Transcending scales in the nexus: Governance and policy

Critical to governing the WEF nexus is a robust evidence base of compliance, necessitating companies and agencies to feedback data to ensure specific standards and obligations are being met. For example, the Environment Agency is responsible for the management of all river systems in England, tasked with ensuring water quality meets the standards required under the EU Water Framework Directive (2001). This necessitates the provision of data to ensure companies are compliant, with sufficient frameworks in place to guide, reprimand or censure those in breach. In short, the availability of data is an imperative to efficient governance across nexus practices. WEF nexus policies challenge past reforms and current governance configurations to increase cross-sectoral integration and management. Therefore, in this context, some fundamental questions of WEF nexus policy revolve around the issues of policy capacity and the instruments of cross-sectoral integration. First, the latter require the capacity to stir and coordinate a wide range of sectoral organisations (both public and private) whose interests are diverse and often conflicting. Second, WEF nexus policies are a matter of selection of the preferred solutions for integration. They can range from a complete bundling (or re-bundling of the three systems) to "lighter" solutions of knowledge and information sharing. In this regard, again, the role of data is crucial for the development of an evidence base that is used to inform policy-makers in the process of policy formation and implementation.

4.3 | Transcending scales in the nexus: Data

4.3.1 | National

Closely linked to scale is the question of data availability, where accessibility is a key challenge. A recent publication by McCarl et al. (2017) highlights the significance of data accessibility in WEF nexus analyses, identifying availability issues at increasingly small granularity. At the national or transnational level, data are often readily available in open accessible databases (e.g., FAOSTAT, AQUASTAT and the UNSD). Much of the data that are pertinent to nexus assessments are not centrally located under the authority of any one particular agency, primarily as a consequence of longstanding data management practices within sectoral agencies. Furthermore, paywalls and data sensitivity often mean that existing important data from other sources are often not readily available to researchers. Supermarkets rely on a significant amount of infrastructure and logistics to function successfully, serving as a hub for selling local, national and internationally produced goods. Concurrently, many of them have active programmes in place to reduce their environmental impacts. For example, Tesco operate a 24-hour monitoring service that captures energy and water consumption data across their entire estate, with the data being sent to a monitoring facility in Bengaluru (The Guardian, 2013). While this type of monitoring is a step toward supermarkets being able to determine their role in the wider nexus and address issues of sustainability and environmental accountability of their own practices, data are rarely externally available due to proprietary interests (McCarl et al., 2017).

4.3.2 | The institution and household scale WEF nexus

Increasingly, local authorities, institutions and households are monitoring their WEF usage and waste accordingly via an array of smart-meter technologies. For example, in the UK, central government buildings in London all report sub-daily data of energy and water usage, while local authority buildings (e.g., libraries, council offices, schools and health centres) are also increasingly monitored. Buildings or companies that are food intensive (e.g., restaurants, cafes and food production companies) are increasingly being encouraged to reduce their food waste (Garrone et al., 2016). For example, the inclusion of smart technology (and linked apps in phones/tablets) in refrigerators has enabled the monitoring of food practices, though much of this technology remains experimental and is not widely utilised (Farr-Wharton et al., 2014). At the individual level, food diaries have provided some insight into the practices associated with food. Issues around data sensitivity often mean that such data are unavailable to researchers, and as a result, this can often serve as a barrier to inclusion in wider nexus assessments (Hebrok & Boks, 2017). Unlike energy and water, food consumption and waste data remain elusive at local scales. For example, the annual Food Survey in the UK provides some insight into average family food-related purchases, and HMRC trade data elucidate revenue and trading locations of food produce with the rest of the world.

Domestic-scale electrical and gas consumption is comprehensively captured across the UK via electricity and gas meters connected to mains supply, though data accessibility remains an issue. Water consumption is captured in some parts of the UK through the incentivised rollout of water meters. Relatively recent policy changes have meant that new residential developments must include the installation of resource monitoring systems. However, this rollout, while progressive, is slow moving. Aside from capturing overall resource consumption within specific dwellings, there has been an additional rollout of incentivised schemes that target consumption awareness, with electricity consumption being the main focus of these schemes. As a result, a number of businesses have developed consumer grade "smart monitors" that can be attached to energy meters. The majority of these monitors have focused on providing the total consumption; however, as these devices have evolved, newer versions aim to disaggregate energy consumption down to appliance level. While water and gas monitors have been slow to reach the consumer market, there are some consumer-grade monitors that are available, such as the Smappee Gas and Water monitor.[4] Similar to traditional energy monitors, gas and water energy monitors capture total domestic consumption, but no such monitor exists for food consumption.

