Stephan Hülsmann
Reza Ardakanian *Editors*

Managing Water, Soil and Waste Resources to Achieve Sustainable Development Goals

Monitoring and Implementation of Integrated Resources Management

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Contents

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The Nexus Approach as Tool for Achieving SDGs: Trends and Needs

Stephan Hülsmann and Reza Ardakanian

Abstract The Nexus Approach is increasingly evolving into an integrative concept which bridges sectors and considers interrelated resources in an unbiased way to achieve sustainable resources management. Nexus-oriented resources management is thus imperative for achieving the United Nations Sustainable Development Goals (SDGs). The other way around, a resource perspective on the nexus should be helpful given that virtually all SDGs imply and rely on sustainable resources management, in particular addressing water, soil, and waste. The interrelatedness of SDGs provides another strong case for a Nexus Approach. Here we briefly lay out the background and conceptual outline of the book, addressing key aspects of nexus implementation including monitoring of resource use, closing cycles of key elements, utilize proven methods of stakeholder participation and its mapping and monitoring and mainstreaming of thresholds and policies across scales and governmental levels. We then summarise these key aspects addressed in subsequent chapters and highlight the interrelations. Overall, this volume provides a strong case for strengthened monitoring frameworks and for close involvement of all stakeholders in the process of implementing a Nexus Approach. It adds to the ongoing process of consolidation and diversification of the Nexus Approach and provides specific recommendations of how to advance it.

1 Introduction

The nexus concept is progressively evolving as the integrative approach which bridges sectors and considers interrelated resources in an unbiased way to achieve sustainable resources management. It builds upon earlier integrative concepts which, however, still had a single-resource perspective [for example, Integrated Water

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Resources Management (IWRM) (Global Water Partnership (GWP) 2009)] and incorporates various simultaneously evolving research initiatives and management concepts eventually converged into the Water-Energy-Food (WEF) nexus. Mentioned for the first time in relation to resources management during the 1980s, the term "nexus" gained prominence in this context particularly since the year 2000 as reviewed by Scott et al. (2015), providing a historic perspective of the Nexus Approach. These authors emphasise that the WEF nexus indeed represents a comprehensive concept of integrated resources management which captures the interlinkages of water, energy, and food at multiple levels. They argue that "the nexus is fundamentally about resource recovery, closing the loop and capturing true efficiency gains". It is also, however, about mitigating trade-offs and promoting synergies. As such, the Nexus Approach thus represents a path towards sustainability and indeed its relevance for sustainable development and a transition to green economy was a major focus of the Bonn 2011 conference (Hoff 2011), which marked an important milestone for the Nexus Approach to become internationally recognised.

Since 2011 the Nexus Approach has, despite some concerns and criticism (e.g. Wichelns 2017) consolidated as a concept but at the same time diversified, while it is acknowledged that the basic concept is far from new. In fact, it has been argued that even ancient civilisations understood and practised the Nexus Approach when cultivating their land (Lal 2016). Among the added or alternative perspectives on the WEF nexus is to look at the other side of the coin, asking which resources have to be managed in a sustainable manner to achieve the sought water, energy, and food security put forward at the Bonn 2011 conference? This aspect has since its inception in 2012 been emphasised by the United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES). A kick-off workshop in 2013 in Dresden, Germany elaborated on these ideas and proposed to focus on water, soil, and waste (Hülsmann and Ardakanian 2014). The governance aspect of the Nexus Approach was addressed in a book which emerged from that workshop (Kurian and Ardakanian 2015). The Nexus Approach to the sustainable management of water, soil, and waste emphasises the interrelatedness of these three resources along with the cycle of research to implementation. This "Dresden Nexus", promoted in particular in the Dresden Nexus Conference series which emerged from the 2013 workshop (DNC), is strongly related to the Water, Energy, and Food Security Nexus (Hoff 2011), but emphasises the resources perspective (Hettiarachchi and Ardakanian 2016a).

Focusing on the challenges posed by different aspects of global change (climate change, urbanisation, population growth) on environmental resources management a recent series of papers explored how a Nexus Approach may help to cope with them (Hettiarachchi and Ardakanian 2016b). A clear conclusion was that applying a Nexus Approach is key for the sustainable use of environmental resources under conditions of global change. It will, therefore, be instrumental for achieving the Sustainable Development Goals (SDGs) (United Nations 2015), which will frame the international development agenda for the coming years.

2 The Nexus Approach and SDGs

While the importance of the Nexus Approach for achieving the SDGs can be deduced rather straightforwardly from conceptual considerations, the more complex question remains *how* to adopt and implement it. With the adoption of the SDGs in autumn 2015 the overall targets related to resources management are clear. Many of the SDGs are interrelated, which already points to the need for a Nexus Approach. The sustainable management of environmental resources is of particular relevance for goal 2 (*Zero hunger*), goal 6 (*Clean water and sanitation*), goal 7 (*Affordable and clean energy*), goal 11 (*Sustainable cities and communities*), and goal 15 (*Life on land*), but strong links exist also to less resources-related SDGs (see Bringezu 2018). A common theme and potentially strong integrator is therefore the need for *monitoring strategies* reflecting the Nexus Approach and the SDGs. These strategies and the respective data are crucial to be able to evaluate any advance towards sustainable environmental resources management and achieving SDGs and have to be a decisive component of policies and guidelines for the *implementation* of integrated management approaches.

Given that sustainable resources management will be mandatory for UN Member States in the context of SDGs, there is a strong need to focus in depth on monitoring and implementation strategies. Issues related to data requirements as well as data quality and efficient data management, strengthening of monitoring programmes, and of feedback loops to resources management (to assess advance and success of implementing integrated management approaches) are critical in this regard. Moreover, governance frameworks for integrated resources management, incentives for resource recovery and efficiency, and the economic framework facilitating the implementation of sustainable environmental resources management strategies need to be established and/or strengthened.

3 Trends and Needs for Implementation of a Nexus Approach

With respect to the Nexus Approach as a tool for achieving SDGs, the contributions to this book focus on various key aspects of monitoring and implementation strategies, taking some ongoing trends further and responding to needs as elaborated below. They were conceptualized to provide food for thought for participants of the Dresden Nexus Conference 2017 (DNC). This second issue of DNC aimed to provide a platform to discuss the state of the art related to “SDGs and Nexus Approach: Monitoring and Implementation”. Emphasis was placed on providing examples of nexus research—critically relying on monitoring of resource use—and implementation through case studies and integrating participatory approaches to foster involvement of all participants (gaming session, World Café).

To set the stage, the second chapter elaborates on “Key strategies to achieve the SDGs and consequences for monitoring resource use” (Bringezu 2018). Taking a systems perspective, Bringezu first explores how monitoring based on Material Flow Accounting effectively links resource use with its environmental impacts. Key indicators related to the use of land and water resources, of material extraction, use and consumption, and GHG emissions cover the major pressures on resource use and obviously reflect the management of water, soil, and waste. Applying a life cycle perspective, these indicators translate into footprints, which proved particularly useful when comparing the performance of countries with regard to sustainable resource use. Putting this into perspective at a global scale implies that countries’ resource use is to operate within limits set by their respective share of the safe operating space (Rockstrom et al. 2009) for the respective resource.

With regard to the implementation of SDGs it is apparent that a sustainable use of resources is a prerequisite to achieve them, since indeed all topical goals are directly related to natural resource use as Bringezu points out. A basic question is how to achieve goals which emphasize sustainable supply of resources such as SDG 2 (food, agriculture), 6 (water) and 7 (energy) without compromising goals which address the preservation of life-sustaining systems, for example goal 13 (climate), 14 (oceans) and 15 (terrestrial ecosystems). The inherent trade-offs as well as synergies are apparent even between targets of single SDGs. This holds for SDG 6 which is about water supply (target 6.1), but also addresses protection and restoration of water-related ecosystems (target 6.6). Increasing resource productivity, but also closing cycles by fostering reuse and recycling are key for minimising trade-offs or even turning them into opportunities. Monitoring the outlined footprints is essential for evaluating the effectiveness of resource policies across scales. To this end, Bringezu proposes specific institutional developments to be considered.

A concrete and specific example of how closing cycles and increasing resource efficiency may help achieve SDGs and stay within—or rather return to—planetary boundaries of sustainable resource use is given in Chapter “The Urgent Need to Re-engineer Nitrogen-Efficient Food Production for the Planet” by Pikaar et al. (2018). Addressing a key challenge of sustainable development, ensuring food security as captured in SDG 2, they argue that re-engineering the nitrogen cycle within the context of the Nitrogen/Water-Waste-Energy Nexus is essential for achieving sustainable solutions. With the invention of the Haber-Bosch process a century ago, converting atmospheric nitrogen into reactive nitrogen, a major limiting factor in agricultural food production was neutralised and ultimately enabled the massive population growth ever since. Negative side effects (externalities) of massive N-fertilisation are nowadays evident and current anthropogenic nitrogen flows are clearly beyond the safe operating space (Rockstrom et al. 2009).

Sustainable solutions ultimately require restoring the link between the nitrogen and the carbon cycles. Pikaar et al. promote (i) the use of Haber-Bosch nitrogen for protein production by microbes for human nutrition and (ii) its upgrade into slow-release fertilisers. Both measures would help to close the nitrogen cycle. Another measure to this end is the recovery of nitrogen from wastewater and other organic waste. In the nexus context, these technological and engineering opportunities need to be backed up by shifts in attitudes and policies, with regard to drastically reducing food waste and increasing acceptance of alternative protein sources. Besides SDG 2 proposed measures are highly relevant for SDG 12 (*Responsible consumption and production*, see also Chapter "Integrated SDG Implementation—How a Cross-Scale (Vertical) and Cross-Regional Nexus Approach Can Complement Cross-Sectoral (Horizontal) Integration") and SDG 6, addressing sustainable management of water and sanitation.

In Chapter "Participatory Processes and Integrated Modelling Supporting Nexus Implementations", Smajgl (2018) explores the relation between the Nexus Approach and SDGs from a process-oriented perspective. He argues and demonstrates, in several examples, how participatory approaches and integrated modelling may support nexus implementation, which links to the aspect of public attitudes (raised also in Chapter "The Urgent Need to Re-engineer Nitrogen-Efficient Food Production for the Planet"). Smajgl argues that progress in nexus implementation hinges on two challenges: the lack of appropriate tools allowing nexus assessments and effectively involving stakeholders concerned with implementation thus bridging the science-policy divide. An example of how to address the methodological challenge is provided by applications of agent-based models. This type of models is capable of capturing highly complex relationships built from a bottom-up perspective (individuals, households, communities, etc.). The given example of a model developed for the Mekong region is particularly insightful since it was imbedded in a participatory process to facilitate stakeholder learning and policy uptake.

The issue of appropriate nexus tools is increasingly recognised as critical for enabling nexus assessments, which refer to, for instance, estimating the effects of certain management interventions on various interrelated resources both in terms of quantity and quality. Besides agent-based models a plethora of various modelling tools for resources management are available. Therefore, selecting the most appropriate (set of) nexus tool(s) is a challenge in itself and requires facilitation (Mannschatz et al. 2016). Using such tools for informing decision makers about policy options and potential scenarios implies making use of smart visualisation techniques (Mannschatz et al. 2015). Ultimately, decision support systems (DSS) should be helpful for adopting nexus solutions, but only a few promising examples have come to the fore (Daher et al. 2017). In many cases, DSS projects have failed and it can be assumed that this is due to fact that their development has not followed a participatory approach. The framework described in detail in Chapter "Participatory Processes and Integrated Modelling Supporting Nexus Implementations " was applied successfully in various instances and two exemplary case studies are introduced. These examples show that whatever the exact process design and framework, participatory approaches should be the method of choice to enhance policy uptake and effective implementation of a Nexus Approach.

In Chapter "Games for Aiding Stakeholder Deliberation on Nexus Policy Issues" Mochizuki et al. (2018) expand on the issue of stakeholder involvement. The authors report on encouraging experiences with using integrated simulation games, reflecting different nexus problems, to get stakeholders interested and involved in the process of developing nexus solutions. Several games dealing with nexus issues are already available, illustrating a somewhat simplified and condensed form of real life situations requiring nexus solutions. Among various methodologies to facilitate stakeholder engagement, serious games are increasingly used and have been found to be effective in provoking critical questions, promote systems thinking, and walking the players involved through a decision-making process. The introduced games deal with different aspects of nexus problems; one focusing on agent behaviour and unintended consequences, another on wicked problems, and one on social dilemmas. The games illustrate in particular the social dimension of the nexus and its associated complexities.

Each game also addresses different stakeholders. Players represent either policymakers, citizens, or a mixed community exposed to different governance regimes. The learning goals emphasised in Chapter "Participatory Processes and Integrated Modelling Supporting Nexus Implementations" for stakeholders within participatory processes could in many instances be achieved or at least supported by nexus games. Conversely, successful implementations of nexus solutions besides being comprehensively documented for "conventional" knowledge transfer should be translated into nexus games to provide an additional means of promoting a nexus mindset.

Another tool which has proven helpful for analysing stakeholder involvement and their interactions is explored in Chapter "Governance of Water-Energy-Food Nexus: A Social Network Analysis Approach to Understanding Agency Behaviour" by Kurian et al. (2018). They applied the Social Network Analysis to map stakeholder relations within nexus settings. The authors argue that studying nexus governance requires besides analysing the policy framework in terms of laws and policies an in-depth analysis of institutional capacities, based on the notion that achieving a critical mass of interests is critical for nexus implementation. Social Network Analysis may help to determine the degree to which coordination between actors actually seems to occur in nexus systems—under the premise that a high level of coordination is required to indeed achieve nexus solutions. Essential elements in this analysis are centrality, the extent to which individual nodes (typically representing institutions) are connected to other nodes in the network, and density, which relates the actual number of ties to the potential number.

The authors then put the approach of Social Network Analysis in perspective, in particular for the situation in developing countries with low institutional capacities, high vulnerability to environmental hazards and data scarcity, and propose steps to address these issues. Creating and validating synthesised data sets comprising ground stations, Earth Observation data, and model results are critical not only for enabling climate change adaptation, but also represent a process of stakeholder engagement, coordination, and cooperation. Condensing data into meaningful indices has to follow a participatory approach, thus establishing and strengthening ties within social networks. Collecting this data and making it available via a Nexus Observatory (Kurian et al. 2016) can also be looked at as a networking process.

Finally, Chapter "Integrated SDG Implementation—How a Cross-Scale (Vertical) and Cross-Regional Nexus Approach Can Complement Cross-Sectoral (Horizontal) Integration" elaborates on how a vertical Nexus Approach can and should complement horizontal (cross-sectoral) integration. Hoff (2018) emphasises the progress made in nexus research in recent years and the achieved consensus about key elements of the Nexus Approach, its focus on critical interlinkages, synergies, policy coherence, reuse and recycling, thus increased resource use efficiency, while striving to minimise trade-offs and negative externalities. Slowly, but increasingly, positive examples of nexus applications become visible and available for replication, transfer, and upgrading. Hoff argues that so far the main emphasis has been on horizontal integration across resources, sectors, and disciplines, but that this needs to be complemented by vertical critical interlinkages across hierarchical levels and spatial scales.

A key mechanism is mainstreaming via various entry points such as national strategies for bioeconomy, energy, or agriculture and environmental planning. An example provided relates to the topic addressed in Chapter "The Urgent Need to Re-engineer Nitrogen-Efficient Food Production for the Planet": the new German Nitrogen Strategy, which needs to be aligned between the national, sub-national (*Länder*), and global levels. The latter can be derived from planetary boundaries which require much stronger reductions of nitrogen application than even the strictest national or European limits. Cross-regional coordination and mainstreaming is also required when looking at (external) land and water footprints of specific products (see also Chapter "Key Strategies to Achieve the SDGs and Consequences for Monitoring Resource Use"). In the example of soy, massively imported e.g. from Brazil by Germany and other countries in Europe, it is shown that the total demand, including virtual import, is twice as high as physical imports documented in trade statistics. Appropriate tools and monitoring data are required to analyse these vertical nexus dimensions to guide sustainable consumption and production across regions. Clearly, setting respective limits or targets based on planetary boundaries is not only a scientific, but even more so a political task, which requires respective dialogues, which should be guided by participatory processes as outlined and referred to in Chapters "Participatory Processes and Integrated Modelling Supporting Nexus Implementations, Games for Aiding Stakeholder Deliberation on Nexus Policy Issues, and Governance of Water-Energy-Food Nexus: A Social Network Analysis Approach to Understanding Agency Behaviour".

Overall, contributions to this book aim at contributing to the earlier described consolidation and diversification process with regard to the Nexus Approach by highlighting key aspects of monitoring and implementation. All of them contain important lessons on the way forward, among them:

- Monitoring of resource use at the international level should be backed up by institutional developments (Chapter "Key Strategies to Achieve the SDGs and Consequences for Monitoring Resource Use");
- Serious efforts need to be made to close the nitrogen cycle by applying new/additional technologies for protein production from synthetically produced nitrogen, N recovery from waste (including wastewater), and developing a new generation of more efficient fertilisers (Chapter "The Urgent Need to Re-engineer Nitrogen-Efficient Food Production for the Planet");
- Nexus implementation can effectively be facilitated by using and promoting participatory approaches based on established frameworks and by making use of

suitable nexus tools and models (Chapter "Participatory Processes and Integrated Modelling Supporting Nexus Implementations");

- Serious games can be an effective tool to enhance stakeholder participation, support systems thinking, and create the required nexus mindset (Chapter "Games for Aiding Stakeholder Deliberation on Nexus Policy Issues");
- A thorough analysis of the social networks associated to nexus problems, making use of formalised procedures and approaches is essential to map the social landscape and document developments in the effectiveness of nexus governance. A Nexus Observatory can be an important mechanism for making data available, accessible, and put them to use for stakeholders (Chapter "Governance of Water-Energy-Food Nexus: A Social Network Analysis Approach to Understanding Agency Behaviour");
- A vertical nexus considering critical interlinkages across hierarchical levels and spatial scales needs to complement the horizontal nexus across resources and sectors. Exemplified by the case of nitrogen, global thresholds based on planetary boundaries should be mainstreamed with thresholds and respective policies at regional, national, and sub-national levels (Chapter "Integrated SDG Implementation—How a Cross-Scale (Vertical) and Cross-Regional Nexus Approach Can Complement Cross-Sectoral (Horizontal) Integration").

Progress towards achieving the SDGs critically depends on applying a Nexus Approach to resources management. It is hoped that this book contributes to promote and advance nexus thinking and inspire new research and development projects to strengthen and accelerate nexus implementation and make progress towards the SDGs.

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Key Strategies to Achieve the SDGs and Consequences for Monitoring Resource Use

Stefan Bringezu

Abstract The chapter introduces a systems perspective on the physical economy and its interactions with the environment. Indicators on the use of materials, land, water, and GHG emissions (the “Four Footprints”) play a central role in linking human activities with environmental impacts. A basic goal of sustainable development is to foster social progress within environmental limits, and to enhance the safety of humans while reducing their dependence from constraints. Both intentions are reflected in existing resource policies of countries, where both supply security and the decoupling of welfare and social progress from natural resource use are central goals. The chapter summarises the state-of-the-art of the application of accounting methods and data provision for national material flow derived indicators, including the material footprints, as well as land and water footprints. In a systematic manner, the Sustainable Development Goals (SDGs) are discussed with regard to their relation to resource use, and it is argued that the information on resource use, in particular the four footprints (including carbon footprint), across levels will be necessary for a consistent implementation of the SDGs. Improving the knowledge base on global resource use will require further institutional development also on the international level. Towards this end, options are outlined comprising the build-up of regular monitoring, a global resource data base, the development of an international competence centre, and an international programme for global sustainable resource management.

1 Introduction

This chapter argues that the SDGs of Agenda 2030 will only be reached when sustaining resource use throughout production and consumption of every country, and that progress is required to monitor their domestic and global use of resources. Many goals and targets directly address natural resource management (target 12.2), waste minimisation (target 12.5) and decoupling of economic growth and natural

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resource use (target 8.4) with developed countries being expected to take a leading role (UN 2015a). The interconnected nature of the SDGs requires natural resource management policies to go beyond traditional approaches, such as management and governance of a field or a forest by a local community and how to avoid the overuse of a fishing ground. In a globalised economy, the sustainable use of natural resources requires simultaneous monitoring and management at different scales, from local to global. Policy formation and management practices will require sound scientific information. Monitoring is essential for the success of existing and new policies and business strategies in order to provide orientation and direction for decision makers.

The use of natural resources such as raw materials (minerals, biomass) is still mainly regulated by property rights in the ownership of land containing natural deposits or agricultural fields or forest area (UNEP 2016a). Responsible use by those owners in mining, agriculture, and forestry may be subject to voluntary standards of good practice and varying local to regional mandatory requirements regarding environmental quality standards, labour conditions, and social acceptance. The environmental and social implications of the subsequent material flows through manufacturing, final production, consumption, recycling, and final waste disposal are then subject to specific regulatory requirements of health and environment regulating the release of pollutants to air and water and final waste deposition by companies and communities. Those regulations mitigate possible negative impacts of resource flows at the local to regional scale.

As global resource flows grow and impacts are rising, those approaches are insufficient to keep the magnitude of global resource use and its environmental and social impacts within a safe operational level corridor which can be supplied sustainably (e.g., UNEP 2014a; b; Bringezu 2015a; UNEP 2016a). While many businesses in natural resource sectors now operate globally, the governance of resource and material flows at the national, supranational, and international level is still in its infancy. In lack of an international or even global institution, global resource management is currently enacted through national and sub-national resource policies. A growing number of countries have developed resource policies aiming to decouple economic growth and human development from natural resource consumption (examples are given below). While the proximate goal of the national policies is to enhance the competitiveness of their economies and become independent of resource supplies, they also act in a responsible manner in the interest of the global environment. For these purposes, they established goals, objectives, and targets, and use indicators to measure progress. Some countries also implemented instruments to support and incentivise actors in industry, households, and public administration to foster resource efficiency with a life-cycle-wide perspective.

An essential component of effective policies is the orientation towards overarching goals and the measurement of progress through indicators (Davis et al. 2012; Cucurachi and Suh 2015). For global resource use, it is argued here that indicators derived from national Material Flow Accounting (MFA), in particular the footprints on (primary) materials, land, water, and GHG emissions, can play a central role measuring the performance of production and consumption, because they cover major environmental pressures, and can be applied across sectors and over all scales, from national to local. Together with good practice examples showing multiple win options for people, economy, and environment, the orientation by indicators and reference values for assessing progress will be essential to promote a more sustainable use of global resources across countries. For instance, good practise examples for increasing systems-wide (life-cycle-wide) energy and material efficiency of products and services show technical and economic feasibility, and information on resource intensive sectors (with large footprints—can be used to adjust policies in order to adjust the incentive framework of their businesses to enhance the search for more resource efficient products and services (e.g. UNEP 2014a).

A definition of natural resources is an important starting point to devise monitoring systems. In a narrow sense it includes abiotic materials (e.g. fossil fuels, metal ores, and minerals), biomass (e.g. from agriculture, forestry and fisheries), water, air, and land. Primary energy may be used as a separate category, with the option to distinguish fossil and renewable energies. Some include ecosystem services such as biodiversity and life-sustaining functions of earth and ecosystems including climate stability. Focussing on the material-based use of natural resources this chapter will adhere to a definition which excludes a broader suite of ecosystem services and relies on a definition of natural resources which is compatible with national accounts and the System of Environmental and Economic Accounts (SEEA) framework.

Global consumption of natural resources has been growing rapidly since the 1970s and has led to a multitude of environmental impacts including depletion of natural resources, acidification, and eutrophication of land and water, waste problems, air pollution, and climate change. Increasing extraction of natural resources has also resulted in increasingly negative social repercussions. The annual global extraction of raw materials grew from 24 billion tonnes in 1970 to 70 billion tonnes in 2010 (UNEP 2016b).

Global resource consumption of raw materials is expected to grow further as will their various environmental impacts and social repercussions including those of climate change. Material extraction has accelerated since the year 2000, at a time when the global economy and population growth have slowed (UNEP 2017). With a growing world population and a growing middle class, especially in developing countries, business as usual suggests that 125 billion tonnes of materials in 2030 and 180 billion tonnes of materials in 2050 will be required to fuel the global economy (Schandl et al. 2016). When materials that are mobilised in the process of materials extraction but not further used economically are included, the projected overall extraction of primary materials in 2030 ranges between 300 and 335 billion tonnes (Bringezu 2015a).

The number of local social conflicts caused by environmental disturbances and community displacement because of fast-expanding extraction infrastructure, refining, and manufacturing activities and final waste disposal is rising and of growing concern [see: https://ejatlas.org/, the former Ejolt project which was further developed to the Environmental Justice Atlas)]. It should be noted that these local conflicts, for instance, when involving extractive industries, are largely driven by demand in distant regions and result from patterns of manufacturing and consumption, which have become unsustainable.

Water consumption is expected to increase in all sectors of production. Growing water withdrawals for agriculture and energy can further exacerbate water scarcity. By 2030, under the business-as-usual climate scenario, the world is projected to face a 40% global water deficit (WWAP 2015).