5 | THE WEF NEXUS IN THE UNITED KINGDOM: A CASE STUDY

A key objective of the EPSRC WEFWEBs project is to undertake a multi-scale, multi-level assessment of the WEF nexus of the United Kingdom to identify key entry points for decision and policy makers. Here, we discuss the process of assessing the WEF nexus for a small, experimental catchment in the south-west of the country in Plymouth and the surrounding Tamar valley. This case study touches upon some of the issues presented earlier with regards to scale and data, and presents a brief discussion on how a participatory stakeholder workshop in conjunction with a data-based analysis of the region has aided our understanding of the nexus in this region.

5.1 | UK WEF case study: Tamar catchment

The Tamar catchment in the south-west of the United Kingdom covers west Devon and east Cornwall, with the river Tamar rising in the north Devon hills and flowing 78 km downstream into the English Channel at Plymouth. The catchment covers an area of 1,800 km^2 and is predominately rural, whereby 73% of the catchment is comprised of agricultural landscape, with only 4% urban or suburban land-use. Approximately 300,000 people live across the region (with 85% being concentrated in Plymouth).

The interactions within the nexus are evident in the Tamar in a number of different contexts and at different scales, from household (as discussed previously) to catchment. At the catchment scale, the Tamar (along with the rest of Devon and Cornwall) is considered to have some of the highest potential for onshore renewables in the UK (Regen, 2016). However, this brings with it concerns and considerations over various aspects of the nexus, including the loss of land from agricultural production due to the instalment of solar farms or production of bioenergy crops and the effect of these technologies on local climate and on soils and thus water regulation (Armstrong et al., 2014). The dairy industry is also important in the catchment and the nexus emerges both on farms and in subsequent processing. Energy use in dairy farming is high (DEFRA, 2016) as it is required for milking and for cooling milk. Additionally, manure management as well as other on farm measures are important to reduce pollution to water courses (Collins et al., 2018). There is also a large creamery in the catchment, as well as processing that is carried out on farm. This creamery uses river water for cooling during processing and uses energy for water treatment before it is returned to the stream.

As agriculture (in particular, dairy farming) is important to the area, it is informative to consider a specific example. One such example is Langage farm, which is home to 250 cattle and also contains an on-site dairy, producing clotted cream, ice cream, yoghurts and cheeses. Significant energy requirements stem from equipment used during dairy production. While dairy production usually takes place "off site," many farms are increasingly seeking to make secondary products that can be sold in farm shops, at local farmers' markets or in nearby shops and supermarkets, which are increasingly pushing their efforts to promote local producers. Langage Farm utilises an on-site anaerobic digester, which converts food waste into energy, resulting in an entirely self-sufficient system. In addition to energy, dairy production requires a significant volume of water throughout the process. Between 50% and 75% of water on dairy farms is used for livestock drinking, while the remainder is used for washing of equipment and processing areas, and water flow in the cooling process.

Seeking to map the WEF resources and flows within the Tamar using existing nexus frameworks presents a number of challenges. The limitations imposed by data availability make many of the frameworks presented in the section "Methodologies for assessing the nexus" difficult to implement at this geography. Table S4 highlights the data collected for this case study, elucidating the available data and gaps that exist across WEF themes. From both an Environmental Accounting and LCA approach, there is a dearth of available data to track many of the more local connections across WEF resources, particularly within the water sphere. While the identification of primary WEF stocks and consumption patterns are supported by available data, it is often the flows between the stocks and intermittent stages that is not. For example, the volume of water used in energy production or food manufacturing, or indeed the amount of energy used in water extraction, treatment or distribution, or food manufacturing, is often proprietary and sensitive information. Often, tracking the origins or end destinations of some resources is difficult owing to the existence of a centralised infrastructure network. For example, energy created locally is sent into the National Grid and cannot be traced from source to sink. Similarly, existing data enable the identification of food that is grown or produced within the Tamar region. Concomitantly, data are available for average family food purchases. At small scales, the nexus can almost be conceived as a "black box" from a data perspective, whereby the inputs and outputs are identifiable, but it is often the in-between connections that remain poorly elucidated. Within the Tamar, this is certainly the case: while sources and sinks of WEF resources are readily identifiable, the connections between them are entirely hidden. The frameworks presented in Table S3 rely on extensive data inputs that are often unavailable at increasingly local spatial scales (McCarl et al., 2017). While several of these frameworks have been successfully implemented at specific geographies (e.g., WEF Nexus Tool 2.0, National Outlook Model Australia, Delphi-Mekong Model), with specific questions based on local production, economy and climate data, they have not been transferred to other areas. The data requirements within these frameworks are driven by national-level questions, and support assessments of changes in management and policy across transnational scales, where such data are available. Drilling down to more local geographies such as the Tamar requires access to data that are mostly unavailable due to concerns around privacy or sensitivity. For example, a critical component of WEF analyses is a robust dataset around the water balance and water dynamics, including how water is used in specific processes or products, which is not openly available at such local geographies. The Foreseer tool has been applied to visualise energy systems at the large geographies including California, China and the UK. Large-scale flow data of water and energy resources are available in the national accounts of these respective areas, but to date, no application of the tool has taken place at smaller geographical areas.

As part of the WEFWEBs project, a programme of participatory stakeholder workshops has been developed and implemented across the UK. Within the Plymouth, Dartmoor and the Tamar Valley region, a workshop that focused on sustainable livelihoods resulted in local land owners, farmers, councillors and business owners from across the region gathering to discuss many of the nexus-centric issues that are currently emergent within the catchment. This utilised a robust methodology that asked participants to map out key factors across the WEF sectors that are central to sustainable livelihoods within Plymouth Dartmoor and the Tamar Valley region. Participants were then asked to identify a future vision of what sustainable livelihoods within the Tamar would look like. They were then facilitated in applying a backcasting (Dreborg, 1996) approach to determine the steps needed to advance from the status quo to their future vision. Key topics that emerged from this workshop related to the role of governance across the multiple scales and landscapes within the Tamar Valley, and how this impacts on the day-to-day practices of some land owners and businesses. A number of levels of governance were identified within the region, including the European Union, UK Government, Devon and Cornwall regional councils (the Tamar Valley straddles both counties), Plymouth City Council and Dartmoor National Park. During the projection and backcasting process, an anecdotal narrative concerning the functioning of nexus management emerged through which participants identified a number of concerns that reflect on the capacity of existing governance structures to manage the nexus. This included issues of trust and credibility in current governance structures. Participants also identified a lack of coordination between organisations operating at the same scale, and between governance structures operating at different levels. Further concerns were identified in relation to the sectoral basis on which some governance structures were organised, and which presented challenges to efforts to coordinate governance across the nexus. In the backcasting process these issues were identified as significant obstacles which needed to be addressed in achieving the group's future vision. Many participants suggested radical change would be necessary in the Tamar governance landscape to make sustainable and prosperous livelihoods a reality. Proposals included the development of a local forum to enhance local access to governance decision makers and even re-structured governance arrangements which would provide for the direct involvement of NGOs and civil society groups in nexus governance. In addition to general governance structures, the issue of Brexit (the UK's decision to remove itself from the European Union) often dominated discussions. Owing to the significant presence of agriculture and renewable energy installations in the region, Devon and Cornwall have been significant recipients of funding and subsidies from the European Union over the years. In spite of this, many participants viewed the decision for the UK to leave the EU as an opportunity to eradicate some of the perceived bureaucracy that underpins planning and hinders commercial development in the area. Conversely, other participants expressed genuine concerns regarding a loss of subsidies and potential seasonal labour in farming-intensive areas. The stakeholder engagement process yielded some qualitative insights into some of the dynamics within the Tamar region, and highlighted some critical conflicts or issues that were not otherwise readily apparent in the quantitative data that the project had collected prior to the workshop. Boundaries and trans-boundary governance emerged as a critical issue in the Tamar area, with multiple bodies exerting control over very local pockets (and resources) within the catchment (e.g., National Government, Devon and Cornwall County Councils, Plymouth City Council and Dartmoor National Park all controlling particular aspects of the Tamar region; Larcom and van Gevelt [2017]).

6 | FUTURE WORK AND GAPS

We remain a considerable way from fully comprehending, or being able to implement analyses of, the WEF interconnections and feedbacks across varying spatial and temporal scales. Many of the existing frameworks remain theoretical and require extensive data inputs to assess the interlinkages and feedbacks between the three sectors. This is particularly evident at local scales, where data are not readily available (McCarl et al., 2017). Stakeholders involved in the Tamar case study elucidated some of the challenges involved in working across institutions and with different governance structures to achieve an operational nexus within the Tamar, Plymouth and Dartmoor areas, citing a need for more transparent practices to facilitate trust and collaboration. To achieve this, clearer communication of goals, practices and data-monitoring processes, and a resultant stronger culture of collaboration are needed between academia, industry and government, to foster a more effective cross-sector relationship. To this end, an understanding of data requirements and their availability across sectors is essential. Data that would aid in nexus assessments are often unavailable, either due to non-measurement, or commercial security concerns. The emergence of new monitoring technologies providing ways to capture data at increasingly high spatial and temporal resolutions will help to deliver a better understanding of where nexus components intersect at increasingly local levels. However, the nature of these data may add a further layer of computational complexity, owing to their quantity, diversity and structure.