Land use will significantly change land cover, impact hydrology, and contribute to loss of biodiversity and increasing greenhouse gas (GHG) emission (UNEP 2014b). From 2005 to 2050, unrestricted expansion of built-up land will more than double, reaching 260–420 Mha worldwide (Electris et al. 2009), often accomplished through transformation and loss of fertile agricultural land. The growing world population, changing diets, levelling of yield increases, and degradation of soils will lead to a significant expansion of cropland into grasslands, savannahs and forests, mainly in tropical countries. From 2005 to 2050, business-as-usual gross expansion might be in the range of 320–850 million hectares (UNEP 2014b). Monitoring of global land use by regional or national activities can draw from various modelling exercises, although data gaps would need to be filled and sustainability indicators and targets would need to be integrated (O'Brien et al. 2017).

Against this background, approaching a liveable future on the planet will require effective resource governance, and to design, implement and evaluate appropriate instruments, policy informative analysis and monitoring of resource use across scales both in aggregated and detailed manner will be required. For setting the policy framework right, aggregated information on overall resource use of countries´ activities is required, while detailed information is needed to find locally adapted solutions.

The objective of this chapter is to convey a systematic understanding of basic cause-effect relationships between human activities and its interference with the natural environment; of the ways how these can be measured by key indicators; of important strategies necessary to decouple socio-economic progress from natural resource use and related environmental impacts, and the key role of resource efficiency to reach the SDGs. Against this background shall the institutional development be outlined which is required to establish regular monitoring and management of global resource use by countries and at the international level.

This chapter will start with unfolding a systems perspective to indicate how material flows in the economy link with the environment, and provide an overview of key indicators to measure resource use, considering both the domestic situation and the global footprint of national economies. The basic goal of social progress within environmental limits is then theoretically reflected with the concept of Safe Operating Range and the concept of Safe Operating Space, and exemplified with actual resource policies of countries. The SDGs will then be systematically reflected with regard to their relation to resource use and the key strategy of resource efficiency. Finally, the institutional developments, which are required for further improvement of worldwide monitoring and controlling resource use, will be outlined.

2 Natural Resource Use from a Systems Perspective

Monitoring the resource use of human activities requires a systematic approach. This section describes how material flows induced by economic activities are linked to environmental impacts, and that resource policies aiming to reduce the demand of production and consumption of natural resources are necessary to mitigate those impacts. The section also describes the resource "footprints" as key indicators of resource use.

2.1 Material Flows Linking Human Activities with the Environment

In the 1990s, the Driving Forces-Pressure-State-Impact-Response (DPSIR) framework had emerged, and provided a consistent overall frame of indicators (EEA 1999), also adequate to include the indicators derived from national Material Flow Accounting. In order to be controllable, the key indicators should be pressure type indicators within the DPSIR framework, linking activities in production and consumption with their environmental impacts and representing the physical exchange between nature and anthroposphere (Fig. 1). In order to be meaningful, the key indicators should comprise relevant pressures and be robust against substitution within their major categories. There are basically two types of material flow based pressure indicators: turnover based indicators on resource flow volumes addressing the system input and throughput (such as material input and water consumption), and impact-based indicators (such as global warming potential, ozone depletion potential, etc.). Both types of indicators are complementary and may not substitute each other (Bringezu et al. 2003).

Recently Steinmann et al. (2016) found that the life-cycle-wide input of fossil energy, materials, land, and water ("resource footprints") together explained 82% of the variance of all environmental LCA impact categories covered in a standard data base. They concluded that "the plethora of environmental indicators can be reduced to a small key set, representing the major part of the variation in environmental impacts between product life cycles."

As countries are interwoven in physical exchange of global trade, the application of a life-cycle perspective of traded products requires that the imports and exports are related to their primary extraction when the global resource basis of a country shall be depicted. Thus, the key indicators should be applicable not only within a country-based, national accounting framework, but also within an LCA framework for selected products. Moreover, in order to compare the dynamics at the national scale with development at lower scales such as regions, communities, companies, and

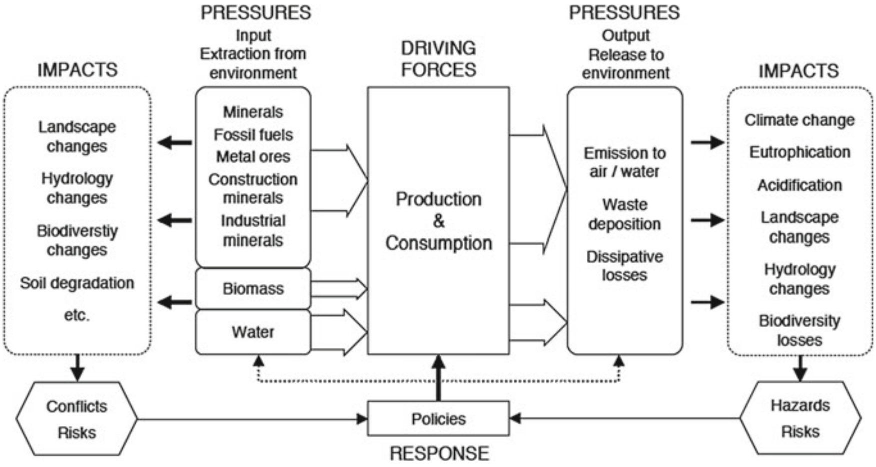

Fig. 1 Overview scheme of the physical economy within the DPSIR system (Extended from Bringezu 2015a)

households, it is necessary that the key indicators are consistently applicable across scales (Bringezu et al. 2016, Integrated SDG Implementation—How a Cross-Scale (Vertical) and Cross-Regional Nexus Approach Can Complement Cross-Sectoral (Horizontal) Integration).

2.2 *Key Indicators of Resource Use*

With the systems perspective outlined above, the use of raw materials, land, water, and air are of special importance when comparing resource use and consumption of countries, (Table 1). Whereas indicators of material input, land use, and water consumption represent inputs from the environment to the economy, the use of air may be better represented by the output of GHGs emitted to atmosphere (the latter is usually also proportional to the input of fossil energy). Thus, four major pressures of resource use would be represented (which according to Steinmann et al. (2016) also might cover more than four fifths of the variance of all output-related environmental impacts).

For each domain of natural resource use, territorial and life-cycle or global perspectives can be applied, the former confining the system boundary to the political boundary of the country, the latter applying a whole of life-cycle system boundary, i.e., focusing on exchanges between nature and society worldwide. When the life-cycle perspective is applied to a country´s performance, two questions may be answered: what is the resource use for both production and consumption within the country (including resource use for production of exports), and what is the resource use of the final consumption in the country (excluding the resource use of exports).

Table 1 Overview of types and examples of key indicators of resource use: territory and life-cycle perspective (Extended from Bringezu et al. 2016)

	Territory or national perspective	Global supply chain or international perspective
Materials a. Abiotic b. Biotic	Domestic extraction, use, and consumption DEU, DUE, DMI, DMC	Primary material resource requirements of production (RMI, TMR) and consumption ("material footprint": RMC, TMC)
Land	Artificial land or built-up area	Direct and indirect land use for consumption of biomass-based products focussing on cropland ("cropland footprint")
Water	Water withdrawal	Direct and indirect water consumption (e.g., "water" footprint)
Air	GHG emissions (t)	Direct and indirect GHG emissions (both carbon and non-carbon emissions, the "carbon footprint")

Note: *DE* Domestic Extraction, *DMI* Direct Material Input, *DMC* Domestic Material Consumption, *RMI* Raw Material Input, *RMC* Raw Material Consumption, *TMR* Total Material Requirement, *TMC* Total Material Consumption

When the whole life-cycle of all products consumed in a country is measured the indicator is termed "footprint". The literature now speaks of a set or family of footprints (Galli et al. 2012) which include material footprint, energy footprint, water footprint, land footprint, and carbon or GHG footprint (carbon and GHG emission footprint may differ when the former is defined only on the basis of carbon dioxide and other carbon-based emissions such as methane, while the latter includes also, e.g., nitrous oxide emissions). Relating the indicators for natural resource use to Gross Domestic Product (GDP) allows monitoring of the progress of decoupling natural resource use from economic development (OECD 2008; UNEP 2011).

2.2.1 Material Resources

Human-induced material flows and related environmental and social impacts are expected to grow significantly over the coming decades (UNEP 2011, 2016b; Bringezu 2015a; IRP 2017). As demonstrated for the case of nitrogen by Pikaar et al. (2018, Chapter "The Urgent Need to Re-Engineer Nitrogen-Efficient Food Production for the Planet") this growth of flows and impacts is often associated to technological inventions and ongoing since decades or even centuries.

Data on territorial extraction and harvest of minerals (metals, industrial minerals, construction minerals, fossil fuels) and biomass (agriculture, forestry, fisheries) are mostly available for more than 200 countries worldwide. A new data set of the International Resource Panel provides detailed data for material extraction and trade and also aggregated data for main resource categories, as well as national indicators such as Direct Material Input (DMI) and Domestic Material Consumption (DMC) and also material footprint (MF) of final demand data and indicators (data available at www.uneplive.org). A regular update of this data would allow us to monitor progress of material productivity and thus decoupling of direct material flows and economic development. This could be done country-wise or for world regions. In recent years, international comparisons of material consumption and productivity have been provided by UNEP (2011), Dittrich et al. (2012), UNEP (2015a, 2016b).

Accounting for the material footprint of countries requires a more comprehensive analysis of the indirect flows of material resources associated with imports and exports. This may be done by input-output analysis (Tukker and Dietzenbacher 2013). For international comparison, such an analysis was performed by Wiedmann et al. (2015) and UNEP (2016b) conveying the performance of Raw Material Consumption of countries. EEA (2013) commissioned a comparative sectoral analysis, comprising both used and unused extraction for European countries, thus showing results for Total Material Consumption.

2.2.2 Land Use

Land is quite a specific resource where the limits and the competition of various sectors are rather obvious, although the driving forces are more and more distant from their effects. For instance, while land use for biofuel crops expands in tropical countries, shifting food crop production into savannahs and forests, the inducing activities of car holders consuming biofuels in Northern countries are far away. Global land use change is mainly driven by expansion of urban area and agricultural area and a reduction of forest area (UNEP 2014b).

Worldwide area of cropland and pasture land as well as of forests is regularly recorded by FAO. Data on urban or built-up area is rather poor.

Land footprint analysis, which links major types of land use with a life-cycle perspective to final consumption of products in a country, so far has been performed on the basis of research projects by institutes for single countries or regions such as the European Union (O'Brien et al. (2015) and references therein). Statistical offices have only started to adopt the method (DESTATIS 2014). The land footprint is determined by either a coefficient approach following national material flow analysis method, or by input-output analysis, mainly by a combination of land use data with economic input-output tables. Thus, material, land, and carbon footprint can be analysed consistently (Tukker et al. 2013).

Land use change has been modelled extensively in pursuit of various research questions. Only recently, land use change induced by countries' consumption has also been studied in view of synergies and conflicts in implementing the SDGs (UNEP 2015b).

2.2.3 Water Use

Water consumption will meet increasing scarcity of clean freshwater (Alcamo and Henrichs 2002), in particular as water quality in various world regions is decreasing (UNEP 2016c). UN-Water[1] and others are reporting on water withdrawal, water scarcity and quality, on sanitation, etc. Efficiency of water use has not yet been recorded regularly and could potentially receive higher attention. A specific aspect in this regard is addressed in a recently proposed Wastewater Reuse Effectiveness index (WREI, Kurian 2017), addressed also in Chapter "Governance of Water-Energy-Food Nexus: A Social Network Analysis Approach to Understanding Agency Behaviour" (Kurian et al. 2018).

Different accounting schemes have been applied and various data bases exist to describe water management (UNEP 2012a). Water consumption per capita may be related to water availability of regions or countries, e.g., by the withdrawal-to-availability ratio (Alcamo and Henrichs 2002). UN-Water reports renewable freshwater availability per capita and the percentage of withdrawals from total renewable available water as well as other indicators for all UN countries.

The water footprint concept as developed by Hoekstra et al. (2011) in general captures direct and indirect consumptive uses and pollution of water of countries, considering also import and export-related product water footprints. It comprises three elements: green water footprint (mainly evapotranspiration in agricultural fields), blue water footprint (withdrawal from surface or groundwater without return), and grey water footprint (theoretical volume required to dilute pollutants below environmental quality standards). While the water footprint has been determined for all countries with more than 5 million inhabitants (Hoekstra and Mekonnen 2012), its interpretation is not straightforward. Evapotranspiration of natural vegetation is often much higher than for cropping fields, and also very difficult to measure. Measuring pollution by required dilution volume could require a tremendous amount of data, depending on the number of pollutants and regional standards. Therefore, when considering regular reporting and benchmarking of countries, a concentration on the blue water footprint could be an option. This indicator, however, excludes withdrawals which are returned to the same catchment area and thus excludes, for instance, cooling water for power stations which is not evaporated but returned to the river (with increased temperature), a flow which dominates water withdrawal in industrial countries like Germany. Moreover, the water footprint is a pure volumetric indicator, which neglects water availability, which is becoming serious in various world regions.

A water scarcity index (WSI) has been developed (Pfister et al. 2009) which is available for all countries. It is based on the relation of freshwater withdrawals to hydrological availability of more than 10,000 watersheds (Alcamo et al. 2003). WSI has been developed as characterisation factor in LCA. It could also be applied to weigh domestic blue water consumption, thus providing a comparable benchmark for international comparison, and as a basis to measure decoupling.

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[1] See e.g., http://www.unwater.org/kwip.

Altogether, the territorial accounting of material, land, and water use seems to be well-established to provide kind of a basic version for regular accounting. Methods and indicators for calculating global footprints for the consumption of those resources have been developed. International comparison and data base seem most advanced for the material footprint, which could possibly provide the starting issue of a regular report of global resource use. Nevertheless, institutional improvements are necessary to establish the operational basis for a regular data up-date and provision of key indicators based on national Material Flow Accounting.

3 Basic Goals and Resource Policies

The basic rationale throughout the Agenda 2030 is to promote human well-being and social progress while keeping development within environmental limits. This section provides a short overview of the theoretical concepts of Safe Operating Range and Safe Operating Space and their implications for monitoring progress towards more sustainable resource use. It will then provide an overview of actual resource policies of countries.

3.1 Expansion of Safe Operating Range Within Safe Operating Space

Historically, humans have expanded their chances for survival, improved livelihoods, and well-being by means of technological and institutional innovations (Bringezu 2015b). In technical terms, Human-Technology-Institution-Systems (HTISs) have increased their safety in a wider sense while becoming independent from proximate constraints. This more or less continuous development has been associated with an expansion of the *"safe operating range" (SOR)* of the HTISs in space and time. The SOR may be defined as *actual* capability of an HTIS to survive physically and economically in a decent manner under acceptable conditions (including a liveable environment) over time and at certain locations; while what is "decent" and "acceptable" may change over time. The SOR is multi-dimensional and comprises components such as safe livelihood, quality of life, security, monetary stability, supply security, and quality of the environment.

In contrast to SOR, the safe operating space (SOS), as defined by Rockström et al. (2009), comprises dimensions only relating to environmental resources in a wider sense (absorption capacity for GHG emissions, cropland use, etc.), and reflecting the boundaries for potential low risk development given by the earth system. Following Bringezu (2015a, b), this chapter argues that the SOR of countries may continue to expand in various social, economic, and environmental quality domains while keeping the overall resource use within the SOS (or bringing it back to those levels).

This will require further institutional development to foster the independence of that constraint such as improved monitoring and management policies.

The SOR is the multifunctional "safety" room *actually* realised by an HTI. In contrast, the safe operating space as defined by Rockström et al. (2009) is a *potential* of a low risk use of the natural environment specified by key components or sub-dimensions of resource use in a wider sense such as GHG emissions, nutrient emissions, land use (Fig. 2b). The determination of an SOS involves normative assessments on the acceptance of environmental change and associated risks. It is scale dependent as discussed by UNEP (2014b) for the sub-dimension of land use. When defined for the global scale, the countries need to be attributed their fair share of resource use (usually done on a per person basis) in order to know whether they perform within their SOS or beyond.

The SOR seems to expand in all aspects. While there may be some trade-offs between domains, e.g., restricted mobility and thus reduced quality of life due to higher security precautions, in the long run progress may be expected in every domain. In contrast, resource use or pressure to the environment may expand sustainably, if the SOS threshold is not yet reached,[2] or needs to be constricted, if exceeding that limit.

It seems important to note that the concept foresees that SOR might grow further in its domains, while development is kept within SOS boundaries. In other words, it is assumed that quality of live and safety of living conditions can be improved (within and between countries) while keeping resource consumption within environmentally safe limits.

There is evidence that developed countries with limited resource endowments have become more material efficient and thus reduced their dependence on supply with foreign raw materials. This decoupling of value creation and material consumption was enabled by improved knowledge which again led to higher innovation capacity (Bringezu 2015b).

3.2 Resource Policies

National resource policies reflect the basic goals of enhancing safety while becoming more independent from constraints. Both intentions can be found in the sequence of progressing strategies (Bringezu et al. 2016):

A. *Resource access policies*: The goal is to ensure continuous supply of affordable natural resources. Within their own country, spatial planning, for instance, assigns priority areas for mining in order to keep out competing land uses.

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[2] For instance, Rockström et al. (2009) suggested that global cropland could be expanded sustainably by 400 Mha without reaching the planetary boundaries, which was critized by UNEP (2014b) pointing to the associated loss of biodiversity which should be avoided. The example shows that defining sustainability thresholds of resource use is still a challenge.

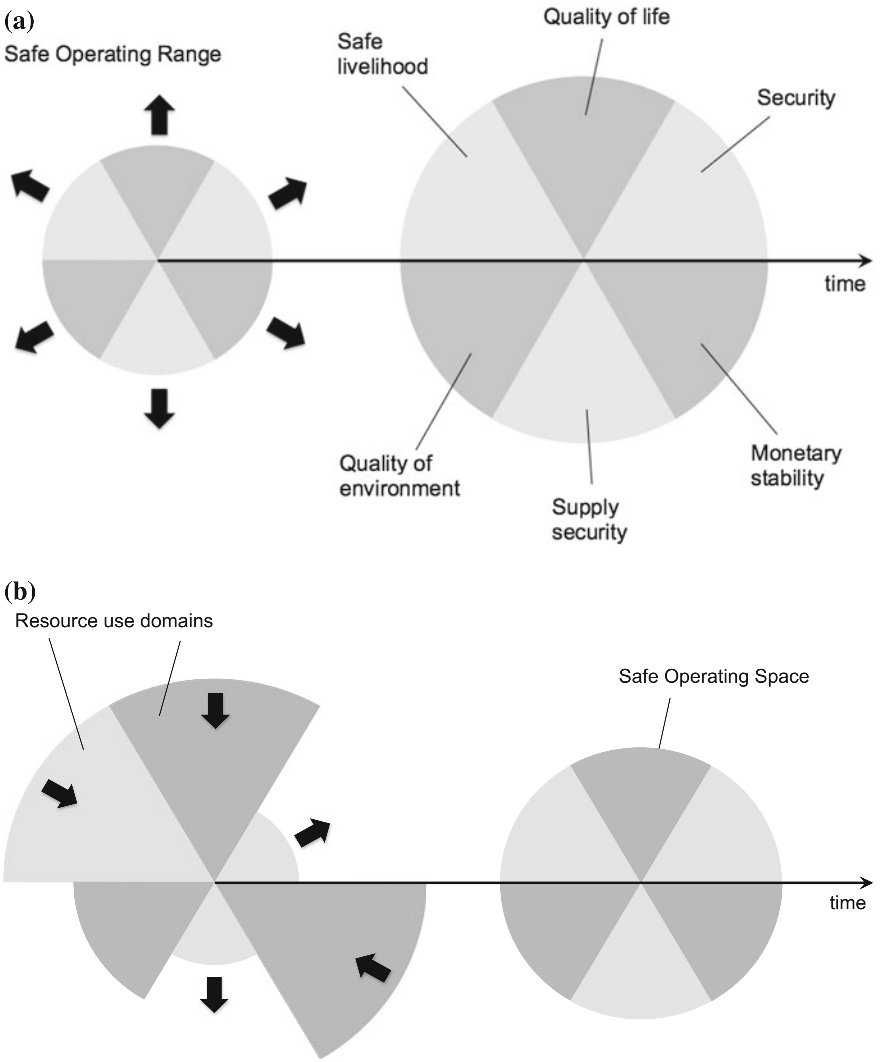

Fig. 2 **a** Extension of the domains of the Safe Operating Range (SOR) (Bringezu 2015b), **b** Resource use develops into the Safe Operating Space (SOS) (Bringezu 2015b)

Beyond their border, contracts with foreign governments and also B2B negotiations supplied with economic incentives have the function to secure supply.

B. *Resource efficiency policies*: The objective is to enhance decoupling of economic growth and natural resource consumption. Often, the underlying goal is to become more independent of imports of resources, and to enhance competitiveness by cost savings and innovations. Thus, the economic benefits are also key incentives, while the relatively reduced environmental burden is readily accepted as a bonus.

C. *Sustainable resource use policies*: The goal would be to use natural resources not only efficiently but also in an internationally fair, secure, and environmentally safe manner for the provision of welfare and well-being. This will require complementing resource efficiency with the consideration of rebound effects and a shift towards resource sufficiency in terms of absolute levels of resource consumption.[3] It also requires mainstreaming of respective national or regional (e.g. European) targets and limits with global values set by planetary boundaries (Integrated SDG Implementation—How a Cross-Scale (Vertical) and Cross-Regional Nexus Approach Can Complement Cross-Sectoral (Horizontal) Integration).

The more advanced resource policies are, the more aspects they integrate. As a consequence, sustainable resource policies would clearly supersede single ministries' scope and fall under the responsibility of prime ministers, so that they become horizontal policy used to steer the direction of all the governmental policies.

In the European Union, the raw material initiative (EC 2008) comprises three pillars where two are aiming to secure supply, whereas the third aims to increase resource efficiency and thus enhances independence from foreign supply. The latter is particularly supported by the flagship initiative for a resource efficient Europe 2020 (EC 2011b) and the roadmap for a resource efficient Europe (EC 2011a). The dualism between resource security and resource efficiency policies can be observed in many countries. While the former usually aim at an increase of resource extraction and harvest, the latter tends to mitigate demand and has the opposite effect. Meanwhile, an efficient—or smart—use of material resources has been formulated as policy goal in China, Japan, South Korea, the EU, Austria, Estonia, France, Finland, Germany, UK, Hungary, Poland, Portugal, Romania, and Slovenia, with quantitative targets on resource productivity set by nine countries (EEA 2016; Bahn-Walkowiak and Steger 2015). Japan and Germany are also frontrunners with regard to policy programmes fostering resource efficiency throughout the economy, within industries, public administration, and households.

Sustainable resource use policies are more difficult to determine. While the aspect of international responsibility of resource use is acknowledged by several countries at the general policy level, quantitative indicators of progress—in particular targets on absolute resource consumption—are still limited. A reduction of scarce aggregate extraction has been the objective in Sweden, Denmark, and the UK, mainly driven by proximate constraints. Austria set a target to reduce domestic material consumption from 2008 to 2020 by 20% (with implementation programme), Italy announced to aim at a 90% reduction of TMR until 2050 (without implementation programme yet), Switzerland aims to reduce their consumption to "environmental footprint one" (Bahn-Walkowiak and Steger 2015). Discussions on possible absolute targets of resource consumption are ongoing in various countries.

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[3] The reader will note that sufficiency in terms of resource consumption is NOT tantamount to sufficiency in terms of final consumption of goods and services, as the latter may be associated with different amounts and impacts of life-cycle-wide resource requirements.

Addressing possible policy targets of resource consumption is hampered by the circumstance that the scientific debate on the outline of a sustainable corridor of global resource use seems to be still in an early phase (Bringezu 2015a), and that any such policy target would reflect normative settings of social acceptability of (risks of) environmental change rather than deduction from earth science modelling. The discourse on potential targets is ongoing, and in conjunction with the selection of key indicators seems to be part of a societal learning process (Bringezu et al. 2016).

4 SDGs and the Use of Natural Resources

Policy demand for regular monitoring material, land, and water use, and their footprints might grow with the knowledge on how these indicators can support the implementation of the SDGs (UN 2015).

The 2030 Agenda comprises 16 topical goals (Table 2). The interconnectedness of the goals has been shown, for instance, by Hall et al. (2017) for water use and sanitation. It has become clear that a systems approach is required to reflect this interconnectedness and search for multi-beneficial strategies which allow reaching various goals simultaneously. Applying a systems perspective, UNEP (2015b) has already pointed out that a more efficient and sustainable use of natural resources would be a prerequisite to reach many of the SDGs.

Indeed, all of the 16 topical goals relate directly or indirectly to natural resource use (Bringezu et al. 2016):

I. Goals emphasising preservation and sustainable use of earth systems: 13 (climate), 14 (oceans), 15 (terrestrial ecosystems)
II. Goals emphasising sustainable supply by resource sectors: 2 (food, agriculture), 6 (water), 7 (energy)
III. Goals emphasising social and technical improvements of the economy: 1 (poverty), 8 (economic growth), 9 (infrastructure, industries), 10 (inequality), 11 (cities), 12 (consumption and production)
IV. Goals emphasising cultural improvements of society: 3 (health), 4 (education), 5 (gender), 16 (peace)

Obviously, goals of groups II–IV aim to expand with the SOR of humanity and every HTIS, while those of group I aim to keep development within the boundaries of SOS. In other words, the basic question is how goals of groups II–IV can be reached without compromising our life-sustaining basis reflected by goal group I, or: How can a sustainable resource use be reached which preserves and improves the living environment while supporting progress towards goal groups II–IV. Concrete modes and options for implementation must be considered, as well as potential conflicts and synergies.

Pursuit of goals in group II requires efficiency increase in the use of agricultural resources, water and energy, comprising technical and organisational improvements

Table 2 SDGs with explicit relevance for resource use (modified after Bringezu et al. 2016)

SDG	Key resource strategy	Challenge—risk	Information required (selection)
Goal 1. End poverty in all its forms everywhere	Clarify land ownership and property rights in particular for the poor	Property rights and land ownership—if legally established—must be accompanied by responsible use rather than license to extract resources	Land registers and transparency in foreign investments
Goal 2. End hunger, achieve **food** security and improved nutrition, and promote sustainable **agriculture**	Sustainable intensification of agriculture Minimisation of food waste Shift to healthier diets	Local limits to intensification may lead to expansion of intensively cultivated land and loss of biodiversity	Good agricultural practice for local resource management Data on biomass flows, including waste; self-supply ratio and physical trade balance; land footprint and reference values for assessing its sustainability
Goal 3. Ensure healthy lives and promote well-being for all at all ages	Health requires a healthy environment	A more sustainable resource use tends to favour a healthy environment. However, both may become the privilege of the rich. Therefore, this goal may not be reached in contradiction with Goal 12.	See Goal 12
Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	Better education fosters independence on natural resource use	Better education is therefore synergistic with more sustainable resource use	Information on resource consumption, including resource footprints, resource productivity, and good practices of sustainable resource management from local to national and global
Goal 5. Achieve gender equality and empower all women and girls	Gender equality tends to foster more sustainable use of natural resources	Gender equality is therefore synergistic with more sustainable resource use	Like for Goal 4

(continued)

Table 2 (continued)

SDG	Key resource strategy	Challenge—risk	Information required (selection)
Goal 6. Ensure availability and sustainable management of **water** and sanitation for all	Water use efficiency Water quality management	Resource intensive infrastructures for water supply and sanitation Overuse of water despite high use efficiency	Information on resource efficient technologies Water balances for regions; water footprint weighed with water scarcity; information on water quality
Goal 7. Ensure access to affordable, reliable, sustainable, and **modern energy** for all	Energy efficiency Shift to renewable energies	Problem shifting by growing use of certain renewable energies such as those based on energy plants	Reference values for resource footprints of energy technologies (e.g. RMI per kWh) Resource Footprints at the national level covering energetic and non-energetic material flows, land use, water withdrawal, and GHG emissions to detect problem shifts
Goal 8. Promote sustained, inclusive and sustainable **economic growth**, full and productive employment and decent work for all	Decoupling of both economic value creation and employment from resource use	Growing resource consumption despite relative decoupling Shifts of resource-intensive industries to resource extracting countries	Monitoring of territorial and global resource use of national economies; including all resource footprints, international comparison of resource productivity and resource consumption per person; reference values for resource footprints, in particular material footprint
Goal 9. Build resilient **infrastructure**, promote inclusive and sustainable **industrialization** and foster innovation	Resource efficient infrastructures Resource efficient industries	Build-up of infrastructures in DCs and maintenance in ICs in a highly resource-intensive mode Copying technologies of IC by DCs may multiply problems	Information on resource efficient infrastructures Information on development and operation of resource efficient industries and companies, incl. sectoral resource footprints of their products

(continued)

Table 2 (continued)

SDG	Key resource strategy	Challenge—risk	Information required (selection)
Goal 10. Reduce inequality within and among countries	Foster resource efficiency in order to allow poorer countries and people to attain well-being and welfare more easily and less burdensome	Resource efficiency increase also leads to enhanced competitiveness of countries and thus may tend to increase inequality This goal can only be implemented together with Goal 12	See Goal 12

on the local to regional scale. Information on the resource efficiency of food systems and supply technologies are needed. Whether sectoral improvements lead to an overall improvement and not just to transregional problem shifts will also require a monitoring of resource footprints at national level.

The implementation of goals in group III seems most challenging. The conventional approach of alleviating poverty, promoting economic growth, providing higher welfare for all, generating better utilities and prospering industries, and allowing consumers to satisfy their wishes, has been and still is associated with growing consumption of natural resources. Thus, the pursuit of the group III goals is inherently conflicting with goals of group I. A sustainable resource use must build a bridge, and the increase of resource productivity and the decoupling of resource use with well-being will be key towards this end. Monitoring progress thus requires recording resource consumption, including global resource use by national economies, and relating this to the socioeconomic progress indicators. Monitoring the Four Footprints will contribute essentially to evaluate the effectiveness of cross-scale resource policies at country level.

In contrast, the implementation of goals in group IV seem rather synergistic with a more sustainable use of natural resources and therefore also with reaching goals in groups I–III. As health requires a healthy environment; education widens perspective and provides the basis for innovation; women empowerment often goes along with a wiser use of resources; and peace is a precondition for reliable living conditions, while unsustainable resource use may lead or foster military conflicts; a more sustainable resource use will be fostered by progress towards those goals, and potentially also vice versa.

It seems important to note that goals of group I—climate stability, biodiverse, and functioning ecosystems—cannot be attained without more efficient and sustainable use of natural resources across scales, in particular without significant progress towards more sustainable consumption and production systems, at the level of infrastructures, cities, and whole economies.

Table 2 provides an overview of key resource strategies which may help to approach the SDGs, the challenges (leading to potential conflicts between goals), and information required to enable actors at different scales to make knowledge-based decisions for a more sustainable resource management (amended from Bringezu et al. 2016).

Improvement of the information base, including on the resource effectiveness of technologies, organisational changes, and policy instruments is required across scales. The further development towards a most synergistic pursuit of the SDGs via a multi-scale sustainable resource use requires progress in particular on the monitoring of global resource use on the national and sub-national level. Towards this end, institutional development is needed, as is also required by SDG 17.

5 Institutional Development Required for Monitoring and Managing Global Resource Use

Implementing the SDGs will require rethinking the way humanity uses its natural resources. New tasks are emerging, as described in column 4 of Table 2. Some of them such as the monitoring of national resource consumption can be adopted by existing institutions like statistical services reporting on progress towards sustainability, while for international comparison and a worldwide picture the establishment of new institutions may be required. Managing global resource use, for instance, by policy programmes and instruments to foster resource efficiency, on both the national and international level will have to rely on solid information on past, current and future trends of resource use and decoupling from socio-economic progress, as well as on success and failure cases from the various countries and across levels (including the cities and companies). This will be required as a reference to inform decision makers in public policy, businesses and NGOs on problems and perspectives of the physical basis of economies and societies. Bringezu et al. (2016) started the debate and various options will have to be considered seriously.

The further development towards global sustainable resource management will significantly rely on the improvement of the knowledge base.

Monitoring global resource use

Monitoring global resource use and benchmarking countries regularly regarding their resource consumption and productivity might be an effective instrument not only to improve the knowledge base, but also to foster a fruitful competition amongst countries towards sustainability.[4] If authoritative and legitimate information were to be provided, the monitoring would be conveyed by international governmental organisations. The status of natural resources and the global environment has been reported in the GEO reports by UNEP (2012b). The use of material resources and the footprints of countries or country groupings have been reported for European countries

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[4] An example for benchmarking of countries with regard to their resource productivity is the European Resource Efficiency Scoreboard: http://ec.europa.eu/eurostat/web/europe-2020-indicators/resource-efficient-europe.

by EEA (2013), for OECD and BRIICS countries by OECD (2015), and worldwide, including world regions and with selected county profiles, by the IRP (UNEP 2016b). The latter report may be taken as pilot to provide key elements for regular reporting. As an option, a regular reporting mechanism on global resource use of countries, including their resource productivity (to record progress on decoupling) and their resource footprints (to monitor progress towards sustainable resource consumption) could be established within the UN institutions. The IRP could potentially supervise the reporting and assist with the assessment. Further outlets of key indicators could be, for instance, the Green Growth Knowledge Platform.[5] Ultimately, countries' reporting capacity needs to be supported so countries regularly report their economic accounts and satellite accounts for natural resource use, emissions, and waste.

Establishment of an international data base on global resource use

The need for an international data base on global resource use, potential content, and the requirements for set-up had been described by Giljum et al. (2009). The data basis could be aligned with the Eurostat Data Centre for Natural Resources[6] and the OECD data base on material flows. Different institutions such as the Vienna University of Business and Economics, the Institute of Social Ecology in Vienna, the Wuppertal Institute, the Institute for Energy and Environment Research (IFEU), and the Center for Environmental Systems Research (CESR) of Kassel University in Germany, the United States Geological Survey (USGS), the Commonwealth Scientific and Industrial Research Organisation (CSIRO) of Australia, and Nagoya University of Japan have hosted global data sets. Based on existing data sets, the most recent and comprehensive data base on national MFA and derived indicators was compiled for the UNEP (2016b) report. Institutional settings will have to be explored in order to organise a regular update with rigorous quality check within an international government-based frame. Ideally, a *Global Resource Data Centre* could be established, which provides national MFA data for all countries with derived indicators on material and resource productivity and consumption, including the four footprints, specifying resource groups, covering both used and unused extraction, and providing information on critical and otherwise relevant raw materials including both primary and recycled.

Development of an international competence centre on sustainable resource management

An information hub for governments, NGOs, and industry is needed on the knowledge base for global sustainable resource management at different scales. This could comprise the coordination of the development of an international protocol for national MFA and derived indicator accounting methods—based on EUROSTAT and OECD guidelines—on how to monitor resource consumption, footprints, and productivity. With regard to lacking statistics and methodological know-how in many developing

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[5] http://www.greengrowthknowledge.org.

[6] http://ec.europa.eu/eurostat/web/environmental-data-centre-on-natural-resources.

countries, such a centre would essentially contribute to capacity building in countries of the Global South. The competence centre could be active in initiating, supervising, and interpreting light-house studies to promote global sustainable resource management, and providing reference values for the assessment of resource consumption such as safe operating space level corridor of global resource extraction. In order to support sustainable solutions, the competence centre could provide compilations of good practice examples as well as failure cases on resource policies and studies on the effectiveness of certain instruments and measures.

Development of a Global Sustainable Resource Management Programme

Ideally under the auspices of the United Nations, and aligned with ongoing activities of UN Environment, UNIDO, and UNICEF, complementing and providing synergies with UN conventions on climate change, desertification, biodiversity, and taking up outcomes of institutions such as FAO, WMO, and WTO, an international policy programme to foster global sustainable resource management could be developed. Such a programme could be based on the achievements of the International Resource Panel which may continue to serve as an advisory body within such a programme. The new programme would support and help implement initiatives such as the Green Economy initiative of UN Environment,[7] the Green Growth Strategy of OECD,[8] and the Global Solutions Network.[9] While the programme could be developed as a pilot based on existing regulations, the full establishment would require a legal basis in the form of an International Convention. A promising institutional home for a global SRM programme is the newly formed United Nations Environment Assembly (UNEA), which jointly with the High Level Political Forum could draft a mandate and take the lead in developing an International Convention for Sustainable Resource Management.

The primary task to improve the knowledge base for Sustainable Resource Management underpins the important role of science in the further development. While conducting studies and providing data on resource use and efficiency including future scenario modelling will enlarge the information basis available, research institutions are also challenged to "activate" relevant information assisting societal transformation towards more sustainable development. Towards this end, more communication between science and society and more dialogues between research and policy will be necessary. As resource efficiency both requires and drives innovation (Bringezu 2015b), informing policies on ways how to promote efficient and sustainable resource use will be crucial also for technical and socio-economic progress. In order to provide more decision oriented and policy relevant information, research alliances and international research projects might be helpful, in particular to form precursors of a *Global Resource Data Centre* and an *International Competence Centre* for Sustainable Resource Management.

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[7] http://www.unep.org/greeneconomy/.

[8] http://www.oecd.org/env/towards-green-growth-9789264111318-en.htm.

[9] http://gsnetworks.org.

6 Conclusions

Various countries have started to develop resource policy programmes, both to enhance supply security and to increase resource efficiency. Strategies in pursuit of sustainable resource use might be a prerequisite as well as synergistic in the implementation of the SDGs. Still, however, the knowledge base for global sustainable resource management at different scales needs to be improved, both on the national and international level. Towards this end, further development of existing or new institutions will be required at the international scale. In particular, regular monitoring of global resource use of countries, a consolidated and regularly updated data base, an international competence centre, and an international policy programme based on a UN convention for sustainable resource management would represent important milestones on the way towards a sustainable future. The International Resource Panel may support the further process, including monitoring and estimating future trends (to enable early warning), assist with institutional development and thus strengthen the science-policy interface. Research institutions working in the field are invited to join forces in order to develop a global network and an international competence centre for sustainable resource management.

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The Urgent Need to Re-engineer Nitrogen-Efficient Food Production for the Planet

Ilje Pikaar, Silvio Matassa, Korneel Rabaey, Bronwyn Laycock, Nico Boon and Willy Verstraete

Abstract One of the major “sustainability challenges” is to manage the unprecedented demands on agriculture and natural resources to match the increasing human population and consumption of nutritious protein and calories, while dramatically decreasing the environmental footprint in order to maintain the resilience of our planet. Global nitrogen pollution is of particular concern and is already beyond the Earth system’s safe operating space. To meet the world’s future food security, food production needs to be doubled by 2050 and as such will result in further increasing human pressure on the global nitrogen cycle. We argue that there is an urgent need for re-engineering of the anthropogenic nitrogen cycle in order to find a long-term sustainable solution. Firstly, the massive production of plant protein to be upgraded to animal protein has a far too heavy water and land-use footprint to be sustainable. It seriously threatens our freshwater resources by inducing harmful algal blooms through inefficient nutrient use. Secondly, it leads to large scale deforestation in biodiversity hotspots such as the Amazon and Sub-Saharan Africa. Third, the current production chain of plant and animal protein depends strongly on the implementation not only of fertilisers but also of pesticides, pharmaceuticals (e.g., antibiotics), and disinfectants, which indirectly are documented to create phenomena such as multiple antibiotic-resistant bacteria and lower immunological defence and the presence and accumulation of antibiotic-resistant bacteria in agricultural soils. We argue that the line of direct protein production as animal feed or even for human consumption

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by using microorganisms is a welcome opportunity to alleviate the very significant burden that the contemporary food production systems have on our planet.

1 The Nitrogen/Water-Waste-Energy Nexus

1.1 The Haber-Bosch Process: One of the Greatest Inventions that Changed the World

In his book *An Essay on the Principle of Population* published in 1798, Thomas Malthus (1766–1834) was the first known to state that the increasing population would suffer hunger due to the limited capacity of the earth to produce food crops (Malthus 1798). Although Malthus was heavily influenced by the severe famines in Ireland induced by plant diseases, this was particularly caused by the lack of reactive nitrogen in the biosphere (although Malthus was at the time of writing not aware of that fact), which in those days was the limiting factor in agricultural food production. About a century later, in 1908, Fritz Haber patented the Haber-Bosch process, the so-called "synthesis of ammonia from its elements", in which dinitrogen (N_2) was converted to reactive nitrogen (NH_4^+) to produce ammunition. From the war industry, mankind serendipitously begot industrial fertiliser and stepped up agricultural production of food crops intensively (Erisman et al. 2008b).

The Haber-Bosch process is one of the world's most important inventions, ultimately allowing mankind's population to grow to 7 billion people.

1.2 Haber-Bosch Nitrogen Is Essential to Human Health

At present around 100 million tons of Haber-Bosch reactive nitrogen are used in agriculture annually (Bodirsky et al. 2014). Besides Haber-Bosch nitrogen fertilisers, some crops such as legumes (e.g., soybeans) are capable of fixing nitrogen biologically (Galloway and Cowling 2002); so-called biological nitrogen fixation (BNF) represents a much smaller fraction compared to Haber-Bosch reactive nitrogen, with about 35 million tons of nitrogen being fixed by means of BNF yearly (Bodirsky et al. 2014). In addition, biological nitrogen fixation (BNF) is a process characterised by a low efficiency (Oldroyd and Dixon 2014) despite intensive research over the past decades. Under the best of conditions, a plant needs to metabolise some 12 kg of glucose (i.e. ~190 MJ) of energy to fix 1 kg of N_2 via root-nodule-based bacteria, which results in a maximum efficiency of only 12% (Board 2004). Hence, plants fixing nitrogen with the help of partner bacteria have to pay a considerable price in the form of carbohydrates delivered to the bacteria per unit of nitrogen received. Overall, in terms of thermodynamics, the prospect of improving BNF or introducing it to a variety of crops such as wheat, rice, sugarcane, or potato does not offer sufficient perspective to create a major impact (Boddey et al. 1995). It has thus become clear that BNF will not be able to substitute Haber-Bosch nitrogen, not so much because the N-fixing genes of biochemistry cannot be transferred to other crops, but because the price the altered plant has to pay in terms of its biologically fixed nitrogen is too high. In contrast, the chemical industry has achieved a remarkable upgrading of the process efficiency and currently, with the use of optimal catalysts and operating conditions, produces reactive nitrogen at an energy cost that is close to the thermodynamic minimum, i.e. 32.8 MJ/Kg NH_4-N (Zhang et al. 2013). Research for deep rooting plants with low nutrient requirements or novel vegetables can open new perspectives (Gilbert 2016; Cernansky 2015), but the improvements cannot be expected to remediate the inefficient use of nitrogen in agriculture, which is inherently linked to hard-to-control soil processes such as leaching and denitrification (Bodirsky et al. 2014).

It is clear that considering the soil ecosystem and the nature of the plant nitrogen uptake mechanisms, current knowledge and agro-technological processes offer limited possibilities to reconcile the increasing pressure on agriculture to provide mankind with animal feed and food without relying on the Haber-Bosch process to provide crops with essential reactive nitrogen.

Providing a detailed trajectory of the future is difficult, but it is evident that Haber-Bosch nitrogen is of crucial importance in the overall strategy to feed the world at present and even more so in the foreseeable future.

1.3 The Nitrogen Cycle to Come

While the Haber-Bosch process has allowed agriculture to greatly increase food production, thereby enabling human population growth, it has also led to a host of serious environmental problems, ranging from eutrophication of terrestrial and aquatic systems to climate change and global acidification (Gruber and Galloway 2008; Rockstrom et al. 2009; Steffen et al. 2015; Tilman et al. 2001; Mosier et al. 1998), due to the so-called nitrogen cascade effect (Galloway et al. 2003). Recent analysis has revealed that current anthropogenic nitrogen flows are already outside of the safe operation zones (Steffen et al. 2015). Although the rate of population growth is estimated to decrease, the overall world population is still going to rise and expected to grow to 9–10 billion by 2050 (United Nations 2015). Moreover, a higher fraction of the population will require access to highly nutritious protein due to

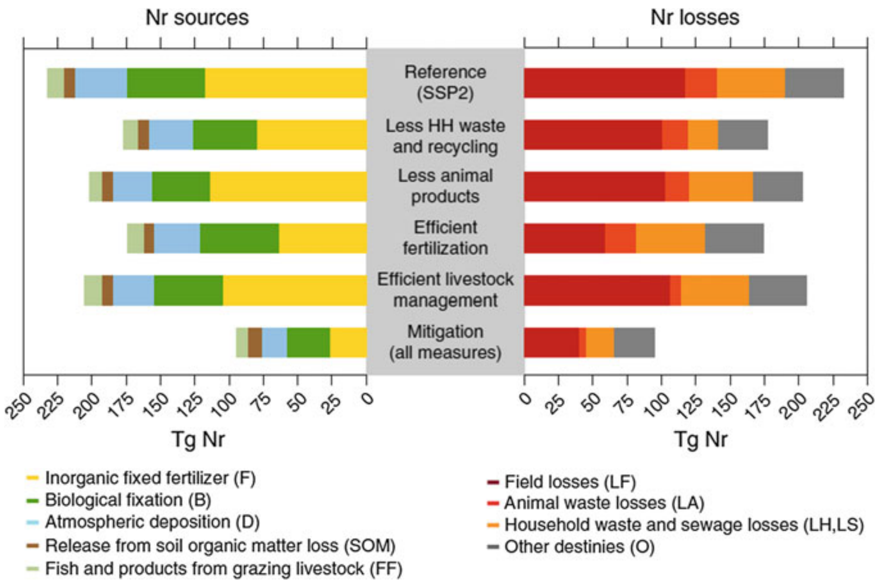

Fig. 1 Sources and losses of reactive nitrogen in the agricultural food supply chain in 2050 using the MAgPIE model from (Bodirsky et al. 2014). HH refers to household waste

increase in wealth (Godfray et al. 2010; Bodirsky et al. 2015). To match this increasing demand for food, the Food and Agriculture Organization (FAO) of the United Nations estimates a further 50% increase in N fertiliser demand by 2050. Predictions about reactive nitrogen losses to the environment thereby are as high as 70% by 2050 (Sutton and Bleeker 2013; Bodirsky et al. 2012). Matching the increased demand for food while reducing the environmental footprint of agriculture remains one of the main challenges mankind faces in the 21th century and beyond (Godfray et al. 2010). Available mitigation measures to reduce environmental pollution include: less household (food)waste, lowering consumption of animal products, more efficient fertilization, bettering livestock feeding and more manure recycling (see Fig. 1). Clearly, the factor of field losses of reactive N is the key problem and this burden directly necessitates the input of fertilizer. However, even under ambitious mitigation efforts that combine all the above measures effectively, through the use of precision agriculture for example (Bouma 2016), it is still not certain that sustainability targets can be reached and the nitrogen cycle can return to within planetary boundaries (Steffen et al. 2015). Additional to conventional nitrogen mitigation measures listed in Fig. 1, it is therefore necessary to think outside of the box for new innovations that can achieve major improvements rather than incremental changes in nitrogen efficiency.

Note that in all scenarios the losses in the field and those via the households are predominant. Units are in Teragram (*Tg*) reactive nitrogen (*Nr*); 1 Tg corresponds with 1 million metric tons. All scenarios are based on the shared socioeconomic pathways (SSP2), while they differ in respect to the implemented mitigation measures. Please refer to Bodirsky et al. (2014) for a detailed description of all the mitigation methods and simulated reactive nitrogen flows.

1.4 Externalities of Nitrogen Pollution

In addition to the detrimental impact on the environment from losses of reactive nitrogen, the externalities in terms of the costs on human health caused by e.g. air and water pollution are enormous, with an estimated magnitude of 0.3–3.0% of the global gross domestic product (GDP), which equals a staggering \$225–\$2250 billion dollar a year (Sutton et al. 2013). This is in agreement with other recent studies (Sobota et al. 2015; Gu et al. 2012, 2015; Van Grinsven et al. 2013; Kusiima and Powers 2010; Erisman et al. 2013; Muller and Mendelsohn 2010) that showed that potential economic damages due to reactive nitrogen loss associated with agricultural N loss are enormous, with values estimated at \$157 billion year^{-1} (ranging between \$59 and \$340 billion year^{-1}) in the US (Sobota et al. 2015) and €35–€230 billion year^{-1} in the EU (Van Grinsven et al. 2013), respectively. Considering a global market value of soy of around \$113 billion year^{-1} (at a price for soy (at about 35–50% protein content on dry matter) of around \$450/ton at the current global soy production of 276 Mton per annum) and the estimates for externalities described above (i.e. estimated up to \$2200 billion annually), it is evident that the externalities of nitrogen pollution outcompete the global soy market. This is in agreement with a study by van Grinsven et al. (2013), where it was estimated that damages from agricultural nitrogen pollution exceeded economic benefits of increased agricultural production by a factor up to 4 in a European context (Van Grinsven et al. 2013). Hence, there is an urgent need to reduce this enormous negative economic impact and internalise these costs within the price of agricultural products. Indeed, in a recent report by the Global Partnership on Nutrient Management (GPNM) and the International Nitrogen Initiative (INI), a shared aspirational goal to improve nitrogen-use efficiency by 20% by 2020 has been set. Their cost-benefit analysis revealed that this 20% increase would result in a net saving of approximately US\$170 billion (Sutton et al. 2013).

The environmental externalities of global nitrogen pollution are very large, but so far these externalities have not been taken into account in food prices. In order to create a change and stimulate nitrogen-efficient solutions there is an urgent need to internalise the externalities of nitrogen pollution. Only then can a sufficient number of innovations reach their full maturity and be successfully introduced and replicated in the market economy within a reasonably short timeframe.

1.5 Nitrogen-Carbon-Climate Interactions

As previously discussed by Gruber and Galloway (2008), there are many interlinked nitrogen-carbon-climate driving forces. The authors concluded that the two of the most important drivers to consider are (i) changes in the reactive nitrogen inventory through changes in nitrogen fixation, denitrification, or mobilisation and (ii) the decoupling of the nitrogen and carbon cycling through changes in the C/N ratios of autotrophs.

Changes in the reactive nitrogen inventory through changes in nitrogen fixation, nitrification, denitrification, or mobilisation: In the past decades, the progress made in terms of biological nitrogen fixation and control of nitrification and denitrification has been rather limited, not to say disappointing. The best way to address this discrepancy in the long term is the development of tailored slow release fertilisers that match the nitrogen release from the fertiliser with the nitrogen uptake by the plants. However, these technologies have not been used widely thus far (although a substantial amount of research has been conducted in this area, as well as on-going development and progress as outlined in the following sections). This again is directly related to the fact that nitrogen pollution is not internalised; while nitrogen loss can be reduced, the overall crop yield increase is rarely observed despite the additional costs (Guertal 2009). However, we argue that there is significant potential to successfully develop and introduce these types of slow release fertilisers.