A step towards open data that are not prohibitively expensive or institutionally exclusive would enable nexus researchers and policy-makers to have the necessary information to make informed assumptions where more specific data are unavailable. There has been a growing shift from local authorities and private institutions (e.g., universities) to publish open-access data on components of the WEF system, providing a potential future source of disaggregated data. For example, the Carbon Culture website[5] provides energy and water usage data for local authority, and University College London buildings in London, providing half-hourly measures of energy and water consumption. Such platforms not only provide researchers and the public with access to such data, but also highlight the steps large agencies, institutions or companies are taking to enhance sustainability of their practices with regard to energy and water (with limited data available presently on food or waste behaviour). Furthermore, local councils, especially city authorities, have increasingly opened up data access at the city level. Glasgow City Council recently launched Data Launchpad[6] that provides access to data from the city, including transport, electricity consumption, health and environmental quality metrics. What is needed to utilise such databases is consultation with researchers or practitioners to assess data needs, to create a mutually beneficial dissemination of regional data. Such open data are significant in allowing researchers to address some of the grand challenges society faces. While water use data for specific crops and farm types across England are available (DEFRA, 2016), our ability to understand them spatially relies on a dataset that identifies national crop distributions. While such a dataset exists, accessing the map for the entire UK would be prohibitively expensive for most researchers (c. £35k for the area of the UK), thus requiring estimates to be made, based on freely available but often poorer resolution data (Centre for Ecology and Hydrology, direct communication). Furthermore, cohesion of data acquisition policies is necessary across the devolved administrations of the UK. DEFRA (2016) remains responsible for the implementation of environmental policies across the UK, and as such, a central database that compiles environmental data from across the devolved administrations of the UK would be a pragmatic step to understanding how pressures and needs change across the country. By improving data access and enhancing our understanding of how the nexus emerges at multiple scales, then, and only then, can we tackle the creation of a framework or set of tools that enable us to assess the connections and interdependencies reliably and robustly.

7 | CONCLUSIONS

Although WEF nexus research has accelerated since the 2011 Bonn Conference, the widespread translation of "nexus thinking" into "nexus doing" has not yet been realised. A critical reason for this is an absence of available inter-linked and consistent data, to enable researchers and policy-makers to identify the connections and feedbacks that exist. While no perfect "plug and play" tool exists for decision-makers, many of the existing frameworks continue to expand and improve, being applied to case studies in increasingly diverse locations. Despite the continued global funding of the nexus, the scope for the development of a holistic tool that incorporates all aspects of the nexus, stakeholder inputs, policy perspectives and future scenarios for change remains a near impossible task owing to the levels of complexity involved. Rather than developing new situation-specific tools, there needs to be a more integrated effort to understand the pros and cons of existing frameworks, with research groups undertaking a critical assessment of their requirements from a framework, rather than immediately seeking to develop their own fit-for-purpose approach. While the scientific literature continues to extol the virtues of the nexus, there is a pressing need to now "walk the nexus walk," and this requires the breakdown of silos and opening of new collaborations to ensure that sufficient data and tools are available to those who need them most (Flammini et al., 2014). Finally, there is a significant need to incorporate those outside of academia into nexus partnerships, with private companies such as supermarkets, utility companies and farms being ideally positioned to assist (and be aided by) the academic community. A step towards open data is urgently needed to enable scientists, researchers, policy-makers and industrial partners to work together to tackle many grand societal challenges that face us today. Restrictions in data availability are a hindrance to tackling such problems successfully, and it is imperative that data accessibility is improved to help us overcome this. An example of this would be transparency of seemingly commercially sensitive datasets if deemed to be in the public interest.

ACKNOWLEDGEMENTS

We are grateful to the EPSRC for funding this research under grant number EP/N005600/1. Rothamsted Research receives strategic funding from the Biotechnology and Biological Research Council of the UK. The authors are also grateful for the excellent comments and recommendations of two anonymous reviewers, which helped improve the quality of the manuscript to its finished status. We are also grateful to the tireless work from the editor, Keith Richards, and his team of supporting staff who aided in the production of this manuscript with clear and timely updates throughout the publication process.

ENDNOTES

[1] See www.gla.ac.uk/research/az/wefwebs/

[2] https://simapro.com/about/

[3] www.ecoinvent.org/about/about.html

[4] See www.smappee.com/au/gas-and-water-monitor

[5] https://platform.carbonculture.net/landing/

[6] https://data.glasgow.gov.uk/dataset

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1. Sustainable development goals (United Nations, 2015).

Table S2. Overview of conceptual frameworks used in nexus assessments across the literature.

Table S3. Overview of analytical frameworks used in nexus assessments across the literature, adapted from UNECE (2014) and IRENA (2015).

Table S4. Summary of data availability and gaps within the Tamar Region of the UK.

How to cite this article: McGrane SJ, Acuto M, Artioli F, et al. Scaling the nexus: Towards integrated frameworks for analysing water, energy and food. *Geogr J*. 2019;185:419–431. https://doi.org/10.1111/geoj.12256