Decoupling of the nitrogen and carbon cycling through changes in the C/N ratios of autotrophs: The full focus can be set on the alteration of the amount of CO_2 incorporated in plants and the subsequent food chain per unit residence time of the nitrogen entering the biosphere. Before the occurrence of the Haber-Bosch process, one mole of dinitrogen (N_2) became, either through lightning or by biological nitrogen fixation, two mole of reactive nitrogen (i.e. ammonium, nitrate) within the biosphere, and was generally upgraded to protein. Thus, it was used intensively in the form of a cellular component, particularly if it was incorporated into a functional protein. In the latter case, it typically became part of the biosynthetic pathways, thus giving rise in the case of plant autotrophic anabolism to the intensive conversion of CO_2 to organic molecules such as various carbohydrates, oils, and lignins. In this way each N-atom yielded a high number of carbon atoms captured (CC) during its stay in the biosphere, further referred to as Biosphere Retention Time (BRT); thus a high CC to BRT ratio was achieved. If one considers that the C/N ratio of trees and crops such as grasses and carbohydrate-rich crops such as sugarcane is of the order of 100 (Fortes et al. 2013), and given the fact that the BRT of the natural plant-soil system is of the order of 635 years, it follows that every mole of N_2 entering the natural biosphere becomes 2 mol of protein-N and achieves a capture of at least 50 mol of carbon per mol N during its stay in the biosphere. Yet, since the plant-soil system has a turnover time of 50 years, it means that these 50 mol have to be multiplied by the times this carbon has been renewed over the stay of the unit of N in the biosphere i.e. with a factor 635/50. Hence it can be estimated that a single mole of reactive N entering the biosphere fixes some 635 mol of Carbon. When the latter value is compared with that of contemporary agriculture a totally different ratio appears. Indeed in modern agriculture, the C/N ratio of the crops is not 100 but rather 10. In addition, the reactive fertiliser N is subject to intensive nitrification and denitrification and other rapid losses (i.e. there is too little long-term storage in the agricultural sector). Overall, it has a residence time in the biosphere of the order of a few years instead of the 635 years mentioned above. Hence for intensive agro-protein based production systems, the ratio can be estimated to be in the order of 0.1–1.0, which is 2–3 orders of magnitude lower than that of natural systems.

In order to find a long-term sustainable solution for the nitrogen nexus, we ultimately need to return to the nitrogen cycle as evolved before the industrial revolution; i.e. where for every mole of nitrogen entering the biosphere as reactive nitrogen, a substantial amount of CO_2 carbon is captured.

2 Opportunities for Improving the Nitrogen-Use Efficiency

Clearly, in order to find a long-term sustainable solution for the nitrogen nexus, we ultimately need to return the nitrogen cycle to a situation where the reactive nitrogen species remain longer in the system and bring about intensive CO_2 carbon capture. Considering the above, there are four main points of intervention/opportunities for engineering and biotechnological solutions that would significantly improve the nitrogen nexus (Fig. 2).

2.1 Direct Upgrading of Haber-Bosch Nitrogen into Microbial Protein

The renaissance of the industrial production of microbial protein

Contrary to popular belief, microbes have always played an important role during food processing and their use dates back a long time; for example, the producing of bread by fermentation of dough using baker's yeast, milk to cheese and yoghurt, and hop to beer amongst others, allowing their long-term preservation (Caplice and Fitzgerald 1999). Microbes are often divided into the following groups: bacteria, fungi, yeast, and microalgae. In addition to their important role in ancient and current food processing techniques, they are also used directly as food in the form of fungi, yeast, and microalgae (Anupama and Ravindra 2000). In fact, bacterial proteins are at present already an excellent source of protein—the production of microbial protein (MP) as animal feed and/or human consumption is not new at all. A lot of research was

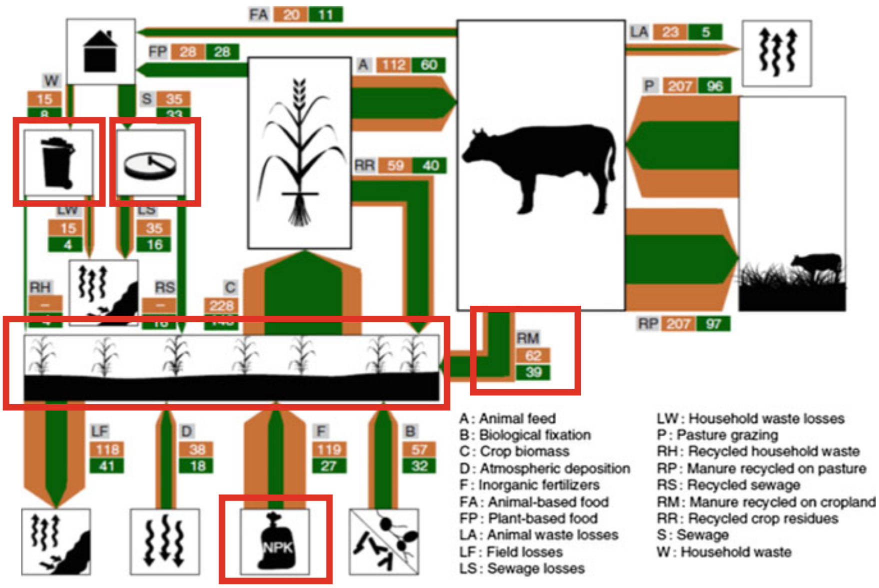

Fig. 2 Schematic overview of the main routes of reactive nitrogen flows and losses to the environment within the agricultural food supply chain (Bodirsky et al. 2014). Red squares represent the potential points of intervention in order to improve the nitrogen efficiency within the agricultural food supply chain. The industrial induced reactive nitrogen losses related to fossil and biofuel combustion processes are not considered. Note that the putative interventions in these conventional routes have a rather limited overall impact. Please refer to Bodirsky et al. (2014) for a detailed description and explanation of the different mitigations options, scenarios and methods used

conducted in the 1960s–80s (Matassa 2016), with industrial-scale protein production achieved in the 1960s–70s. The Russians especially were proactive in this period. As described in a CIA report from 1977 (that was only de-classified in 1999), the Russians had an extensive R&D programme on the production of microbial protein in the form of yeast using hydrocarbons in the form of n-paraffin as growth substrate, the so-called “Soviet Hydrocarbon-Based Single Cell Protein Program” (CIA 1977). The rationale of such a programme was strongly politically-oriented; due to the lack of protein-rich feedstock for livestock production, Russia was highly dependent on protein imports in order for the livestock industry to further expand. By 1977, Russia had progressed to the point where there were six ‘high-capacity n-paraffin based’ production factories, with two more being constructed.

In addition to these efforts, which were predominantly politically driven, in other parts of the world other efforts to develop microbial-based feed and food sources were being made, driven by a growing public awareness of the need to find more sustainable pathways to feed a growing population. These mainly used methanol and methane as growth substrates, which in those days were low-cost substrates. A good illustration of the effort towards more sustainable food production at that time was the UNESCO Science Prize given to Alfred Champagnat and his team in 1976 for his efforts to achieve large-scale and low-cost production of “microbial proteins from oil”. In 1980, Imperial Chemical Industries Ltd (ICI) was the first to commercialise their product called Pruteen®, produced using the microbe *Methylophilus methylotrophus* grown on methanol (Teller and Godeau 1986). In addition to all the efforts made on the production of MP, significant efforts were also made in this same period on establishing its suitability as animal feed, by means of feeding trials using all types of livestock (Øverland et al. 2010), most of which had very successful outcomes. In fact, MP outcompetes the amino acid composition of soy and resembles that of fish meal (considered as a high-quality feed supplement) (Matassa 2016).

Despite all these efforts and successes, MP never managed to become a mature technology. The reason for this is mainly economic and not product quality-related. The very low prices of conventional protein sources such as soybean and fish meal in the late 1970s severely hindered the widespread adoption of MP technologies. Another disadvantage was the underdeveloped state of the fermentation technology in those days. This combined with an increase in oil prices in the decades afterwards further decreased the interest in MP and in fact led to bankruptcy of the ICI enterprise (Matassa et al. 2016). However, the times have changed and we argue here that the timing of a new era in engineered microbial protein production has arrived, due to:

1. The realisation and acceptance that contemporary agriculture will not suffice to solve the nitrogen problem and alternative protein sources are needed to feed the next generations in a sustainable way;
2. The enormous progress that has been made in the last decade in fermentation technology, the design and engineering of microbial metabolism of pure and mixed microbial cultures, food safety and process automation and control;
3. The increase in soybean and especially fish meal prices in the last years;
4. The successful market introduction of fungi-based production as human food in the form of Quorn™;
5. Finally, and maybe the most important aspect: the increased awareness and absolute will to curb the enormous detrimental environmental impact and economic repercussions of the agriculture-based food supply chain in general, and global nitrogen pollution in particular.

Challenges and opportunities

In order to adhere to the recently signed Paris Agreements, countries not only have to decrease their carbon emission; but in fact need to capture carbon from industrial sources as well. The latter represent a novel opportunity for the production of microbial protein as a means to bring CO_2 emissions from industrial point sources to value. By 2050, about 66% of the world population will be living in urbanised areas. It is estimated that by 2040, the human population will be mainly living in megacities (i.e. >10 million or more), thereby concentrating the energy consumption (and thus CO_2 emissions from industrial point sources) as well as the demand and consumption of protein in a few “hot spots” on Earth (Canton 2011). As a direct consequence of additional N fertiliser production and use on arable land, nutrient losses and GHG emissions will rise and intensify around the most densely populated areas.

Autotrophic microbial protein production using hydrogen as an energy source could be advantageously combined with capture of CO_2 emissions from industrial point sources. The ultimate deciding factor here is the availability of CO_2 from industrial point sources at concentrations that warrant economic use. Based on different scenarios, the International Panel for Climate Change (IPCC) calculated that already in 2020 the technical potential of CO_2 capture associated with point sources will range from 2.6 to 4.9 $GtCO_2$ per year (0.7–1.3 GtC) (IPCC 2005). Considering an average C/N of 5 for MP production (Matassa et al. 2015a, b), the 2.6 $GtCO_2$ per year could potentially support the production of 140 million tons of nitrogen in the form of microbial protein (thus yielding some $140 \times 6.25 = 875$ Mtons of protein dry matter per year). The nitrogen thus potentially incorporated by upgrading CO_2 is by itself more than the amount of Haber-Bosch nitrogen added as fertiliser in agriculture. Here, we highlight a unique opportunity that can achieve efficient capturing CO_2 and transforming the captured CO_2 into proteins in an economically desirable way. In the context of microbial production it must be pointed out that one ton carbon (C) incorporated in MP corresponds with 3.66 ton CO_2. Hence per ton of nitrogen incorporated in MP at a C/N of 5, one can capture 18.3 ton CO_2. Assuming a world market price of €30 per ton of CO_2, the latter predicts a "positive" cost of $18.3 \times 30 =$ €549 per ton of MP produced when considered simply as an emission decrease. However, in case one deals with low stabilisation climate targets such as the Representative Concentration Pathways (RCPs), a RCP of 2.6 should be reached (van Vuuren et al. 2011) and in that context a price of \$150–220 per ton CO_2 in the year 2050 would be required. In the latter case, this would correspond with a positive cost of \$2745–4026 per ton microbial protein produced.

Ultimately though, mankind will be forced to gradually abandon the burning of fossil fuels. As such, carbon capture from industrial CO_2 point source is not expected to provide the long-term solution for many generations to come. This means that the approach of linking CO_2 emission abatement with microbial protein production certainly holds the potential to help achieving the Paris Agreements but must be considered a transition to a different platform of protein production in a sustainable way.

Moreover, there is the route of using plain organotrophic microorganisms which can be set to grow on organic carbon sources such as carbohydrates, starch, pectin, lipids, and oils, and even plain hydrocarbons. In the framework of this chapter, the focus is on plant grown carbohydrates, for instance, those produced on less productive soils without implementing intensive agricultural practices (e.g., fertilisers, pesticides). The key feature is that by using specialised cultures and in particular by using optimised microbiomes, one can use mineral nitrogen produced by the Haber-Bosch process and achieve cellular yields of about 0.4 kg microbial biomass (with protein contents of 75% or more!) per kilogram organic carbon source fed to the bacteria. Clearly, in the aerobic fermentation reactor, one can assure that all mineral nutrients added (particularly the N and P) are almost completely utilised (which is hardly possible in open agriculture). When one compares such in-reactor conversion technology with conventional animal production, protein generation from the input materials is of the order of 3–10 times more efficient. Clearly, this domain is well-established in terms of bioprocess technology but has not been allowed to come to maturity due to the low market prices of conventional plant-grown proteins. It offers plenty of potential in terms of making new types of protein (based on microbial components with specific properties such as nutritive amino acid spectrum, digestibility, and palatability) and a new platform of feed and food formulations.

Pilot cases and ongoing initiatives towards implementation

The most advanced and established route to produce microbial protein is the production of so-called Mycoproteins, a fungi-based protein source. In the production process, food grade glucose syrup is used as energy and carbon source, whereas Haber-Bosch nitrogen is added as the nitrogen source. This form of protein is solely used for human consumption and is known under the name Quorn™ (http://www.quorn.com/). As glucose is used as carbon source, this line of protein production is not completely independent of agriculture inputs. However, as Quorn is considered as a meat replacement, the overall nitrogen efficiency is significantly higher.

Another route that has recently gained substantial interest that is already reaching the market economy is the production of bacterial protein using *Methylococcus capsulatus* grown on natural gas (Øverland et al. 2010). An industrial plant with initially a capacity of 20,000 tons per year to over 200,000 tons per year when operating at full capacity is expected to commence operations in 2018. The main market for this type of microbial protein is as an alternative protein source in aquaculture rather than livestock. Important to note, however, is that various animal feeding trials are underway using different types of livestock, such as chicken and pigs at different growth stages, as reviewed by Øverland et al. (2010). A key advantage is that natural gas is a readily available and cheap commodity. Furthermore, it is a completely agriculture-free process and independent of climatological conditions. Considering the above, large scale industrial plants can be developed and placed on marginal land and even in urban areas. In terms of sustainable development, however, this line of protein production will not be able to provide the ultimate solution in the longer term, as the production heavily depends on the use of natural gas.

Research needs

The key feature in producing microbial protein in the 'new mode of maximal N-sustainability' is directly related to the use of microbiomes. This stands in contrast to using 'pure' cultures as practised in the past to make microbial protein. Indeed, if one uses axenic production technology, the costs for maintaining sterility are considerable. Moreover, single strains will be restricted in the range of carbon sources used and will tend to drop in vitality with time. In contrast, when one uses microbiomes, the latter constantly adjust and optimise their functionality to assure a maximal use of all 'free energy' potentialities available and thus generate, under the conditions of aerobic fermentation, basically no residual direct (from the input) or indirect (from the microbes themselves) wastes.

The disadvantages of working with microbiomes are, however, considerable and must be addressed with an open mindset. Firstly, the operator must create a set of conditions in terms of pH, dissolved oxygen, temperature, hydraulic and cell residence time, and specific biomass loading rate so that the microbiome achieves good conversion yields. Secondly, it is of crucial importance that the end-product, i.e. the microbial biomass which is harvested, has a constant composition and quality. In other words, although the microbiome does not have to have always the same microbial composition, the overall quality of the end-product in terms of parameters such as percentage of protein, digestibility, amino acid composition, and nucleic acid content has to be stable in order to attain the level of a feed/food component. Thirdly, the end-product must, upon in-depth genomic analysis, be composed of species which comply with the status of GRAS (generally regarded as safe) species. Fourthly, the functional microbiome should not generate at any point any metabolite (e.g., colour, odour, taste, and allergens) which deters the attractiveness of the end-product to the consumer. Fifthly, in the market economy, it is quite an advantage if the microbiome as such can be described so that intellectual property rights can be attached to it. These criteria are quite demanding, and although there are plenty of fermentations based on 'open microbiomal selection', such as brewing certain types of beer (geuze), preserving feed and food by silaging, making certain natural fermented cheeses, there is very little knowledge at present on how to install advanced monitoring of such dynamic microbiomes and, in particular, how to steer them in time to operate in the proper zones of productivity and feed/food safety.

Clearly, meta-molecular analyses can help to guarantee the output of open microbiome production of microbial protein. In addition, it is very necessary to learn more about the dynamics of change in microbiomes in relation to their diversity in species. Of course, tools such as the use of plant extracts such as hops which control lactic bacteria in beer fermentation might also be of utmost value for steering protein producing microbiomes. In this respect, the search for natural chemicals, produced by plants, which can be integrated in good manufacturing practices of feeds and foods, need to be explored to see if they might be an asset in the control of aerobic fermentations leading to high quality microbial protein.

2.2 Direct Upgrading of HB Nitrogen into Slow and Controlled-Release Fertilisers

The global nitrogen-use efficiency of crops, as measured by recovery efficiency in the first year (that is, fertilised crop nitrogen uptake—unfertilised crop N uptake/N applied), is generally considered to be less than 50% under most on-farm conditions (Tilman et al. 2002; Balasubramanian et al. 2004). The latter is directly related to the fact that the majority of nitrogen fertiliser is added in the form of urea, ammonium sulfate, or ammonium nitrate. Further, the Intergovernmental Panel on Climate Change (IPCC) has set a default emission factor for N_2O emissions at 1.25 ± 1.0 percent of N applied, although this varies with nitrogen source (Charles et al. 2017), with anthropogenic N_2O emissions from the application of nitrogenous fertilisers in agriculture being around 1.7–4.8 MT N (N_2O) year^{-1} (Ciais et al. 2013). This is particularly significant, since N_2O is approximately 300 times more potent in absorbing thermal radiation compared to carbon dioxide (CO_2). In addition, agriculture accounts for about 75–85% of projected global NH_3 emissions throughout 2000–2050 and it is likely that regions with soils and ecosystems where reactive nitrogen loads are already high will be more prone to reactive nitrogen deposition-induced N_2O emissions (Reay et al. 2012). Ammonia can be naturally lost from leaves, but the rate is generally low (at ~3 kg N/ha.crop) (Hayashi et al. 2011).

In order to find a long-term sustainable solution for the nitrogen nexus, we ultimately need to move away from the use of conventional fertiliser and create fertilisers with a nutrient composition and mode of release that more closely matches the nutrient uptake of the plant, enabling a reduced number of fertiliser applications over a season. The latter will be extremely challenging and difficult but important tasks considering the complexity of the plant-soil nature.

Challenges and opportunities

As already discussed, significant losses of reactive nitrogen to the environment occur in cropping when NH_3 and nitrogen oxide gases, particularly nitrous oxide (N_2O), are released from the soil, and where nitrite and more significantly nitrate (NO_3^-) are leached from the soil and/or run off from the surface to transfer to waterways (Reay et al. 2012). Overall, the challenge is to more appropriately match crop demand in terms of timing, placement, form, and quantity of nitrogen to nutrient supply from fertilisers (Byerlee et al. 2014). It has been estimated that nitrogen-use efficiency, for example, could be increased by up to 50% (Erisman et al. 2008a) by practices such as changing the source of N, using fertilisers stabilised with urease or nitrification inhibitors, slow- or controlled-release fertilisers, reducing rates of nitrogen application in over-fertilised regions, and optimising nitrogen fertiliser placement and timing (Del Grosso and Grant 2011; Johnson et al. 2007; Snyder et al. 2009; Smil 2001). The use of precision agriculture to improve nutrient use efficiency is one strategy being widely researched and adopted, enabling modern farming practices to account for landscape variability and thus significantly reducing the use of agrochemicals such as fertilisers (Stoorvogel et al. 2015). In light of this, however, there is still need to improve the overall efficiency of the fertilisers themselves, particularly in tropical environments.

Enhanced efficiency fertilisers (EEFs) are those that are being developed to maximise nutrient use efficiency, particularly of the macro-elements nitrogen and phosphorus, and thus minimise losses of reactive nitrogen (Trenkel 2010b; Shaviv 2001). The general classes of EEFs are foliar fertilisers, stabilised fertilisers, and slow- and controlled-release fertilisers (including stimuli-responsive formulations). Foliar fertilisers are sprayed directly onto the leaves and thus avoid any immobilisation or leaching from the soil. However, because they can cause leaf burn at high concentrations and can also be washed off by the rain, they typically require multiple applications and hence are currently uneconomic as the sole source of necessary additional plant nutrients. Stabilised fertilisers are those that have a nitrogen stabiliser incorporated into the matrix. Nitrification inhibitors [such as *1-carbamoyl-3-methylpyrazole*

(CMP), *dicyandiamide*, and *nitrapyrin* (*2-chloro-6-trichloromethylpyridine*)] delay the biological (bacterial) oxidation of ammoniacal-N to nitrate-N, by depressing the activity of *Nitrosomonas* bacteria for between 4 and 10 weeks. A urease inhibitor (such as *N-(n-butyl)thiophosphoric triamide*) prevents or suppresses the hydrolytic action of the enzyme urease, which catalyses the transformation of amide-N in urea to ammonium hydroxide and ammonium. There is a great deal of ongoing research into slow- and controlled-release formulations (Guertal 2009; Timilsena et al. 2015; Majeed et al. 2015; Ussiri and Lal 2013; Davidson and Gu 2012). Of the different formulations and materials available, the main categories include:

- Materials of a complex/high molecular weight structure of low solubility that release nutrients on hydrolytic and/or microbial (enzymatic) degradation—examples include urea-aldehyde condensation products such as urea-formaldehyde, isobutylidene diurea/crotonylidene, methylene diurea/dimethylene triurea, urea acetaldehyde/cyclo diurea, urea-triazones and so on. Oxamide, produced from hydrogen cyanide, is another example of a synthetic slow-release product that hydrolyses to form ammonia. Inorganic compounds with low solubility such as metal ammonium phosphates also fall into this category. An important subclass of slow-release compounds is organic nitrogen, particularly in the form of proteins and peptides/amino acids, some of which are being commercialised for slow-release fertiliser applications (see for example the arGrow® technology developed by Torgny Näsholm and his team).
- Coated/encapsulated fertilisers, including those with sulphur- or mineral-based coatings, or sulphur plus polymer coatings (including polymeric waxes), or organic polymer coatings. Polymer coatings can be thermoplastics or resins, and typically are semi-permeable or impermeable, and within those categories can be biodegradable or non-degradable, although the common polymers used for coating are the non- or slowly-degradable polyethylene, polysulfone, cellulose acetate, and polyacrylonitrile. The range of polymers now being developed for controlled release applications is very broad, and also includes bioderived coatings such as lignin, humic acids, starch, cellulose, modified natural rubber, alginates, neem, chitosan, polyhydroxyalkanoates, etc. as well as biodegradable but not bioderived materials such as polylactic acid, polycaprolactone, polybutylene succinate, and polydopamine, although many of these are not in commercial production (Mulder et al. 2011; Majeed et al. 2015).
- Matrix materials in which the active agent is dispersed throughout the pellet, slowing down dissolution, including hydrophobic (rubbers and polyolefins) as well as hydrophilic, biodegradable, and/or hydrogel-type matrices. All of these can in turn be coated. NPK fertilisers and urea have also been dispersed within a three-dimensional network structure formed from modified clays (such as attapulgite or montmorillonite), optionally with hydrophilic polymers such as polyacrylamide or polyacrylic acid added to form slow-release networks (Cai et al. 2014; Rashidzadeh and Olad 2014). It should be noted that while the choice of both matrix and coating materials is broad, the selection of nondegradable materials can leave residual microplastics in the environment.

- Those formulations that rely on a small surface-to-volume ratio to slow release.
- Materials such as guanyl urea sulphate, which are readily soluble in water but adsorbed onto soil colloids, slowing the mineralisation.

These slow- and controlled-release fertilisers can be further classed as having a linear or sigmoidal release profile.

Pilot cases and ongoing initiatives towards implementation

One meta-analysis evaluated the overall effectiveness of nitrification inhibitors, polymer-coated fertilisers, and urease inhibitors on N_2O and NO emissions (Akiyama et al. 2010), and was based on 113 data sets published in 35 different studies. It found that the polymer coated fertilisers significantly reduced N_2O emissions (by an average of 35%, with a confidence interval of 58–14%), as did the use of nitrification inhibitors (mean: −38, 95% confidence interval: −44 to −31%). However, there was a lot of variability in the results for the coated fertilisers across different soil types, with no effect being observed in well-drained Andosol fields.

More recently, fertilisers are being developed that are "intelligent" materials, being stimuli-responsive (e.g., triggering release of nutrients based on crop signals related to growth stage or nutrient requirements) (Ma et al. 2013) or that have targeted delivery such as by holding the nutrients until the plants require them. It is known, for example, that the rhizosphere is typically lower in pH than the bulk of the soil (by around 1–2 pH units) (Nye 1981). Thus the presence of the growing root tip can trigger nutrient release in materials designed to respond to such a change in pH. Nanofertilisers are also being developed for both foliar and soil-based application, although the ethical and safety issues in the use of such nanomaterials need to be carefully assessed. In addition, the use of microbial stimulants to enhance the soil/fertiliser/plant interactions as well as other techniques for manipulating the root structure and soil/root nexus are being developed and commercialised.

Research needs

The use of slow- and controlled-release fertilisers, although growing at a rate of around 9% p.a., is still very limited at less than 1% of the global fertiliser market, due to their relatively high cost and inconsistent outcomes with respect to rate of release, despite the potential benefits (Trenkel 2010b). Significant efforts still need to be made (Azeem et al. 2014; Majeed et al. 2015; Trenkel 2010a; Timilsena et al. 2015) in areas such as:

- The development of more cost-effective advanced technologies for the preparation of efficient slow-release fertilisers.
- Understanding the by-products formed from such materials and their associated impacts (e.g. microplastics).
- Understanding the effect of incorporation of micronutrients to address hidden hunger on nutrient use efficiency and plant nutrient uptake in different soils and environments.

- Improved understanding of the mechanisms controlling the pattern and rate of release in soils and the major environmental factors (e.g., temperature, moisture, microorganisms, soil organic carbon content, acidity, soil type, rhizosphere chemistries, etc.) that affect them.
- Improved characterisation of the forms of nitrogen in the soil and their transformations (particularly organic vs. inorganic N and relative plant uptake and use).
- Development of predictive models of nutrient release under laboratory and field conditions, taking into account both the materials and the physical characteristics of the nutrient delivery product (composition, degradability, shape, type of structure (simple matrix, core shell, thin coating, etc.), porosity, diffusibility of the different components and so on) as well as soil-nutrient diffusion and elemental transformation modelling following release.
- Better characterisation of the effect of the plant rhizosphere-fertiliser interactions including the effect of microbial inoculants.
- Overall assessment of the techno-economic and life cycle impacts of alternative fertiliser formulations, processes, and application strategies. Consideration must be given not only to the benefits but also to the potential side effects of the use of novel formulations. Ikeda et al. (2014), for example, reported that the controlled-release nitrogen fertiliser urea-formaldehyde unexpectedly modified the microbial community structure in the phyllosphere of crops, although this change was found to be beneficial in this particular case.

Similar to engineered microbial protein production, it is essential to internalise the environmental costs of conventional inorganic fertilisation. Only then, there will be a sufficient incentive to create a widespread demand for controlled-release fertilisers.

2.3 The Need to Create a Circular Nitrogen Economy

Although substantial improvements can be made by widespread implementation of microbial proteins and slow- and controlled-release fertilisers, the majority of the nitrogen ultimately ends up in waste streams including agricultural by-products, industrial and domestic wastewater. In addition, a large fraction of the food is not being consumed and ends up as food waste (see Sect. 2.3.3 decreasing food waste and opportunities for reuse). Therefore, it is paramount that the development of strategies that allow recovery of reactive nitrogen from these sources will play a decisive role in further decreasing nitrogen pollution.

2.3.1 Nitrogen Recovery from Wastewater

For more than 100 years, the conventional activated sludge process has been implemented and applied successfully worldwide for the treatment of domestic wastewater. This concept is based on treating the wastewater by means of total decomposition of ammonium and organics by biological oxidation to atmospheric nitrogen gas and carbon dioxide by means of the traditional nitrification/denitrification pathway. Short-circuiting this traditional nitrification/denitrification pathway of the conventional activated sludge process can be achieved by using anammox (anaerobic ammonium oxidising) bacteria (Lackner et al. 2014). The latter process has a significantly lower energy footprint than conventional processes and as such is regarded as a step forward for water utilities (Schaubroeck et al. 2015). However, this process does not only dissipates ammonium into harmless N_2, it also generates N_2O, an important greenhouse gas (GHG) responsible for up to ~80% of the total GHG footprint of WWTPs (Kampschreur et al. 2009). In fact, a recent study revealed that N_2O emissions comprised a large share of the overall environmental footprint of wastewater treatment plants (WWTPs) (Schaubroeck et al. 2015). As such, a significant reduction in the carbon footprint and environmental impact of domestic WWTPs can be achieved in cases where ammonium remains in its reactive form and is recovered from the wastewater. While technologies for recovery of reactive nitrogen from wastewater streams are already available, their economics are in most cases still unfavourable (Matassa et al. 2015a, b) with, to date, commercial nitrogen recovery technologies mainly being limited to side-stream processes and some industrial wastewater streams with high ammonium concentrations in the form of struvite (http://ostara.com/nutrient-management-solutions/) or ammonia stripping (http://www.nijhuisindustries.com). In addition to the costs, from an environmental point of view it is equally important that the energy requirements of any alternative strategy (under the worst case scenario) are equal to that of the Haber-Bosch process, in order to become a viable and sustainable alternative source of reactive nitrogen. As described in detail in a recent study by Matassa et al. (2015a, b), the energy consumptions of current state-of-the-art and emerging concepts for ammonium recovery from wastewater are in the majority of cases larger than for the Haber-Bosch process (Matassa et al. 2015a, b).

Challenges and opportunities

Currently, there are no full-scale technologies available that allow mainstream ammonium recovery. The main reason and bottleneck hindering practical implementation of novel concepts is the low ammonium concentrations (i.e. 30–50 mg NH_4^+-N/L) and presence of pathogens in domestic wastewater. As such, a concentration step followed by an extraction (e.g., stripping, electrodialysis, and membrane process) of ammonium from the concentrated stream is needed. The latter extraction process is also crucial, as domestic wastewater constitutes of faecal matter and, as such, a clear barrier is needed in order to ‘distance’ the recovered nitrogen from its faeces-containing origin.

Opportunities for implementation of technologies enabling reactive nitrogen recovery from domestic wastewater: The current situation of our urban wastewater infrastructure offers a unique opportunity; as in many developing countries and emerging economies, new wastewater treatment infrastructure is being implemented at a high rate over the coming decades. The global expenditure in the domestic wastewater market is currently ~$78 billion annually, which corresponds to a value of some €10 per capita per year. In addition, in developed countries many wastewater utilities will need to upgrade their wastewater service infrastructure over the next 10–15 years, which will require enormous capital investments (ASCE 2011). For example, many WWTPs in Europe were built in the 1970–1990 era, implying that their technical and economic lifetime will end from 2020 onwards, creating mid-term opportunities. For emerging markets outside the EU, the growth of population is a key driver for the realisation of new WWTPs. According to the United Nations, the population growth and urbanisation in countries outside the EU will be enormous over the upcoming years, especially in India, China, Africa, Southeast Asia, and South America. The expected global growth between 2015 and 2030 is approximately 1–1.5 billion people. In line with the UN-Water development goals, especially Target 6.2 ("By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations"), the growth of greenfield WWTPs is addressed with an estimated 1000–15,000 greenfield WWTPs going to be realised in the coming 10–15 years.

Opportunities for implementation of technologies enabling assimilation of reactive nitrogen: Many industrial wastewaters originating from the food and beverage industry have the benefit that they are free of faecal matter. In addition, contrarily to domestic wastewater, they normally have much higher organic contents and nitrogen concentrations (see Table 1). The technological challenges to recover the nitrogen are smaller as there is no need to introduce a 'barrier' between the ammonium and the wastewater and as such any ammonium present in the wastewater can be directly incorporated into 'fresh' biomass high in protein. In fact, although it is counterintuitive as ammonium is a pollutant and often the limiting factor in terms of process design and reactor dimensioning, in some cases it would in fact be very useful to supply additional nitrogen (as well as phosphate and micronutrients needed for optimum growth conditions) to the wastewater to promote the production of bacterial protein with high protein content and desired amino acid composition. Indeed, many industrial wastewaters are in many cases ammonium-deficient if one aims to produce microbial biomass rich in protein, as can be seen in Table 1. While not studied much in academic research, in fact the concept of adding nitrogen to wastewater to promote growth of microbial protein is already being commercialised in recent years using heterotrophic bacteria (http://nutrinsic.com/solutions/#food, http://avecom.be/product/promic-microbial-protein).

Pilot cases and ongoing initiatives towards implementation

There are several ongoing initiatives aiming to produce microbial protein from wastewater with and without faecal matter. Examples of the use of organotrophic

Table 1 Overview of industrial wastewater streams free of faecal matter from the food and beverage industry and their COD to nitrogen ratio

Type of industrial wastewater	Chemical oxidation demand (COD) Content (mg/L)	Total N (mg/L)	COD/N[a]	Maximum Attainable Protein conc.[b] (wt%)	References
Dairy	4000	55	100:1.37	17	Kasapgil et al. (1994)
Dairy	4500	60	100:1.33	16	Koyuncu et al. (2000)
Dairy	4000	60	100:1.50	18	Koyuncu et al. (2000)
Dairy	1745	75	100:4.30	53	Koyuncu et al. (2000)
Dairy	18,045	329	100:1.82	22	Arbeli et al. (2006)
Dairy	4000	55	100:1.37	17	Ince (1996)
Dairy	2800	140	100:5	62	Schwarzenbeck et al. (2005)
Cheese	4430	18	100:0.41	5	Monroy et al. (1996)
Yoghurt and buttermilk	1500	63	100:4.2	52	Koyuncu et al. (2000)
Beverage	1750	28.4	100:1.62	20	Amuda and Amoo (2007)
Distillery	150,000	6000	100:4	50	Mohana et al. (2009)
Distillery (molasses)	55,000	4750	100:8.63	107	Vlissidis and Zouboulis (1993)
Distillery (raisins)	57,500	750	100:1.30	16	Vlissidis and Zouboulis (1993)
Distillery (wines)	27,500	650	100:2.36	29	Vlissidis and Zouboulis (1993)
Distillery (figs)	35,400	880	100:2.48	31	Vlissidis and Zouboulis (1993)
Brewery	4000	52.5	100:1.31	16	Driessen and Vereijken (2003)
Sugar industry (beet)	6300	53.23	100:0.84	10	Güven et al. (2009)
Olive oil mill	40,000–220,000	300–1200	100:0.54 –100:0.75	6–9	Azbar et al. (2004)
Olive oil mill	40,000–195,000	500–15,000	100:0.77 –100:1.25	9–15	Sierra et al. (2001)
Palm oil mill	50,000	750	100:1.5	18	Ahmad et al. (2006)

[a] Note that in almost all cases nitrogen is deficient

[b] Aerobic yield coefficient = 0.5 g COD (biomass)/g COD (removed); N-to-protein conversion factor = N × 6.25

One kg of COD corresponds with about 1 kg or organic matter (sugar, protein, lignocellulose, dry weight)

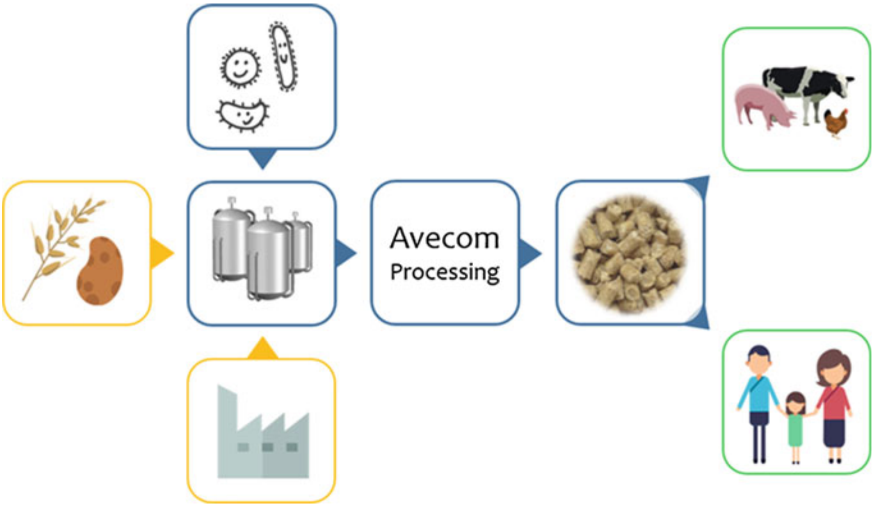

Fig. 3 Avecom's patented process foresees the production of microbial protein from food production side streams, and can make use also of other industrial side streams rich in nutrients and organic carbon. *Source* Personal communication Avecom

production of bacteria directly from wastewater originating from food and beverage processors are e.g., the "ProFloc" concept (http://nutrinsic.com/solutions/#food) and the "Promic" (http://avecom.be/product/promic-microbial-protein) concept by Avecom. Both concepts are patented technologies and are based on direct assimilation of nitrogen (and phosphate) present in wastewater by a mixed culture of heterotrophic bacteria. Nutrinsic currently declares a production of 5000 t/y of its final product from brewery process water, whereas Avecom currently declares a production of 5000 t/y from potato process water (see Fig. 3 for a conceptual diagram of the concept). Importantly, in cases where nitrogen (as well as phosphate and micronutrients) are limited, they can be added to optimise the protein content and amino acid composition.

Another recent imitative is the production of microbial protein from domestic wastewater, the so-called 'Power-to-Protein' concept (https://www.powertoprotein.eu/). The key difference is the need for a clear and robust barrier between the nitrogen and the wastewater. The organics present in the wastewater are used to produce biogas, which is further upgraded to hydrogen gas used by microbes for the production of microbial protein. Rather than using Haber-Bosch to provide ammonium for bacterial growth, ammonium recovered from the wastewater is used as nitrogen source. Figure 4 shows a schematic overview of this concept.

Research needs

While significant research efforts have focussed on the development and use of efficient sorbents like zeolite or ion-exchange resins for the 'up-concentration step', as reviewed previously (Wang and Peng 2010; Hedström 2001), their use has not found widespread application in the context of domestic wastewater treatment as yet.

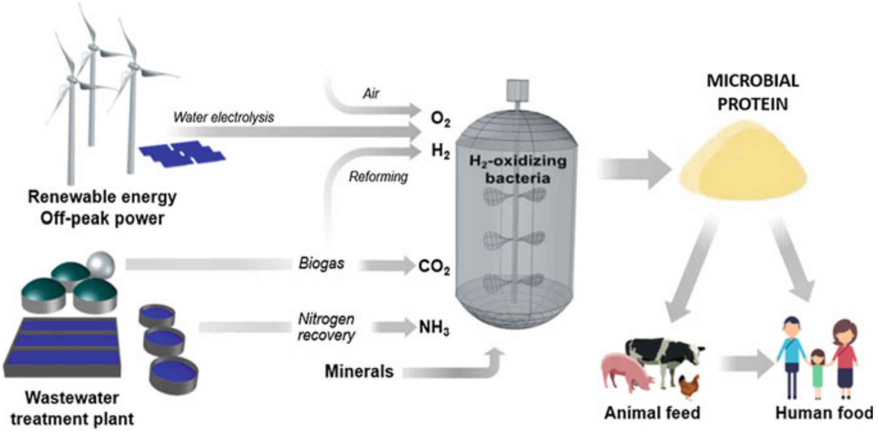

Fig. 4 In the "Power-to-Protein" project the nitrogen recovered onsite of a WWTP is converted into microbial protein by means of hydrogen-oxidising bacteria. The other substrates needed are recovered from biogas (CO_2 and H_2) or produced onsite by electrolysis (H_2 and O_2)

The reason for the latter is not so much related to the capacity to adsorb the ammonium, but related to (i) the occurrence of inorganic scaling (i.e. calcium and magnesium) and biofouling which ultimately leads to a severe reduction in ion exchange capacity; (ii) the need for chemicals (i.e. salt and caustic) for the regeneration step; (iii) the relatively high energy requirements for the subsequent ammonia stripping step (i.e. during the regeneration process the ammonium concentrations are only concentrated up to around 1000–1500 mg NH_4^-N/L (Cooney et al. 1999)); and (iv) the high costs and limited service life of ion exchange resins and zeolite. The abovementioned critical operational constraints negatively affect the process stability and economic viability and as such have hindered their practical implementation for domestic wastewater treatment so far. The challenge will be to develop cost-effective sorbents and ion-exchange resins that can overcome these abovementioned limitations. In case the recovered nitrogen is upgraded at the WWTP into microbial protein, substantial research efforts are needed in this context similar to that of direct upgrading of Haber-Bosch nitrogen into MP as described in detail in Sect. 2.1.

2.3.2 Recovery/Reuse of Nitrogen from Biosolids

The incorporation of wastewater sludge into soils and the use of animal manures (either through direct deposit by animals or by collection and spreading) to provide plant nutrients and build soil quality are long-established and important techniques (Buckwell et al. 2016). However, especially for biosolids and manure in particular, this is not without concern and there is considerable scope to improve the efficiency of recovery and reuse of the biosolids and manure in a more sustainable way. Despite the beneficial reuse of nutrients, the intrinsic properties of manure and biosolids also come with some environmental and human health risks that severely restrict the direct reuse as a viable and sustainable solution in the long term.

First is the occurrence of massive nitrogen losses related to improper storage and handling (Gopalan et al. 2013). In the EU, for example, the nutrient use efficiency for nitrogen in the livestock sector overall was estimated to be only around 18% due to the large amount of leakage from the collection, storage, and subsequent spreading of manure and animal slurry produced by livestock (with this representing ~81% of the nitrogen outputs from the sector) (Leip et al. 2014). This leakage can be in the form of volatilisation to form nitrogen and major greenhouse gases such as nitrous oxides, or as leachates and run-off, which deliver excess nitrogen into waterways causing eutrophication (Davis and Koop 2006). Second, there is an imbalance between the N-to-P ratio in manure and crop requirements; this leads to poor uptake of nutrients resulting in leaching of nitrogen and phosphorus. Third, there is increasing concern that the use of antibiotics in livestock, of which a fraction ultimately ends up in the manure, results in an accumulation of antibiotic-resistant bacteria in agricultural soils (Udikovic-Kolic et al. 2014; Singer et al. 2016; Zhu et al. 2013; Hartmann et al. 2016). The long-term implications of these findings are yet to be determined but should not be taken lightly. Fourth, there is a growing concern regarding heavy metal contamination in soil due to the application of wastewater sludge as a soil conditioner (Khan et al. 2008). Toxic metals present in wastewater sludge such as Cd, Cr, Cu, and Zn are persistent in soil and accumulate over time; this limits the land application rate and therefore reduces the capacity of available land to receive the sludge, particularly for repeated applications (Du et al. 2015; Pritchard et al. 2010). In this context, local land availability is already becoming a limiting factor and transport costs for land application are increasing. In addition, the presence of a large variety of persistent organic pollutants as well as pathogens that could potentially threaten the health and safety of soils is under increasing scrutiny (Westerhoff et al. 2015).

It is clear that in order to find a long-term solution, alternative management strategies are needed; ones that allow the recovery of nitrogen (and the other valuable nutrients) from the manure and biosolids (rather than direct application) while eliminating issues related to toxic metals, pathogens, antibiotic-resistant bacteria, and persistent organic pollutants. In addition, it is crucial to recover the nitrogen in clean and concentrated forms that are safe, easy to store, handle, and use by farmers, and which reduce current N leakage due to nutrient volatilisation and leaching.

Challenges and opportunities

On the storage and handling side, there are surprisingly straightforward modifications that can be made by farmers to deliver immediate improvements to on-farm efficiency including (i) the use of chemical amendments (e.g., aluminium sulfate) that acidify manures in order to reduce emissions of methane and ammonia, although care is needed to avoid any associated toxicities from the use of such amendments; (ii) reducing the area of exposed soils and stripping of ammonia from air in buildings housing animals; (iii) covering of manure storages to prevent both volatilisation and dilution by rainwater; (iv) avoidance of long-term storage of solid manures; (v) the use of chemicals and polymer amendments for manures and effluents that can limit nitrogen losses once these are applied to land; (vi) the use of more precise methods for manure spreading on land, such as adding liquid manure in narrow bands or injecting into the soil—strategies that can result in 40–90% reduction in NH_3 emissions and limit surface run-off; and (vii) appropriate timing of this manure spreading, taking into account crop demand, soil type, and climate (ECOSOC 2014; Rotz et al. 2011; Moore and Edwards 2007).

On the nitrogen recovery side, there are many challenges in recovering nitrogen from manure and biosolids generated in intensive agricultural industries. First, and by far the most important challenge, is the high moisture contents (i.e. often well above 70 wt%). This results in (relatively) low nitrogen concentrations, and as such makes efficient and cost-effective recovery of nitrogen economically challenging (Mehta et al. 2016; Wuana and Mbasugh 2013). Second, they are highly variable in composition, typically have high carbon contents, and contain large amounts of organic materials (e.g., carbohydrates, proteins, fats, oils). Third, the quality and consistency of the recovered nitrogen, in case of reuse as alternative fertiliser product, always has to closely resemble chemical fertilisers (Rahman et al. 2014). As such, one issue will be maintaining consistency of product, including physical and chemical properties, given the variability in starting materials. As with fertilisers, these products should be used in accordance with the 4R's of Nutrient Stewardship: i.e., they should be analysed to determine plant available concentrations of N, P, and other nutrients, applied at the right time, at the right rates (to meet crop requirements), using the right method, in order to minimise losses during and after application. Fourth, it is often very difficult to cost-effectively recover nitrogen at a practical relevant scale in the current market landscape: ammonia is a fairly cheap bulk commodity that can be produced by the Haber-Bosch process in large quantities at a constant quality and composition.

Pilot cases and ongoing initiatives towards implementation

One of the most well-established technology that has been implemented successfully (Qureshi et al. 2006; Shepherd et al. 2009; Dube et al. 2016; Yetilmezsoy and Sapci-Zengin 2009) is anaerobic digestion to generate biogas that can be directly used onsite (Edwards et al. 2015; Mehta and Batstone 2013). The nitrogen can subsequently be recovered from the digestate, through processes such as struvite crystallisation and ammonia stripping (Mehta et al. 2015). Both struvite crystallisation and ammonia stripping are applied at full scale with various full-scale installations worldwide. Struvite crystallisation, however, is not very efficient for ammonia recovery, normally delivering only 20–30% efficiency. Ammonia stripping can achieve very high recovery efficiencies, but requires substantial energy input that is in many cases higher than the energy demand of the Haber-Bosch process. As such it is debatable whether this can be considered a better and more sustainable option. It is also possible to separate slurries into fractions of different nutrient composition (e.g., a fraction rich in N and potassium (K) and a solid fraction rich in carbon and P), leading to the possibility of tailoring N, P, and K nutrient addition to match crop demand (Velthof et al. 2012; Oenema et al. 2012). Finally, it is possible to obtain a concentrated solution of N and K ('mineral concentrate') from manure processing through the use of reverse osmosis of the liquid fraction of separated livestock slurry. This concentrate is typically comprised of ammonium-N (92%) and organic N (8%) (Velthof et al. 2012). A recent initiative and award-winning technology that has sought to integrate many of these developments together is the so-called GENIAAL concept (http://www.nijhuisindustries.com). This manure treatment process involves multiple integrated stages, including the anaerobic digestion of stored manure for biogas and digestate production, then the use of a decanter/centrifuge for solids/liquids separation of a digestate/manure blend followed by flocculation and dissolved air flotation to separate out residual solids before nitrogen stripping of the liquid stream to produce ammonium sulphate fertiliser. Membrane filtration (ultrafiltration and reverse osmosis) of the residue delivers a potassium-rich fertiliser product as well as a clean water stream. This process has a low chemical usage and at present can treat approximately 50,000 tons of manure annually.

Research needs

In the last decades an enormous amount of research has been conducted in the recovery/reuse of nitrogen from agricultural by-products, as outlined above. In fact, similar to the industrial production of microbial protein (Sect. 2.1) many of the recent technological initiatives were already developed and trialled in the 1960s–70s. From a purely technological point of view, a suite of proven technologies is readily available as described above. However, there is still a large amount of work to be done. Not least of this is in the area of techno-economic evaluation. Assessments of the economic feasibility of the emerging technologies and/or established strategies, alone or in combination, should be made in light of local and global economic drivers. These techno-economic evaluations should also take into account the externalities of nitrogen pollution to verify what level of incentives and/or penalties for nitrogen inefficacies are needed to stimulate innovation and rapid market uptake of new technologies. In parallel, further investigation into the impact of type of nutrient delivery product (e.g., organic vs. inorganic, dilute vs. concentrated, etc.) on e.g., plant nutrition, nitrogen losses, soil carbon, and soil acidity, will require significant research efforts.

2.3.3 Decreasing Food Waste and Opportunities for Reuse

According to recent reports of the United Nations, about 1.3 billion tons of food each year is being wasted, which equals to about one third of the world's food production on a mass basis (Chaboud and Daviron 2017; FAO 2013) and about a quarter when expressed in kilocalories (Kummu et al. 2012). The latter does not only come with serious economic consequences, estimated to be of the order of $750 billion on an annual basis, but it also comes with significant damage to the environment in terms of e.g., nitrogen pollution and carbon emissions. In terms of the amount of nitrogen embedded within this food waste, this is estimated to be in the order of 5–15 million tons annually (Matassa et al. 2015a, b; Bodirsky et al. 2014; Grizzetti et al. 2013). In developing countries, almost half of the losses comprise post-harvest and processing losses due to non-optimal transport and storage conditions, while on the other hand, in developed countries, losses are more significant at the consumer/retailer level (i.e. >40%) (Gustavsson et al. 2011). In a recent study, it was revealed that meat accounted for 50% of all the nitrogen emissions associated with food waste in the EU (Grizzetti et al. 2013). Considering that current livestock production only has a nitrogen efficiency of a mere 14% (Galloway and Cowling 2002), it is clear that lowering meat waste represents a key lever in achieving a more nitrogen-efficient food supply chain. To illustrate this, Kummu et al. (2012) found that 25% of the total fresh water withdrawals, 20% of cropland use, and 20% of fertiliser added to the land for the production of food crops, ultimately ends up as part of food wastage (Kummu et al. 2012). Thus, it is evident that independent of the technological advances we can make in the future, we will have to drastically reduce the enormous amounts of food wasted globally.

A large fraction of food waste is comprised of perishable fresh fruits and vegetables (Parfitt et al. 2010), which can be directly reused for agricultural purposes in the form of compost. However, this is still considered a non-optimal and low-value reuse option. Therefore, major efforts are needed to find a better end-use for fruit and vegetable waste. Of particular interest is the use of Black Soldier Flies (*Hermetia illucens*, BSFs) that can efficiently convert food waste into a source of protein and fat that can be used as animal feed or aquaculture as a replacement of fish meal and soy (Kiser 2016; Józefiak et al. 2016; Henry et al. 2015; Makkar et al. 2014). Very importantly, BSFs have been officially recognised as an animal feed supplement. In recent years, various companies have successfully been founded and commenced business. Alternatively to food waste, BSFs can also be effectively grown on manure (Li et al. 2011). From a process technological point of view, there seem to be no critical bottlenecks that would hinder large-scale implementation in the mid-near future. The critical aspect would be more related to quality assurance from a food safety point of view; there is always the risk of contamination and bioaccumulation due to carryover of pesticides, pathogens, and antibiotics in the manure, similar to the risks for the presence of antibiotic-resistant bacteria in the soil associated with addition of manure as an organic fertiliser (Udikovic-Kolic et al. 2014; Marti et al. 2013). As such, special care should be taken and long-term research efforts are needed to ensure that there is no danger for contamination and bioaccumulation when used as animal feed when using manure as energy source for the black soldier flies. Important to note is that considering the simplicity of the process, the use of BSFs may hold great promise, especially for developing countries, where there is often a lack of skilled people and sufficient investment opportunities for larger and more complex infrastructure that would allow for the production of microbial protein.

It is evident that independent of the expected continuous technological advances and progress in the future, a key challenge will be to drastically

decrease the enormous amounts of food wasted globally. The latter requires a change mind set of all of 'us' as retailers/consumers.

3 Re-engineering the Nitrogen Cycle in the Context of Sustainable Development Goals

We have highlighted various engineering solutions that can have a profound impact on the nitrogen-water-waste-energy nexus. Although significant research efforts are needed in the years ahead, in fact the scientific breakthroughs and technological developments that have been made in the last decades together with the ongoing research and initiatives mean that at present the technological capabilities are sufficient to address the nitrogen-water-waste-energy nexus in the context of SDGs to a large extent if widespread implementation of these innovations can be achieved. The efforts that need to be made may in fact be even more important than the technological challenges and research needs ahead.

Policy change drives innovation: While, in theory, the goal for economies is no longer simply to maximise productivity, but to optimise across a far more complex landscape of production, environmental, and social justice outcomes (Godfray et al. 2010), in reality this is often still not the case, with decisions made purely for economic reasons. Policymakers will play a crucial role in driving innovation. While we acknowledge that policy aspects and introduction of new policies and/or legislation are difficult to assess and implement, there are ample examples of cases where policy changes have created a widespread change or introduction of alternative more sustainable solutions. Some examples are e.g., the Montreal Protocol on Substances that Deplete the Ozone Layer, which banned the use of e.g., Chlorofluorocarbons, Hydrochlorofluorocarbons and Hydrofluorocarbons, and prohibiting the use of leaded gasoline. More recently, the Paris Agreements have stimulated governments to reduce their carbon emissions. However, there is still no global international convention that defines targets for better management of global nitrogen and nutrient cycles (Sutton et al. 2013). We therefore argue that there is an urgent need for the introduction of a nitrogen tax (very similar to the carbon tax as agreed upon in the Paris Agreements on climate change). These policies and instruments need to be streamlined across levels to allow effective governance in line with a nexus approach (Hoff 2018, Chapter "Integrated SDG Implementation –How a Cross-Scale (Vertical) and Cross-Regional Nexus Approach Can Complement Cross-Sectoral (Horizontal) Integration").

Customer acceptance and the power of marketing: A key factor beyond the technological challenges will be to promote (i) industrially produced microbial protein as an alternative source of protein for animal feed and human consumption, (ii) the acceptance of waste as a viable and valuable source of nitrogen, and (iii) adequate and effective marketing strategies of any innovative technology developed. Technologies that recover nitrogen, rather than dissipating it, may have the added benefit of potentially engaging the public in a positive sense. If the public perceives a benefit in turning waste into a valuable resource that preserves or increases the quality of life while at the same time aiding the environment, they are more likely to be receptive to the technology. It is therefore important to attract public interest and to promote novel technologies as viable and sustainable solutions. Incisive dissemination strategies that include local actors, potential end-users, policy relevant assessments such as the IPCC, UN, and the general public are needed, with the ultimate goal achieving widespread implementation of these technologies.

Cultural considerations: In general, society has a positive attitude towards technologies that support environmentally-friendly processes. However, attention will have to be paid to providing sufficient information regarding the quality of the treated wastewater and/or waste, the safety and social acceptance of the obtained product, and the overall sustainability of the process. Special attention needs to be given to providing detailed and accurate information on the quality and control strategies in place to assure that a high-quality product is achieved at all times, especially when dealing with product recovered from what is considered a waste stream. To further reduce the societal barriers, the recovered products can be used for different purposes in different countries with less stringent quality requirements. Finally and foremost, very detailed attention will have to be given to cultural attitudes. Depending on the application and origin of the recovered nitrogen, many objections can and will be raised by certain cultural-religious groups and these concerns will have to be respectfully addressed in a proper way. The strategy will need to consist of providing open and transparent communication, involving consumers and policymakers as stakeholders at an early stage and gradually gaining confidence in the context of quality assurance of the recovered products.

4 Conclusions and Outlook

Assessments to develop a detailed trajectory of global development up to at least 2050 and beyond are full of uncertainties. However, it is beyond doubt that mankind will continue to further increase pressure on the global nitrogen cycle with ever-increasing industrial production and inefficient use of Haber-Bosch nitrogen in the food supply system. In order to find a long-term sustainable solution for the nitrogen nexus, we ultimately need to return to the nitrogen cycle as evolved before the industrial revolution; i.e. where for every mole of nitrogen entering the biosphere as reactive nitrogen, a substantial amount of CO_2 carbon was and now again has to be captured. Here we have highlighted engineering and biotechnological opportunities to achieve the latter and have set forward a list of actions that hold the potential to significantly lower the human nitrogen footprint while meeting the future global food. In particular, the use of industrially produced microbial protein as an alternative to plant-based and meat-based protein will become a crucial component of our food supply, as it is evident that the contemporary agricultural-based food supply chain alone will not be sufficient. Indeed, there are still more than a billion people that are undernourished due to lack of Haber-Bosch nitrogen; which needs to be addressed without delay. While we have the opportunities of revisiting contemporary agriculture, much work remains to be done in order to actively put it into action. Agriculture has been labelled as 'history's biggest fraud' (Harari 2014) and the massive use of Haber-Bosch nitrogen certainly is a compounding factor in this. To redress the situation, it is critical that Homo sapiens embark on a new project in which far-reaching policies are developed by governments that place a strong emphasis on planetary concerns, i.e. integration of sustainability policies with economic governance (Biermann et al. 2012). It also requires a correct dialogue with the society at large to inform them about the importance of addressing the third-ranked planetary boundary. First and foremost, the focus should be on industrialised countries, which should take the lead in internalising the full costs of reactive nitrogen. Another critical factor will be a radical shift in people's attitude in order to decrease the amount of food that is wasted annually. Subsequently, industrialised countries should examine the potentials of industrial produced in-reactor microbial protein as an alternative protein source. Clearly plenty of formidable opportunities are awaiting along that line both in terms of process engineering efficiencies and added value generation via the upgrading of mineral nitrogen into high value food proteins (i.e. with a high and targeted functionality and with the desired properties such as aroma, taste, and texture). Only if all of the above can be addressed in parallel, will we start to fix the 'Nitrogen imbalance' and it will be possible to work towards the Sustainable Development Goals and to provide mankind with food in a way that opens perspectives for a healthy society on a planet capable to provide for future generations to come.

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Participatory Processes and Integrated Modelling Supporting Nexus Implementations

Alex Smajgl

Abstract Policymakers and donors are increasingly requesting researchers to investigate the water, food, and energy nexus. This is largely due to the investment risks in the form of unintended side effects causing trade-offs between these three highly connected sectors. Applying nexus approaches requires researchers to step from a pure conceptualisation of the water, food, and energy nexus to nexus implementations that effectively inform policy and planning processes. Nexus implementations, however, come with two major challenges. One challenge is the development of diagnostic and analytical tools that may be applied to (at least) three sectors in an integrative way, which would allow us to investigate cross-sector dynamics. The second challenge is concerned with stakeholder engagement during the implementation, as nexus-related decision making processes involve competing sector interests. Facilitating evidence-based policy negotiation demands research processes to effectively bridge science and a highly contested policy space. This paper explores solutions for these two challenges and presents new and refined approaches to support the implementation of the water, food, and energy nexus in real world planning and policymaking contexts. Nexus implementations can utilise agent-based modelling to simulate possible nexus trade-offs. Bayesian approaches, on the other hand, can quantify probabilities of expected outcomes. Despite the increase in analytical complexity, stakeholder learning and policy uptake can be achieved through participatory processes, using various types of process designs. Robust monitoring and evaluation of research process designs is paramount for improving our ability to effectively implement complex nexus approaches in applied policy contexts.

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1 Introduction

Many assessments of economic development strategies reveal substantial trade-offs between key economic sectors (Bazilian et al. 2011; QEERI 2012). Investments in the energy sector that aim to meet the growing demand for energy trigger in many cases a decline in food security or changes in water availability. Equally, food security-focused interventions can have implications for the energy sector and for water-related issues. Also, water management-focused improvements can impact on food and energy-related goals. These experiences highlight the need for assessments to consider the interactions between these three sectors. With the increasing awareness of the cross-sector connectivity the water, food, and energy nexus emerged as a new paradigm. Increasingly, policymakers and donors demand researchers to apply the nexus paradigm. This is largely due to the risk decision makers perceive in the form of aforementioned potential for trade-offs and synergies between these three highly connected sectors.

Over the past few years numerous papers have been published that present a conceptualisation of the water, food, and energy nexus (i.e. Hoff 2011; Smajgl and Ward 2013a; WEF 2011). However, fewer studies document an application of a nexus concept to a real world case (European Report on Development 2012; Mohtar and Daher 2012) and even fewer studies implemented the applied nexus analysis as part of a policy negotiation (Smajgl and Ward 2013c; Smajgl et al. 2016). Yet, the policy space is where the demand for a Nexus Approach originates from and to which scientists need to present their empirical nexus analysis. Despite the rapid uptake of the nexus paradigm, the implementation of a Nexus Approach is difficult as it introduces two major challenges (Smajgl et al. 2015b). The first challenge is to develop diagnostic and/or analytical capacity that allow for integrated assessments of the water, food, and energy sectors and their relationships in an empirical policy setting. This requires the consideration of many complex dynamics, which defines a methodological challenge. Second, the division of the policy space into sectors or line ministries constitutes competing interests. For scientists to provide evidence to such a contested value space is the second major challenge. The dominant outcomes are for scientific results to either be accepted if they match pre-existing opinions or for them to be disregarded if they contradict prevailing expectations. The challenge is to facilitate evidence-based decision making despite contradicting stakeholders expectations. This challenge is concerned with the design and management of the research-policy interface and the study-related engagement process.

This paper discusses new and refined solutions for these two major policy-related challenges to support the implementation of a Nexus Approach. First, integrated modelling methods are discussed that help investigating cross-sector dynamics. Second, processes are presented that aim to effectively bridge the science-policy gap in complex and contested contexts.

2 Analytical Methods Conducive to Effective Nexus Implementations

The challenge of integration has been a focus of scientific work since the emergence of the sustainability paradigm in the 1980s (Argent et al. 1999; Ascough Ii et al. 2008; Brouwer and van Ek 2004). The Nexus Approach builds on the sustainability commitments of many governments but is more focused on the water, food, and energy sectors (Hoff et al. 2012; WEF 2011). These sectors have been identified as critical for development processes and susceptible to costly trade-offs if investments and their side effects are not carefully assessed. Many investments in one sector can trigger losses or synergies in other sectors.

Most methods deployed during nexus studies have a disciplinary focus, which means that cross-sector trade-offs and synergies are not part of the analytical scope of the calculation or simulation. In these cases, sector-specific results need to be further processed to reveal trade-offs or synergies. Typically, this can be achieved by qualitative methods such as expert panels. For instance, Smajgl and Ward (2013c) designed an expert panel approach that asked disciplinary experts to identify first-order impacts of a variety of disciplinary modelling results. Then, the first-order impacts were presented and experts were asked to identify which impacts are likely to result in consequence. Then, these secondary impacts were again presented and experts were asked to identify tertiary impacts. The combination of first, second, and third-order impacts provided inputs for the development of system diagrams that specified the mechanisms that constitute cross-sector relationships. This approach established (qualitatively) how nexus sectors interact and how these relationships might change over time. Ultimately, the strength of such an approach is to highlight critical factors (or system elements) policy and planning could focus on.

Such qualitative methods allow experts to design likely cause-effect relationships, the specification of risks, and the identification of thresholds. However, the weakness is that complex cross-sector dynamics would not be considered and would require model-based assessment. This could be achieved by combining qualitative methods with disciplinary modelling or with integrated modelling.

Here, nexus-focused scholars can build on many advances sustainability research has made. The sustainability paradigm has guided substantial research towards integrated assessment, including the consideration of multiple sectors and their disciplinary indicators (or variables) (Alvargonzález 2011; Hirsch Hadorn et al. 2006). These methods include agent-based modelling, system dynamics modelling, and Bayesian Belief Network, to name three of the most widely applied methods. Any of these approaches can be combined to cover different types of research questions (e.g., stochastic, deterministic, probabilistic), or assess variables at multiple scales and their scale-specific resolution (Smajgl 2006; Smajgl et al. 2009).

In this paper, particular attention is dedicated to agent-based modelling because of its potential for nexus-type research. The need to improve our understanding of complex social-ecological dynamics created a substantial push for agent-based modelling due to its ability to consider highly complex relationships of multiple variables, including human behaviour (Barreteau and Smajgl 2013; Gilbert 2008). In particular its capacity to incorporate social dimensions creates a methodological advantage over most other modelling techniques (Edmonds et al. 2007; Squazzoni 2010). In an applied policy context, sustainability-focused simulations often require the explicit modelling of social, economic and environmental interactions and feedbacks, which implies mostly non-linear relationships (Edmonds et al. 2007; Wuelser et al. 2012). From a modelling perspective this goal requires the definition of functional relationships in the form of logical rules (behavioural and social variables) and in the form of mathematical equations (biophysical variables) (Axelrod et al. 2006; Gilbert 2008).

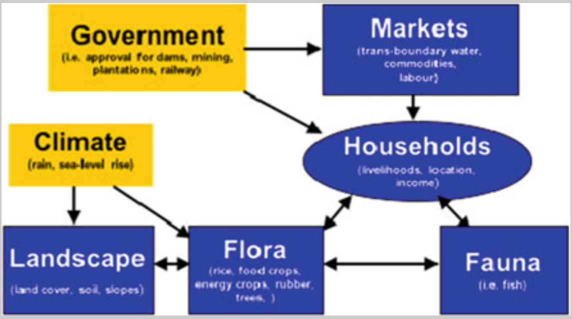
Nexus-focused assessments benefit from these modelling advances as many outcomes regarding water, food, and energy emerge from the bottom up as a result of decision making and interactions of many households. Water demand is often dependent on decisions made by individual farmers that perceive and respond to a variety of factors (i.e. crop prices, water price). In urban settings water demand results from a set of other factors, including habits, type of appliances, or water prices. Energy use depends on similar factors, while energy production is largely a consequence of corporate investment calculations and institutional arrangements. Food production in rural settings is linked to similar factors as water but experiences show a decline due to the increasing profitability of energy crops. All these influencing factors have in common that the decisions are being made by individuals, households, or companies based on what they perceive as effective incentives or constraints. Increasingly, the modelling community acknowledges that designing such modelling efforts from the bottom up is paramount for analysing nexus outcomes and trade-offs.

This requires modelling methodologies that allow for the explicit simulation of human decision making, which is a distinct advantage of agent-based modelling as it allows for the simulation of individual or households and their interaction with the environment (Smajgl and Barreteau 2017; Smajgl and Bohensky 2013). Behavioural rules can be derived from psychological understanding, experimental or monitoring-based evidence for behavioural responses to economic and other incentive changes, and other empirical or theoretical assumptions on human behaviour and adaptation (Smajgl and Barreteau 2013b, 2017). Uncertainties can easily be integrated by defining parameters in ranges instead of point values to capture possible or experienced fluctuations (Barreteau and Smajgl 2013; Müller et al. 2014). The development of such a genuinely integrated agent-based model can draw on widely tested approaches for model parameterisation (Doscher et al. 2014; Smajgl and Barreteau 2013a, 2017), model calibration (Beaudouin et al. 2008; Bohensky et al. 2007) and model validation (Moss 2008; Smajgl et al. 2011).

Many agent-based models have been developed since this methodology emerged in the 1970s and in particular since it started establishing itself in the empirical policy analysis space in the 1990s. One example for an agent-based model that was implemented to support policy-driven nexus studies is the MerSim model, the Mekong region Simulation model (Smajgl et al. 2013), see also Box 1. MerSim was utilised during various policy-focused studies to reveal nexus-related trade-offs and outcomes (Smajgl et al. 2015a, b). Three nexus studies should illustrate the potential of agent-based model. First, the MerSim model was implemented to assess cumulative impacts of Mekong mainstream dams and climate change (i.e. changes in rainfall patterns and sea-level) on rice production, poverty, and migration in Vietnam's Mekong Delta (Smajgl et al. 2015a). Policy outcomes included changes in land-use planning to improve resilience to upstream developments and to sea-level rise. This example explicitly focused on energy (mainstream dams), food (rice production and fish), and water (flow and salinity levels), and provided effective analytical capacity to investigate nexus dynamics for different investment and under different conditions (see for more details, results and policy impacts Smajgl et al. 2015a, b). In another application, MerSim revealed land-use change dynamics in Northeast Thailand involving commodity price-driven decisions at the farm level to replace food crops (mainly rice) by energy crops (cassava and sugar cane) (Smajgl et al. 2015b). These farm-level decisions are either accelerated by government investments in water diversion infrastructure for large-scale irrigation schemes or generate water demands that result in decentralised irrigation. This case portrays another typical nexus situation, which resulted in substantial policy changes concerning large-scale irrigation plans due to the unexpected outcomes the simulation model suggests. In a third policy-focused nexus application the MerSim model was implemented to the Nam Xong sub-catchment in Lao PDR to investigate trade-offs between upstream water uses (mining and rubber plantations), and downstream water uses (agriculture, tourism, and hydropower) (Smajgl and Nuangnong forthcoming). Similar to the Vietnam study, this implementation of the Nexus Approach included water quality indicators as well as water quantity indicators. As a result of this study land-use plans were adjusted and investments in improved water treatment are being negotiated. All three MerSim applications were implemented as part of participatory processes to facilitate stakeholder learning and policy uptake (see ChaRL process—Challenge and Reconstruct Learning process—described in Sect. 3).

Box 1: MerSim model details

The description of the agent-based model Mersim (Mekong region simulation) (Smajgl et al. 2013) follows the ODD (Overview—Design concepts—Details) protocol (Grimm et al. 2006; Grimm et al. 2010).



Purpose of the model: MerSim aims to support the analysis of complex social-ecological interactions.

State variables (selected): Household income, Household livelihood, Household location, land cover, subsistence production and poverty rate, water flow, water quality, food commodity production, hydropower.

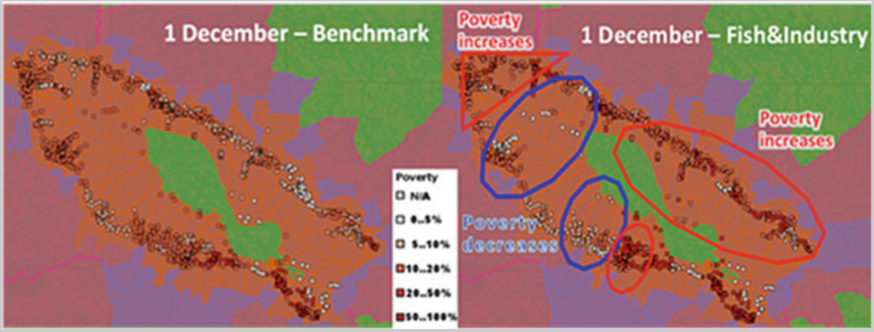
Emergence: Poverty dynamics, spatial poverty patterns, livelihood changes, and land use patterns.

Adaptation and Objective: Household agents respond to changes in the socio-ecological system that affect their livelihoods. Hou seholds' objectives are implicit to their behavioural response functionsthat is derived from intentional data elicited in the large-scale surveys.

Stochasticity: Most parameters are assumed to be stochastic to resemble more realistic model assumptions, including crop prices, productivity, wages, and rainfall.

Initialisation: The MerSim model utilises five sets of GIS data: (1) administrative boundaries down to administrative villages, (2) soil data, (3) land cover data, (4) rainfall projections, and (5) a digital elevation model. These datasets were used to specify the artificial landscape while household attributes and behavioural responses were parameterised based on the household survey.

Submodels: Household income is calculated in weekly steps as the sum of all livelihood activities that all household members engage in. Crop growth algorithms are defined for 16 crop types. Water flow algorithms



The diagram above shows MerSim outputs from a Nexus analysis, which assessed impacts of upstream hydropower on fish population in the Tonle Sap. This scenario includes climate change and government investments in alternative manufacturing focused investments. The poverty maps (dots are villages; increasing red pigment indicates increasing poverty) show the spatial shifts of poverty in Cambodia's Tonle Sap area.

The MerSim applications demonstrate how effectively agent-based modelling can support nexus implementations in real world policy and planning contexts. Unfortunately, so far, no other empirical agent-based model has implemented the water, food, and energy nexus comprehensively. However, many partial nexus applications have been developed as agent-based models, primarily for energy-water analyses (Ng et al. 2011; Santhosh et al. 2014) and for water-food focused analyses (Becu et al. 2003; Sahrbacher et al. 2014; Valbuena et al. 2008).

Agent-based modelling is not the only promising method. Other advanced techniques include games, Bayesian Belief Networks, and hydro-economic models. Several research groups have explored very successfully the effect of *serious games* (see also Mochizuki et al. 2018, "Games for Aiding Stakeholder Deliberation on Nexus Policy Issues") as a method to facilitate stakeholder engagement and stakeholder negotiations (Annetta 2010; Barreteau 2003; Wood et al. 2014). Such games can be designed as computer games, board games, or as role-playing games that target improved systems understanding among stakeholders or to make stakeholder better understand each other's actions by taking on each other's role (Annetta 2010; Barreteau 2003; Zellner et al. 2009). Considering the relevance of conflict, negotiations, and complexity in nexus-type situations, serious games are likely to offer substantial potential to reduce nexus trade-offs and achieve more sustainable outcomes. Many approaches that utilise serious games in participatory processes combine this with, for instance, agent-based modelling.

Bayesian Belief Networks (BBN) provide a different approach to agent-based models. With this modelling technique probabilities can be quantified for expected consequences (Lynam 2016; Sun and Müller 2013). This provides an effective tool if the goal is to quantify the probabilities or risks of specified outcomes (Lynam 2016; Lynam et al. 2007). However, only a few BBNs have been implemented in nexus studies (Biggs et al. 2015; Varis et al. 2012).

Considering that the nexus discussion is largely driven by hydrologists (see discussion in Smajgl et al. 2016), an emerging approach involves the extension of hydrological models by economic variables. Hydro-economic models integrate hydrological variables and their physical dynamics with the economic value of water considering the economic value of water uses (i.e. crops) (Harou et al. 2009). A growing number of hydro-economic models have been developed for the analysis of (mostly partial) nexus trade-offs (He-Lambert et al. 2016; Mainuddin et al. 2011; Singh et al. 2014).

Any of these methods has a specific focus and the complexity of many contexts require the combination of multiple methods, which is often coordinated in so-called decision support systems (DSS). Since the 1970s and in a rapidly increasing number of contexts, stakeholders invest in the development of such DSS (Mysiak et al. 2005). A typical application domain of an environmental DSS is a watershed to help improve water management considering competing water demands (Andreu et al. 1996; Giupponi 2007). These developments facilitated a stronger focus on cross-sector and cross-disciplinary integration and, thereby a broader understanding of emerging data gaps. While this movement is very promising, many of these computer modelling-supported processes are not achieving expected policy outcomes (Loucks 1995; Matthies et al. 2007). In many cases this results from the fact that the DSS development process is driven by modellers, largely separated from the actual decision making or planning process. This separation introduces the risk that these DSS have no policy impacts. Growing evidence emphasises that in situations characterised by high complexity and highly contested values, decision support needs to actively design and employ processes that allow them to engage with stakeholders and, thereby mitigate the policy impact failure risk (Hassenforder et al. 2015; Smajgl and Ward 2013b). Considering that the water, food, and energy nexus is in most situations highly complex and contested, the success of a nexus implementation depends not only on an effective methodology but also on the design of an effective stakeholder engagement process. The following section describes process design options that would benefit the implementation of nexus projects.

3 Process Designs for Effective Nexus Implementations

Applying an effective methodology for analysing cross-sector relationships and how their outcomes change due to certain development investments is only one important challenge of successful nexus implementations. Designing the engagement with decision makers and planners is the second major challenge. By definition, any applied nexus study needs to engage with at least three sector agencies, which have competing mandates. Considering that most of these cross-sector relations harbour complex interactions, the science-policy partnership is problematic because highly contested values establish incentives to argue for the first-best solution for any of the involved sectors. Complexity makes it difficult to dispute the benefits of a particular solution or present evidence for dis-benefits the investment would cause in other sectors.

Complexity is a key characteristic of nexus (and sustainability) focused research (and modelling in particular). Complex systems modelling is applied where system interactions are difficult or impossible to analyse based on human cognition, often simply due to the sheer number of interacting variables and the non-linearity many real world interactions imply. Additionally, sector-specific processes have to be understood as self-organising systems across multiple levels, which emphasises the unpredictability of emerging interactions (Boschetti et al. 2010; Miller and Page 2008; Sawyer 2005). Translating complex model outputs to useful information for multiple, competing stakeholders requires a *process* that guides stakeholder in perceiving and understanding complex cause-effect relationships. Without an effective process design that considers the cognitive aspects of the individual learning experience and the group level negotiation, the translation of complex modelling results is unlikely to have any policy impact.

Thus, in any situation that can be characterised by high complexity and highly contested values (or sector mandates) evidence-based decision making is challenging and demands careful planning of the engagement process with the competing policymakers and planners. Consequentially, the design of research processes and its policy engagement becomes a research topic of its own—to understand which process design options exist and which sequence of what actions is likely to lead to what policy outcome. Mounting evidence points at the effectiveness of participatory research processes to effectively bridge science and policy in complex and contested situations, which implies nexus-relevant situations (Barreteau et al. 2010; Cornwall and Jewkes 1995; d'Aquino and Bah 2013).

Participatory research is a very diverse field, largely applied in the domains of public health, environmental management, and education (Cornwall and Jewkes 1995). The common denominator for participatory approaches is that the (research) process constructively engages non-scientists to consider their knowledge (Cornwall and Jewkes 1995). Cash et al. (2003) argue that for effective participation of affected interests, knowledge needs to be agreed as valid, salient, and legitimate. However, the degree to which stakeholder knowledge is considered, what knowledge is exchanged, and what engagement techniques are being implemented varies widely (Barreteau et al. 2010). Increasingly, scientists observe that studies claim to conduct participatory research while the influence of stakeholders on the research remains minimal. In response, the research community developed robust definitions of what participation needs to entail and what levels of participation exist (see for details Barreteau et al. 2010). In cases with strong utilisation of modelling the terminology mostly changes to participatory modelling. Voinov and Bousquet (2010) provide an excellent overview of participatory modelling. Most prominent examples for participatory research include Community-based Participatory Research and Action Research (Cornwall and Jewkes 1995) and Participatory Action Research (McIntyre 2008). It needs to be emphasised that both of these groups include a range of diverse approaches. Prominent approaches within participatory modelling include Companion Modelling (Barreteau 2003; Bousquet et al. 2006) and Mediated Modelling (Antunes et al. 2006; van den Belt 2004).

These developments are encouraging and establish a new research domain that will benefit nexus-focused research to effectively interact with multiple competing sectors and facilitate evidence-based decision making despite the significance of complex dynamics. One participatory process design that has been successfully tested in a few empirical nexus processes is the psychologically founded Challenge and Reconstruct Learning (ChaRL) process.

The Challenge and Reconstruct Learning (ChaRL) framework (Smajgl and Ward 2013b, 2015b) aims to effectively bridge science and policy by guiding policymakers and planners through a highly structured participatory process (see Fig. 1). This systematic science-policy engagement framework puts stakeholder learning centre-stage. It utilises visions, beliefs, and values as key entry points for scientific evidence to inform policy and planning processes.

The ChaRL framework approaches the introduction of scientific evidence into ongoing policy or planning processes from the perspective of discovery-based learning, aiming to ground truth existing assumptions about cause-effect relationships relevant to the decision-making situation at hand. "Discovery learning occurs whenever the learner is not provided with the target information or conceptual understanding and must find it independently and with only the provided materials" (Alfieri et al. 2011). The ChaRL process elicits and challenges these underpinning causal beliefs (or heuristics) in five steps and *reconstructs* revised beliefs within the understanding of the functionality of the larger systems. The ChaRL process understands such

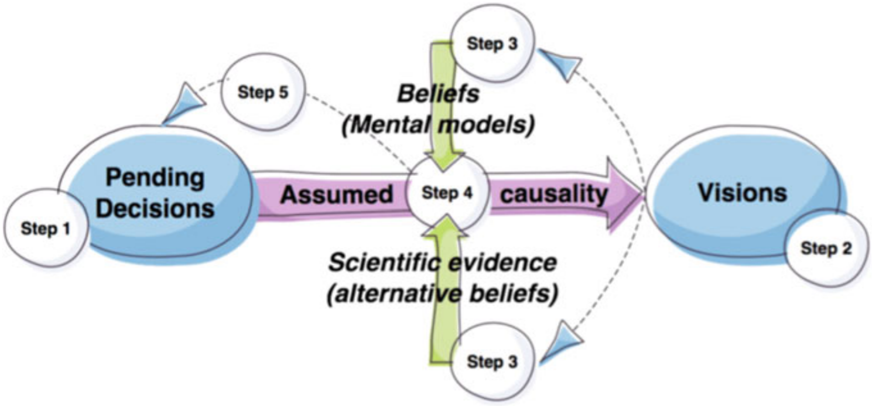


Fig. 1 Five-step process of the Challenge and Reconstruct Learning (ChaRL) design

reconstruction in the tradition of Habermas (2005) as the key process of learning, which is facilitated as an exchange of intuitive knowledge. Thus, scientific knowledge is not a priori assumed to be superior to stakeholder knowledge. The ChaRL process is in line with psychological research, particularly in the domains of cognitive research and discovery-based learning. These research communities provide substantial evidence for the effectiveness of discovery-based learning methods to achieve learning goals if compared with passively perceived instruction (Alfieri et al. 2011; Dean and Kuhn 2006). However, experiments have also emphasised the importance of guidance during the discovery process (Kirschner et al. 2006; Mayer 2004), which ChaRL provides through a highly structured five-step process.

Step 1 scopes out the objectives, including the decision making context and options, and the relevant success indicators as perceived by the decision makers. Inviting the relevant decision makers to co-design the research is critical to ensure high levels of ownership and, therefore stakeholder engagement (Smajgl 2010). Co-designing the research gives stakeholders control over the focus and a commitment that this research is actually addressing their interests and needs (Barreteau et al. 2010). In the ChaRL process it involves at this early stage that stakeholders define principle ‘inputs’ and ‘outputs’ of the analysis. Stakeholders specify a list of external changes (i.e. climate change) and a list of possible intervention options. These *inputs* translate for the analytical steps into scenarios. Additionally, stakeholders define a list of policy-relevant indicators. These two lists provide the foundation for choosing the most effective methodologies (for examples see: Smajgl and Nuangnong forthcoming; Smajgl et al. 2015a, c). To further improve stakeholders’ ownership of the research design, the methodological choice is also made by the participants. The research team presents possible options for effective methods against the backdrop of requested scenarios and indicators. This presentation includes a transparent discussion of methodological strengths and weaknesses, which considers data requirements and available context-specific models. Allowing stakeholders to make these fundamental decisions translates into more active participation and a genuine interest in the progress and results of the study. It also reduces the perception that the research team enters the decision making process with a specific agenda (Smajgl et al. 2015b).

In step 2 visions for a specified geographic location are developed as narratives of plausible futures desirable for all relevant stakeholders (Foran et al. 2013). This step may need to be completed iteratively if the set of decisions are likely to affect multiple action arenas, each demanding separate facilitation. The iterative approach allows revision of the original vision based on presentation of visions from other locations or governance levels. This step is critical to any applied nexus study (Smajgl et al. 2015b) because shared visions are essential to prevent participants from reverting to their own sector goals when debating the benefits of development strategies or the relevance of assessment results. Thereby, visions become normative benchmarks that are shared across competing interests. Without such shared visions, the normative benchmark for participants to perceive research results remains the sector mandate, which means that sector representatives will continued to maximise sector goals instead of taking the overall systems perspective. The shared visions define the most desirable future scenario of the overall systems and re-direct stakeholders' attention towards improving overall system outcomes, which implies for the nexus domain a reduction of trade-offs. Developing shared visions requires focussing on long-term outcomes and indicators that are not sector specific, for instance desired levels of poverty, employment, state of the environment. Past trends (or drivers) need to be discussed followed by future trends and possible shocks. Highly effective is to develop three sets of possible futures with the participants, a most desirable future, a most likely and a least desirable future. For the latter participants develop risk mitigation plans while action plans are developed for the most desirable outcomes. This visioning process produces regularly action plans that combine a variety of interventions across multiple sectors. Foran et al. (2013) provides a detailed description of an effective visioning process. Most importantly, the most desirable vision constitutes a normative benchmark and replaces in the following participatory process the sector mandates to debate the utility of interventions.

Without shifting the normative benchmark to the systems level, scientific evidence is likely to result in two possible policy outcomes, either the evidence matches stakeholder expectations and provides thereby a basis for justifying already prevailing sector arguments, or the evidence gets rejected because it does not match previous expectations. The visioning process facilitates a shift in the normative benchmark and opens the possibility for scientific evidence to contradict initial understanding and yet lead to policy impact. However, shared ownership and shared visions are only two important design principles. Additionally, the evidence needs to be presented as part of a discovery process to facilitate actual learning and result in policy impact, which is largely achieved during the next ChaRL steps.

During step 3 results for the assessment of potential impacts of planned investments on policy-relevant indicators (e.g. poverty, migration, water flow) are presented as preliminary and uncertain findings. The emphasis of uncertainty invites opinions and criticism that reveal how participating stakeholders perceive the world to work from their perspective. These discussions are captured and later analysed to identify statements that specify cause-effect relationships. Cognitive psychology typically refers to these as causal beliefs (Fishbein and Ajzen 1975). These beliefs are later presented and compared between stakeholder agencies (step 4) and then compared with (or challenged by) scientific evidence. This *unsettling* of longstanding beliefs facilitates a cognitive shift that unlocks participants' assertion and opens up their attitude towards new insights. Discovery learning and other empirically tested theories suggest similar approaches to facilitate learning (Alfieri et al. 2011; Mayer 2004). Notably, during ChaRL processes participants do indeed consider the validity of evidence that contradicts their initial beliefs, which is often not achieved by traditional research approaches (Smajgl 2010, 2015b).

The combination of challenging beliefs and operating towards a shared vision creates an effective space for participants with different nexus mandates to discuss revised investments or sector strategies. Experiences demonstrate that during step 5 sector representatives often stop aiming for the sector optimum and start considering second or third best solutions for the sector as long as overall system outcomes are improved; the relevant benchmark is provided by the shared vision. The ChaRL process has been implemented in various applied nexus studies and helped effectively bridge science and policy in very complex and contested decision making situations (Smajgl 2010; Smajgl and Ward 2013a; Smajgl et al. 2015b).

Box 2: Examples for a ChaRL process implementation

The Nexus in Vietnam's Mekong Delta

Salinity intrusion due to sea-level rise poses a substantial threat for rice production in Vietnam's Mekong delta faces. This process is predicted to intensify over the coming decades and substantially accelerate due to the mainstream dams planned for the Mekong river. Considering the considerable challenge these changes pose for existing food production (e.g. rice) it defines an archetypical case of the Water-Food-Energy Nexus. The participatory process involved mainly Vietnam's central Government and province level planning agencies. The policy context involved opposing preferences for adaptation measures between agricultural and environmental agencies. While one side proposed the construction of dykes ('hard' adaptation measures), the other side was endorsing land use and management changes ('soft' adaptation measures). The ChaRL process invited all relevant agencies to co-design the research project. Then, the visioning process was conducted, which requested participants to specify most relevant (and most uncertain) drivers, agreeing on likely future trends of these drivers, and then developing most desirable, most likely and least desirable futures for the Mekong Delta. In a third and fourth workshop, hydrological modelling and household survey results were presented. The assessment focused on dykes and land use change. Participants debated the validity of the presented evidence. During this debate, all statements involving causal relationships (if this then…) were recorded. In a following workshop results from an agent-based model were presented that combine social, economic, hydrological and ecological processes (see Box 1). This integrated assessment focused on the proposed adaptation options and on the recorded belief statements. Belief statements were presented to participants and compared with modelling results. The beliefs that were challenged included the efficacy of dykes, the resilience of land use change, and the likely trajectory of human migration and spatial poverty patterns. Most importantly, results emphasised that dykes are likely to be an efficient adaptation solution in the eastern coastline of the Mekong Delta while in the west of the coastal zone land use change and management changes would be most effective. The ChaRL process was able to bridge the policy factions and facilitate adaptation to safeguard Nexus outcomes for the communities in Vietnam's Mekong Delta. Smajgl et al. (2015a) provides further details for this Nexus case study and how the ChaRL process was effectively implemented (and supported by an agent-based modelling approach).

Development strategies in Lao PDR

The ChaRL process was also implemented in Lao PDR to facilitate stakeholder learning in another Nexus context. This Nexus project aimed to assess trade-offs between water trading, large-scale irrigation, and hydropower development in the Nam Ngum sub-catchment. The process invited the river basin organisation and agencies from central and province Governments to co-design this Nexus focused project and define assessment indicators, scenarios, and select assessment methods. Then, the stakeholder group developed most desirable, most likely, and least desirable futures based on most uncertain and most influencing drivers. During the next workshops, preliminary assessments were presented based on hydrological modelling, household survey analysis, and agent-based simulations. Stakeholders debated the validity of these results. This debate was analysed to identify causal beliefs stakeholders hold. These beliefs were then compared with the scientific evidence available. Based on this participatory process water trading was not implemented and large-scale irrigation investments were withdrawn in favour of small-scale irrigation schemes. These planning and investment changes were due to the surprising contradictions between scientific evidence and initial beliefs, involving expected poverty reductions, environmental flow requirements, irrigation-based food security improvements, and migration based changes in spatial poverty patterns. Smajgl et al. (2015b) provides more details for this Nexus case study.

Typically, these five steps have been implemented over a two to three-year time period, involving a series of four to seven workshops, many face-to-face meetings, and the training of government staff. The processes are normally initiated by a government agency or by a donor agency that observes or expects trade-offs between sector specific investments. Initially, all decision makers that are likely to influence the system level outcomes are invited. This involves multiple tiers of governance from the village and from district, province, and central governments, and sometimes even supranational agencies. The evaluation of past ChaRL process implementations has shown that the best results are achieved if at least three governance levels and all context-relevant sectors (i.e. water, food, energy) participate throughout the process (Hassenforder et al. 2015; Smajgl and Ward 2015b).

Several publications list and compare participatory processes (Barreteau et al. 2010; Cornwall and Jewkes 1995). Such comparisons are useful to guide the selection of the best suited process design for the task at hand. Comparing ChaRL briefly with a few other process designs points out three key differences that can be outlined. First, ChaRL develops shared visions as normative benchmarks to circumvent competitive sectoral interests. Second, in the wider domain of participatory research most approaches work at the level of households or individuals, while ChaRL is designed for multi-level governance interactions. Third, in contrast to most participatory research, ChaRL does not explicitly elicit stakeholder knowledge and treat it as scientific evidence. Instead, both stakeholder and scientific knowledge is elicited or produced, but kept separate to develop contrasts to facilitate learning in the final step 5 workshop. This is also a key difference from most participatory modelling approaches, which aim to translate stakeholders' perception of the world into model design, as implemented in Companion Modelling (Barreteau 2003; Castella and Verburg 2007; d'Aquino and Bah 2013; Le Page et al. 2014), Mediated Modelling (Antunes et al. 2006; van den Belt 2004), or Participatory Simulation (Briot et al. 2007; Diehl 1992; Ishida et al. 2007). The main reason for building the models based on primary data (i.e. information provided by household survey, rainfall data, crop price ranges) and expert knowledge only is to maximise the model's potential to challenge participants' beliefs. Designing the model based on participant beliefs would reinforce existing beliefs and heuristics, constraining debate to align prevailing beliefs instead of potentially contradicting existing beliefs. Maintaining the independence of the two knowledge pools allows for a controlled introduction of evidence and comparative analysis.

The development of improved process designs for implementing a Nexus Approach requires the testing and further enhancement of any of these research process designs. Each process design has a particular strength and is likely to perform better in some circumstances than in others. Nexus implementations could further improve the understanding of the effectiveness of particular process steps or sequences if the process is accompanied by a robust monitoring and evaluation approach to identify contextual strengths and limitations for each design option. This requires collective action within the research community (Poteete et al. 2010) to derive the necessary evidence for enhancing participatory process designs. However, such an experimental approach requires a generic framework for testing research processes to allow for cross-comparative analyses.

So far, the evaluation of participatory research processes and participatory modelling is largely limited to qualitative descriptions of impacts without a systematic and replicable experimental design. Hassenforder et al. (2015) developed a framework for the comparative analysis of participatory processes. Their COPP (Comparison of Participatory Processes) framework defines 30 criteria across 4 dimensions: context (6 criteria), process design (14 criteria), monitoring and evaluation (4 criteria), and

Table 1 Variables for three (of four) dimensions of the framework for the Comparison of Participatory Processes (COPP)

Context	Participatory process	Output(S), outcomes and impacts
• Target system elements • Levels of governance influencing the target system elements • Other past/present intervention attempts • Preexisting relationships among participants • Participants' understanding of target system elements	• Participatory process objectives • Instigator(s) of the process • Team origin of the team • Selection of the participants • Size of the group • Level of participants' process expectations • Governance level(s) engaged • Length of process • Number of events • Degree of participation retention • Setting of exchange • Degree of participation • Participatory methods and tools	• Impact on participants • Impact on actions • Social scales of the impacts • Spatial extent • Time scales of impact

the impacts, outputs, and outcomes (6 criteria). Table 1 lists the variables for the key dimensions of the COPP framework; more details and the actual framework application template are provided in Hassenforder et al. (2015). The framework application elicits evidence to derive testable hypothesis. These hypotheses would state that specific process activities implemented in a particular sequence lead to a particular outcome in a specific context. Ultimately, once widely tested, this evidence would define for a small number of contexts which activities are most critical and which activities should be avoided. Such design principles can provide the nexus community with robust understanding of effective science-policy deliberation processes.

Recent implementations of the COPP framework have pointed at a few design principles (Hassenforder et al. (2015). First, effective engagement processes combine multiple levels of governance. This is supported by other literature (e.g. Daniell and Barreteau 2014; Smajgl 2009; Smajgl et al. 2009; Smajgl and Ward 2015a) and required to facilitate streamlining of policies and regulatory frameworks across levels in terms of a "vertical nexus" (Hoff 2018, Chapter "Integrated SDG Implementation –How a Cross-Scale (Vertical) and Cross-Regional Nexus Approach Can Complement Cross-Sectoral (Horizontal) Integration"). Second, policy impacts are less dependent on methods, which contradicts some other empirical studies comparing disciplinary models with complex system models (Smajgl and Ward 2015b; Smajgl et al. 2015b). These results emphasise the need to further investigate the relevance of methods in the broader research design, which seems also highly relevant for the nexus discussion. Third, high policy impact is more likely to be achieved in two years or more, while low impact studies engaged for twelve months or less. This could mean that there is a threshold for nexus studies and the need to engage for two years or more to make policy outcomes more likely. These types of findings resulting from a wider application of the COPP framework and a subsequent comparative analysis would help develop robust design principles nexus implementations could build on.

4 Summary and Conclusion

This paper presented two major challenges for the implementation of nexus approaches, (1) the need for methods that allow for an effective integration to provide the necessary diagnostic and analytical capacity to investigate nexus dynamics, and (2) the design of processes that facilitate evidence-based decision making despite the competing mandates of most nexus concerned negotiations.

The methodological solutions presented above could provide nexus studies with effective tools to analyse cross-sector dynamics. The political impetus to realise genuine integration in analytical assessment methods is very likely to remain high. The Nexus Approach accentuates this policy demand and continues what various sustainability-focused paradigms flagged as critical for effective decision support for decades. Therefore, it seems paramount to further advance genuinely integrated assessment methods and participatory process designs. This paper presents solutions for these two dimensions that are critical for any Nexus-type situation. However, there are still limitations. For instance, in the domain of agent-based modelling major challenges remain in sourcing data, implementing and parameterising realistic representations of social networks, or linking socio-economic and bio-physical processes. Also, the model validation remains challenging in an applied policy context due to the highly complex model designs. The ChaRL process design can also face substantial limitations or even fail if prevailing power relationships cannot be managed, or informal incentives overwrite policy processes. Effectively advancing this scientific domain requires large-scale initiatives to test a variety of process steps and different implementation sequences while monitoring and evaluating emerging policy impacts with a shared monitoring and evaluation framework.

In the long term, however, research agencies need to adopt these innovative methods more widely. This scientific transformation towards cross-disciplinary or transdisciplinary approaches is slowed down by two important impediments. Research facilities like universities follow a more traditional structure and conduct research activities in disciplinary units. Not many universities have created cross-disciplinary entities. This results in the majority of (applied) nexus studies being designed and implemented by researchers that have a *unidisciplinary* assessment background. This leads to the second factor, which is linked to the change in skill sets. Any established researcher follows strong incentives to use familiar methods. Consequentially, most nexus research has been implemented by disciplinary units trying to connect to groups from other disciplines and each running their own method. However, effective nexus research requires researchers trained in transdisciplinary methods and operating from transdisciplinary research facilities.

Similarly, applied research is still dominated by traditional process designs, which separates researchers and stakeholders in a mostly academically driven research design and implementation approach. Such limited stakeholder engagement (and the resulting lack of stakeholders' ownership of the study and its results) is likely to leave the study to either being accepted because it confirms prevalent beliefs or being ignored because it contradicts initial beliefs. However, nexus research requires robust and effective engagement processes that allow contradicting scientific evidence to still influence decision making. Robustness, however, requires the scientific testing of participatory and other research processes to reveal what engagement process options exist and which process design is likely to lead to real-world uptake in what context.

In addition to these two challenges, applied nexus studies face also other challenges, which have not been discussed in this paper. For instance, most countries do not collect the necessary data for a comprehensive nexus analysis. Many mechanisms that facilitate or accelerate nexus trade-offs are context-specific and involve ecosystem services, social processes, and economic dynamics. Typically, any robust analysis of these relationships depends on highly disaggregated data. This data demand is in addition to the sector-specific data needs to understand hydrological, energy-related, and food-specific data.

In synthesis, applied nexus studies are in high demand and considering the evidence for cross-sector trade-offs the nexus paradigm is likely to continue to influence applied research. Developing solutions for the two challenges discussed in this paper will be an important research agenda to improve the support for robust implementations of nexus studies in the future.

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Games for Aiding Stakeholder Deliberation on Nexus Policy Issues

Junko Mochizuki, Piotr Magnuszewski and Joanne Linnerooth-Bayer

> *Get the beat. Listen to the wisdom of the system. Expose your mental models to the open air.*
>
> Meadows (2002)

Abstract Games can provide an effective and replicable space in which stakeholders learn skills necessary for deliberative and pluralist policymaking. These skills are especially important for "nexus" policy issues that are typically characterised by multiple, competing problem frames involving overlapping networks of stakeholders. In this position paper, we describe three serious games that serve as a space for players (stakeholders) and researchers to jointly explore alternative solutions to complex resource management issues: the Water-Food-Energy Nexus Game (Nexus Game); the Narubu Game of Many Voices (Narubu Game); and the Forest Governance Game (Forest Game). The games contain instructive and reflexive mechanisms that prompt players to self-discover common challenges associated with complex nexus issues, including conflicting institutional mandates, social dilemmas, contending worldviews, and plural interpretations of science.

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1 Introduction

A “nexus” approach to the myriad of environmental, social, and economic policy issues facing the global research community has gained attention with the recent publication of the United Nation’s Sustainable Development Goals (SDGs) (United Nations 2015, 2016). To simultaneously reach the 17 goals, which range from poverty elimination, food security, gender equity to health, sustainable consumption and biodiversity conservation, it will require an understanding of their complex interactions, trade-offs, and synergies. ‘Nexus thinking’, or ‘systems thinking’, takes account of the whole rather than the individual parts, identifies feedbacks and connections, and can lead to the transformation of systems through interventions targeted at the ‘critical nodes’ (Alcamo 2015). By shedding light on the interconnectedness of paths to achieve the SDGs, including those related to water-food-energy (SEI 2014; Le Blanc 2015; Yillia 2016), as well as water-soil-waste (Kurian and Ardakanian 2015), the Nexus Approach offers an alternative to business-as-usual, ‘siloed’ policy development (Ringler et al. 2013; Leck et al. 2015; Rasul and Sharma 2016; Boas et al. 2016).

The benefits of a more holistic approach to policy development are not disputed; yet, there is limited articulation of how such an approach can be operationalised in practice, and especially how it can be operationalised in a multi-stakeholder environment. The literature on policy integration emphasises the importance of early engagement of stakeholders in the implementation of environmental and social policy, especially for issues characterised by competing stakeholder interests and perceptions, what has been referred to as the “contested terrain” (Allen and Gunderson 2011; Verweij and Thompson 2011; Thompson 2013). Following an early call for stakeholder participation by the Rio Declaration (UNCED 1992), and more recently by the European Union, stakeholder engagement has become almost routine in many environmental policy arenas (Aldred and Jacobs 2000; Kallis et al. 2009; Salgado et al. 2009; Jackson et al. 2012). Experience has shown that the involvement of stakeholders can increase public awareness, take account of local concerns, bring new options to light, delineate the space for agreement or compromise and, not least, enhance the credibility of public policies. A participatory process, moreover, can help policymakers understand stakeholder needs and expectations, and enhance consent by sharing responsibility for the decisions taken (Dryzek 2001; Elster 1998; Steiner 2012; Dietz 2013; Fischhoff 2013).

Many tried-and-tested methodologies to facilitate stakeholder engagement in complex policy issues are available (Scolobig and Lilliestam 2016; Renn 2008; Rowe et al. 2004; Webler et al. 1995, 2001) yet, extending these practices to nexus issues raises difficult challenges. Foremost, nexus thinking expands the stakeholder geography to encompass institutions and interested persons across multiple policy arenas that are otherwise addressed separately. This expansion may lead to novel stakeholder coalitions based not only on institutional and individual interests, but also based on underlying values and worldviews. Moreover, the underlying science for nexus issues may be less developed than for singular sectoral issues, which will mean more uncertainty for participating stakeholders.

In this position paper, we describe and discuss integrated simulation games as an emerging stakeholder approach to address nexus issues. The games either directly simulate the nexus of policy issues (in this case the nexus of water and energy) or provide insights on the complexity of resource management in complex policy environments (in this case, flood/drought risk management and forest management). Simulation games—also referred to as serious games or policy exercises—are intended to illustrate social and natural complexities and their interactions. They are designed to provoke critical questioning of siloed mental models. By way of ‘procedural rhetoric’, i.e. illustrating a point by walking someone through a process (Bogost 2008), games encourage stakeholder immersion in the ‘what if’ scenarios of policy challenges. Through the collective exploration of future scenarios and solutions, and by explicit articulation of stakeholder plurality, such games encourage a process of ‘social learning’ (Garmendia and Stagl 2010; Cundill and Rodela 2012; Kristjanson et al. 2014) facilitating the mindset and understanding that supports policy and decision making under uncertainty and ambiguity.

Simulation games are increasingly utilised for stakeholder engagement, communicating trade-offs and synergies that exist between a broad range of policy domains such as climate change mitigation and adaptation (de Suarez et al. 2012; Bachofen et al. 2012; Juhola et al. 2013); flood risk management (Stefanska et al. 2011; Centre for Systems Solutions/IIASA 2016; Harteveld et al. 2009), and land-use and urban planning (Krolikowska et al. 2007; United Nations Human Settlements Programme 2016). Originally developed for research and teaching purposes primarily, games are now played to inform stakeholder decision-making.[1] For example, as part of the European Commission (Climate-KIC) financed project ‘Accelerating Urban Energy Transitions’ (ACCURENT), private, public, and civil society organisations participated in a serious game (the Energy Transition Game) that was followed by visioning and action planning (Centre for Systems Solutions 2016). A game session was also combined with the ‘flexible and forward-looking decision making’ framework in a series of climate change adaptation workshops organised by the African Climate Change Resilience Alliance (ACCRA) in Uganda, Mozambique, and Ethiopia (Jones et al. 2014).

Rigorous empirical studies on the effectiveness of games are an important area of active research (Rumore et al. 2016). Like many other stakeholder engagement methods, evaluations are important to understand what types of settings and approach work the best in encouraging stakeholder participation and learning (Smajgl and Ward 2015; Hassenforder et al. 2015). A growing number of games are produced by non-profit and research organisations and are available for non-profit use under Creative Commons licences (Juhola et al. 2013; Bachofen et al. 2012; Visman 2014; Center for Systems Solutions/IIASA 2016). In addition, online repositories are available that showcase games across policy domains of sustainability issues.[2]

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[1] For further discussions on gaming application in diverse stakeholder settings such as policy exercise and companion modelling, see for example, Ryan (2000), Barreteau et al. (2003), Bousquet (2005), Geurts et al. (2007), Mayer (2009), Duke (2011), Rumore et al. (2016).

[2] See for example: http://www.games4sustainability.org; https://games4democracy.org/.

In this paper, we discuss in detail three distinct applications of integrated simulation games, each of which illustrates the need to manage the complexity of socio-ecological system dynamics, and we demonstrate how these approaches are used in the science-policy-society interface. The three cases are:

The Water-Food-Energy Nexus Game (*Nexus Game*) is an integrated simulation game addressing the interrelated challenges of water, energy, and food production. The game setting contains two riparian countries sharing a transboundary river basin. Through inter-ministerial and international negotiations, players experience and learn not only potential technological solutions but also relational challenges to reducing the country's water, food, and energy footprints.

The Narubu Game of Many Voices (*Narubu Game*) is a role-playing game focused on 'wicked' policy issues characterised by competing policy frames and solutions, and different interpretations of the science. The policy domain is flood and drought risk management in a food-constrained developing country. Building on the theory of plural rationality (TPR), players learn to articulate alternative (and conflicting) policy preferences based on distinct worldviews. The purpose is to demonstrate the role that values and worldviews—in addition to "facts"—play in shaping stakeholder discourses and ultimately negotiated solutions.

The Forest Governance Game (*Forest Game*) focuses on the sustainable management of common-pool forest resources. Although this game does not address a nexus resource issue, it does illustrate how players frame the problem differently and how the choice of governance regimes reflects these frames. Combining insights from game theory and the theory of plural rationality, players choose between different forest management regimes of regulation, privatisation, and revenue sharing. The purpose is to experimentally test the robustness of common-good governance arrangements. Ultimately it shows the need for a governance regime that combines different and competing forms of social organisation.

Each game enlightens the players on the importance of systems thinking. Players engaged with the *Nexus Game*, for instance, are confronted with trade-offs between conflicting goals across water, energy, and food supply, as well as requirements for maintaining ecosystems; the *Narubu Game* introduces players to the complexities of policymaking across conflicting objectives, not only due to budget constraints, but also due to conflicting worldviews and interpretations of the "facts"; the *Forest Game* brings in yet another complicating feature of real-world policy, that is, how societies choose to organise or govern themselves with regard to the management of common resources. Conflicting goals and diverse worldviews often lead to sub-optimal or even catastrophic consequences.

The games presented in this position paper do not feature competition or a singular goal common in entertainment and serious games, but rather on conflicting objectives, policy frames, and worldviews. Players navigate through this complexity, finding their own meaning, and setting their own goals. While offering enough flexibility for players to collectively explore solution spaces, the games follow standardised facilitation protocols so as to produce desired procedural rhetorical impact (Bogost 2008) and provide science and policy messages to be explored collectively.

In addition to embedding the complicated (but clearly identifiable) interconnections of socio-ecological systems (such as the water requirements of agriculture and energy production), the games implant elements of ambiguity and unpredictability, stemming from alternative worldviews and other relational interactions that make the systems inherently ‘complex’. In the *Nexus Game*, unpredictability is added by rainfall variability and players’ actions. In the *Narubu* and *Forest Games*, contesting ‘worldviews’ add further ambiguity.

Gaming sessions—typically lasting a few hours—wrap up with an extensive debriefing session that allows players to digest and reflect on the game messages as they connect with their real-life situations. The debriefing session is arguably the most important phase of serious games since it allows players to apply gaming lessons to their specific issues and concerns. In a reflexive debriefing the facilitator asks the questions: “what?”, “so what?”, and “now what?” (Lubans 2009). The ‘what’ question prompts stakeholders to give their accounts of what happened during the game, including their intuitive and emotional reactions. The ‘so what’ question delves into stakeholders’ interpretations and reactions to articulate the diverse motivations. Participants learn about the many underlying mechanisms and processes embedded in the game, and how the game problems correspond to their real-world counterparts. Finally, the ‘now what’ question draws important takeaway messages of the game, prompting players to identify what they would do differently given their newly acquired knowledge from the game.

The remainder of this paper is structured as follows: Sect. 2 gives an overview of integrated simulation games, describing the types of system-thinking insights that inform game designs. Section 3 describes three recent examples of game applications, illustrating how they provoke systems thinking on complex policy issues. Section 4 then follows with concluding remarks.

2 Integrated Simulation Games to Explore Complex Policy Issues

2.1 Introduction to Games

Throughout the history of systems analysis, games have served as a natural complement to model-based analyses, providing much needed human and social insights into decision and policymaking in a complex world. A simulation game uses ‘considered application of game thinking to solve problems and encourage learning’ (Kapp 2012, 15). This has traditionally taken the form of a board game (sometimes very large as with war games), and more recently also a computer game (or a combination of both), with which stakeholders engage in collaborative or competitive problem solving. Formal settings defined by the rules of the game, together with calibrated parameters ideally closely resembling reality, give players a unique opportunity to experience the world of virtual policy challenges. Games are particularly suited to explore stakeholder dynamics in both competitive and cooperative settings, in which actions generate multiple feedbacks.

What constitutes a game is open to interpretation. Simulation games—as with many other games—share common features such as a storyline, goals, rules, feedback systems, and participant's voluntary involvement (McGonigal 2011). Salen and Zimmerman defined a game as follows: "A game is a system in which players engage in an artificial conflict, defined by rules, that results in a quantifiable outcome" (Salen and Zimmerman 2004). Assigned either exogenously or endogenously, the individual and collective goals of a game, along with its storyline, instil a sense of purpose to players. The limitations and obstacles placed by the rules of a game then necessitate that players engage in strategic thinking and active participation. The feedback system consisting of elements such as scoreboards and game tokens allows players to know how well their strategies are working, so that they may adopt and/or alter strategies as necessary.

All of these elements combined may achieve what Bogost (2008) refers to as the procedural rhetoric of a game. Through a particular choice of storylines, goals, rules, and feedback systems, players make sense of a game's context, such as specific mechanisms, interactions, and policy challenges involved. Instead of traditional means, such as speech and writing, to convey messages in a written or oral form, a game conveys messages through its unfolding storylines and the many actions a player takes. The distinguishing feature of simulation games (as illustrated in this position paper) is the integration of social and natural science insights that are essential for illustrating the complex challenges of nexus policy issues.

Serious games were employed initially for developing military strategies. In this context, the advantages of a game compared to traditional analyses and scenario planning have been elaborated by Averch and Lavin (1964):

> A politico-military confrontation can be viewed as a sequential competitive and/or cooperative process…. [G]aming techniques are useful for studying such processes, particularly when (as is the case for crisis situations) the problem is so complex and so much information is required that an interdisciplinary study team is at an advantage. Generally, a manual game can focus the attention and knowledge of a group of analysts; specifically, a politico-military game without prescribed moves (that is, with open play) aids study of decision making with intricate constraints. (p. 4)

From their military roots, games evolved to address a range of policy contexts including global sustainability issues as Parson (1996a) writes:

> [Policy exercises] are likely to be useful for certain classes of decision problems. These include new, ill-posed issues whose characteristics and relevant aspects are ill understood or contested; issues for which major institutional changes are proposed; and issues for which the consequences of even relatively simple or small policy or decision are hard to assess or predict because of the number of affected actors and their range of potential responses. Global environmental problems clearly have these characteristics, as do other current important policy issues. (p. 18)

2.2 *Games for Nexus Policy Issues*

Complex interactions and feedbacks underpin many, if not all, nexus policy domains including (but not limited to) water, soil, food, energy, and waste. Even standing alone, these policy areas can be complex, and when taken in combination the complexity multiplies in terms of (uncertain) synergies and trade-offs, as well as with regard to the institutions and rules that define the area's governance. Not only may the number of stakeholders and governing institutions burgeon, but policy interventions will have to be re-tailored to take account of the added complexity. Nexus thinking (or systems thinking) recognises these complexities and emphasises the need to look beyond immediate cause-effect relationships, questioning common pitfalls of reductionist models.

Agent behaviour and unintended consequences: the Nexus Game

One common pitfall that is particularly relevant to our focus on stakeholder interaction concerns the behaviour of human agents in policy arenas, where the typical assumption of a 'rational actor with perfect information' contradicts accumulated evidence that people are prone to misconceptions such as: (i) perceiving one-way relationships as opposed to complex interactions; (ii) perceiving central as opposed to decentralised (and self-organising) control; (iii) perceiving linear as opposed to non-linear cause-effect relationships, and (vi) perceiving immediate as opposed to distance cause-effect relationships across time and space (Sterman 2006; Plate 2010). Without a proper grasp of complex system behaviour, policymakers may solve one problem but create unintended consequences. For example, building a dam to protect against flooding may lead to development in a flood-risk area and ultimately increase risk (Newell and Wasson 2002).

The concept of unwanted consequences cascading to other sectors is illustrated in the *Nexus Game*; achieving a successful renewable energy transition requires a sound grasp on the part of the players of the interdependencies across diverse decision outcomes. For example, investing in an improved coal power plant may reduce coal input but increase its water footprint, and options such as micro-hydroelectric plant is cleaner, but may not be reliable under increased rainfall variability.

Wicked problems: the Narubu Game

Due to interlinked system behaviours, along with deep-seated differences in human values, nexus policy domains take on characteristics of 'wicked problems'. In the context of social policy, Rittel and Webber (1973) describe 'wicked problems' as those with multiple stakeholders who may hold conflicting frames of the problem and its causes, and where there are large uncertainties in the underlying scientific evidence. In the words of the authors, "wicked" problems, as opposed to "tame" problems, cannot be definitively described or solved since there are no objective ways to balance values and define equity so "it makes no sense to talk about optimal solutions" (p. 155). They claim that traditional policy analytical approaches cannot be applied to wicked problems—"the search for scientific bases for confronting problems of social policy is bound to fail, because of the nature of these problems" (p. 153). In other words, wicked problems are those for which:

No solution is correct from all perspectives, which means a socially accepted or robust solution can only be that which is agreed upon by the stakeholders;
The agreed solution will depend on the stakeholders' competing policy frames;
Policy frames, in turn, derive from the often diverging worldviews and interests;
The problem is thus never solved definitively.

The anthropological theory of plural rationality (also called cultural theory) as set out by Thompson et al. (1990), Linnerooth-Bayer et al. (2006, 2016), Thompson (2008), Verweij and Thompson (2011)[3] among others, identifies three strategies (with many combinations) to 'manage' wicked problems:

Hierarchical or authoritative regimes seek to tame wicked problems by vesting control in government authorities with their network of experts. These regimes rely on regulations and incentives, among other instruments, to nudge system actors;
Individualistic or market regimes seek to minimise top-down control by vesting property and other rights in individual actors, who advocate the taming of wicked problems through a multitude of individual transactions;
Egalitarian or collaborative regimes seek a shared understanding and moral commitment to solving a wicked problem with coordinated (not top-down) collective action by engaging all stakeholders in the policy process and advocating for equalising solutions.

The two management strategies—hierarchies and markets—are well documented in the literature (see, for example, Williamson 1975). Building on the work of anthropologist, Mary Douglas, TPR adds a third egalitarian strategy of informal networks based on shared responsibility (a fourth strategy, fatalism, also exists but is not influential in policy debates) (see Douglas and Wildavsky 1983).

The *Narubu Game* engages players in negotiating a solution to a wicked problem—managing flood and drought risk in a highly contested context—characterised by multiple competing stakeholders and different interpretations of the science and "facts". The game's message is that 'science- and evidence-based' policymaking is not straightforward particularly in arenas characterised by competing worldviews. The worldviews manifest in stakeholder discourses (or voices), which are plural depending on the social context for which they identify, or depending on the ways in which people organise, perceive, and justify their social relations. Experience with the game has shown that the ultimate compromise reached by stakeholders on options for flood and drought control often has more to do with contending worldviews or 'voices' of desirable futures than the science underlying the options. Also highlighted in the Narubu game is the notion of 'contradicting certitudes', and *not necessarily uncertainty*, that contributes to stakeholder conflict.

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[3] Originally developed by Douglas (1978), cultural theory—a theory of cultural bias—introduces the notion of plural rationalities as a challenge to theories of rational choice and post-structuralism.

Social dilemmas: the Forest Game

One of the overarching questions of the sustainability transition concerns the portfolio of mechanisms and measures that best facilitate sustainable collective action, especially when private incentives to free ride are high as in the case of many nexus resource issues. Indeed, one of the most intractable social dilemmas for the management of common-pool resources, including climate change, the depletion of biodiversity, marine life, and forests, is what is termed the "tragedy of the commons", which describes a situation where individual users of a common-pool resource, acting independently according to their own self-interest, behave contrary to the common good of all users by depleting or spoiling that resource through their collective action. By taking a systems framing on the dilemma of managing the commons, the *Forest Game* explores the different management regimes postulated by the theory of plural rationality, including regulations and incentives imposed by a government authority, privatisation of the forest to simulate a market, and collectivisation of the forest with equal sharing of the revenues. Moving beyond traditional game theory in behavioural economics, in which decisions are framed mostly as one-time comparisons of economic payoffs, the *Forest Game* adds further dimensions, such as the repeated nature of resource harvesting decisions, a plurality of rationalities stemming from worldviews, and different forms of communication among players.

3 Case Studies of Simulation Games for Nexus Policy Issues

Each of the three games described above serves a unique audience and purpose; as such, each gaming approach is distinctively different. All approaches, however, fundamentally challenge the reductionist approach to policy analysis, illustrating the inherent 'messiness' of nexus policymaking. The *Nexus Game* explicitly tackles a nexus policy issue; whereas the *Narubu Game* and *Forest Game* provide insights on issues that characterise nexus policymaking. The *Narubu Game* addresses the use of science in a wicked policy setting and the *Forest Game* shows how collective action responds to different policy regimes.

The reality of nexus challenges is, of course, far more complex than what is represented in the games, because all games—like models—are simplifications of reality. Playing a game hardly substitutes the need for formal analysis and genuine stakeholder engagement. However, just as well-crafted quantitative models can give useful insights on the key relationships among different variables, well-crafted simulation games can give valuable insights on the many factors that shape policymaking. In particular, games can reveal important behavioural and cognitive factors—as well as underlying worldviews—that are often missing in conventional integrated assessment. Games assist players to articulate these underlying human elements of complexity. They help us understand how nexus issues emerge and what we can do—*in theory*—to address them, and also teach us the soft skills needed for effective negotiation and problem-solving—*in reality*.

In this sense, games help bridge what Meadows (2002) calls 'the gap between understanding and implementation' of complex systems where intellectual work of systems analysis ends and the actions of 'human spirit' begin. The latter is a process in which we apply insights gained from analysis to change system behaviours. Meadows lists aspirational principles such as acting with a genuine care for 'what is important' as opposed to 'what is quantifiable' and living up to the standard of 'human goodness' as opposed to human shortcomings so often portrayed in media. In the following section, we describe the games in detail, highlighting how each brings to the fore elements of system complexity in distinct contexts: the water-energy nexus, flood and drought risk management, and forest resource management. We explain how these games teach us to apply systems-thinking insights to making better collective decisions and actions

3.1 The Nexus Game

The *Nexus Game* addresses the complex issue of transboundary resource management. Two countries—one upstream, the other downstream—face interlinked challenges of energy, food, and water provision. For each country, the participants play the roles of the prime minister, water minister, energy minister or agricultural minister, and they are given the task of delivering energy, food, and water depending on their mandate. Beyond these sectoral objectives, an overarching goal for the country is to achieve sustainable development and a good relationship with the neighbour country. Each country must supply energy, food, and water for its people addressing interlinked constraints such as the inter-annual variability of rainfall (including the potential for droughts and floods) and the need to protect local aquatic ecosystems. The game provides insights on establishing effective collaboration mechanisms, making collective decisions to allocating scarce natural and financial resources.

The *Nexus Game* is an integrated simulation game of the interrelated, socio-ecological system. Instead of looking at the natural or social systems in isolation, the notion of socio-ecological systems emphasise interdependency across societal arrangements and natural resource systems. Borrowing on Ostrom's socio-ecological systems (SES) theory (Ostrom 2007, 2009), such combined systems may be understood in terms of:

Resources Systems: such as river, forest, pasture land, and fish, which may be defined in terms of dimensions such as productivity of systems, equilibrium properties, storage characteristics, and location;
Resources Units: such as amount of water, tree, and fish species within resource systems, which may be defined in terms of number, mobility, growth/replacement rate, special and temporal distributions, and economic value;
Governance Systems: formal and informal institutions governing resources and units, defined in terms of government and non-government organisations, network struc-

Table 1 Major characteristics of socio-ecological systems adopted in the Nexus Game

Resource Systems	• A transboundary river basin with tributaries located in the Southern African region • Water storage capacity including a large dam in the upper stream, with smaller storage facilities located across tributaries • No groundwater systems
Resource Units	Highly variable water supply characterised by wet and dry season rainfall
Governance Systems	Water use decisions are made collectively—with Prime Minister assuming overall responsibility in fiscal resources allocation; Ministry of Water in charge of water storage/release decisions; Ministry of Energy in charge of power production; and Ministry of Agriculture in charge of food production. There is a potential to negotiate transboundary treaties between two nations
Users	Water is used for power generation, agricultural production, and final consumption. And there are fixed supply targets to ensure state's 'well-being'

ture, property-rights, collective-choice rules, and monitoring and sanctioning processes;
Users: individual and organisations who depend on resources and units, defined in terms of number of users, socioeconomic attributes, history of use, location, norm/social capital, and technology used.

These four elements characterise the socio-ecological system along with resource use, context, interactions (such as the presence of self-organising activities, information sharing, and/or conflict) and outcomes (such as equity, accountability, and sustainability), and any other positive and negative externalities (Ostrom 2007, 2009). Table 1 summarises key characteristics of the socio-ecological systems depicted in the *Nexus Game*.

The *Nexus Game* describes a stylised transboundary resource management process aimed to support policy development within the Southern African Development Committee (SADC). The SADC is a regional governing body established in 1992 to facilitate collaboration on many issues including resource management. Consisting of 15 member states in the region, SADC has the goal to 'achieve development, peace and security, and economic growth and to alleviate poverty, enhance the standard and quality of life of the people of Southern Africa, and support the socially disadvantaged through regional integration' (SADC treaty Article 5). The region is, in fact, considered as one of the nexus 'hotspots'. Anticipated growth of economic and infrastructure, along with adverse impacts of climate change, is expected to trigger significant challenges for sustainable development. The vision for the region in 2027, for example, promotes ambitious development of water resources including:

Achieving 25% storage of surface water or actual renewable water resource (ARWR) as opposed to the current level of 14%;
Achieving 20% irrigation (or 10 million ha) as opposed to the current level of 7% (or 3.4 million);

Fig. 1 A prototyping session of the Nexus Game

75 GW of hydropower installed as opposed to the current capacity of 12 GW; Serving 75% of people with improved water supply and sanitation as opposed to the current level of 61 and 39% respectively (Entholzner and Reeve 2016).

This is the context in which the development of the *Nexus Game* was commissioned. During World Water Week 2014, WaterNet[4] (a network of water professionals consisting of 72 organisations across 15 Southern and Eastern African countries) requested support in building capacity to address the region's nexus challenges within the UNDP-CAPNET/SE4All initiative. This led to a series of brainstorming session involving end-users and game designers, which resulted in the present version of the nexus game.[5]

Game play

The game begins in year 1 with a rainy season. Players, who are assuming the roles of policymakers in two neighbouring countries, must make initial decisions on water allocation (Fig. 1). Year 1 is followed by a dry season and an 'investment phase' in which players make investment decisions after receiving information on available efficiency improvement options. Throughout the game, players learn of the many interplays that exist across and within water, energy, and food systems and potential 'nexus' solutions that can reduce the country's water, energy, and food footprints (Table 2).

To grasp the fundamental concept of 'stock and flow' relationships, players plan and decide how much resources (water, food, energy, and money) to use or produce,

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[4] http://www.waternetonline.org/.

[5] A series of capacity building activities are currently being developed and planned to be implemented in 2017.

Table 2 Summary of players' decision steps and interdependencies

Players	
Prime Minister	Negotiates and decides how much energy, water, and food should be made available for final consumption (-> affects the state's development level) Allocates subsidies to ministries Negotiates international agreements Takes actions necessary to protect ecosystems (-> receive income from eco-tourism)
Minister of Water	Decides how much water should be stored in the dams and how much should flow through the river and tributaries (-> affects power generation and ecosystem health, fish production, and potential for flood under extreme precipitation) Decides how to distribute stored water throughout all infrastructure (-> affects energy/crop production and water available for final consumption)
Minister of Energy	Distributes energy to meet energy demand (-> affects pollution and energy available for final consumption) Negotiate to invest in new power plants and efficiency improvement options. Purchases resources (i.e. coal). Invests in efficiency improving, demand-side, or renewable technologies (affects water and emissions footprints)
Ministry of Agriculture	Decides how much food tokens should be consumed versus stored for next year Invests in irrigation and water in efficiency improving technologies (affects energy and water footprints)
International NGO	Negotiate and decide on how to allocate additional funding for alternative investment options

and these resources are represented by game tokens. Stocks are the core elements that make up a system—such as the amount of water in a river or number of trees in a forest, which evolves over time in response to the change in a flow. In this case, a flow may be the amount of seasonal rainfall and evaporation or number of trees cut and replanted for example.

In the second step, players make negotiated decisions on how best to allocate these tokens. Sequential decisions made on the water token allocation highlight the fundamental linkages that exist across water, food, and energy. For example, the existing coal plant requires cooling water for proper functioning, while irrigation is needed to secure food production. Based on the existing state of technology and infrastructure development, players learn that meeting food, water, and energy final demand—for both dry and wet seasons—requires forward-looking planning and hard choices between satisfying current needs and investing in development (Fig. 2).

One of the key insights of the *Nexus Game* concerns the multitude of water-energy-food trade-offs that exist within the portfolio of options for reducing resource use and emissions footprint. In evaluating cleaner energy options, players learn that an improved coal power plant may burn coal at a high temperature thus reducing coal needs and GHG emissions while increasing its water footprint. A micro-hydroelectric plant may be a cleaner option to generate power, but its capacity may not be reliable in

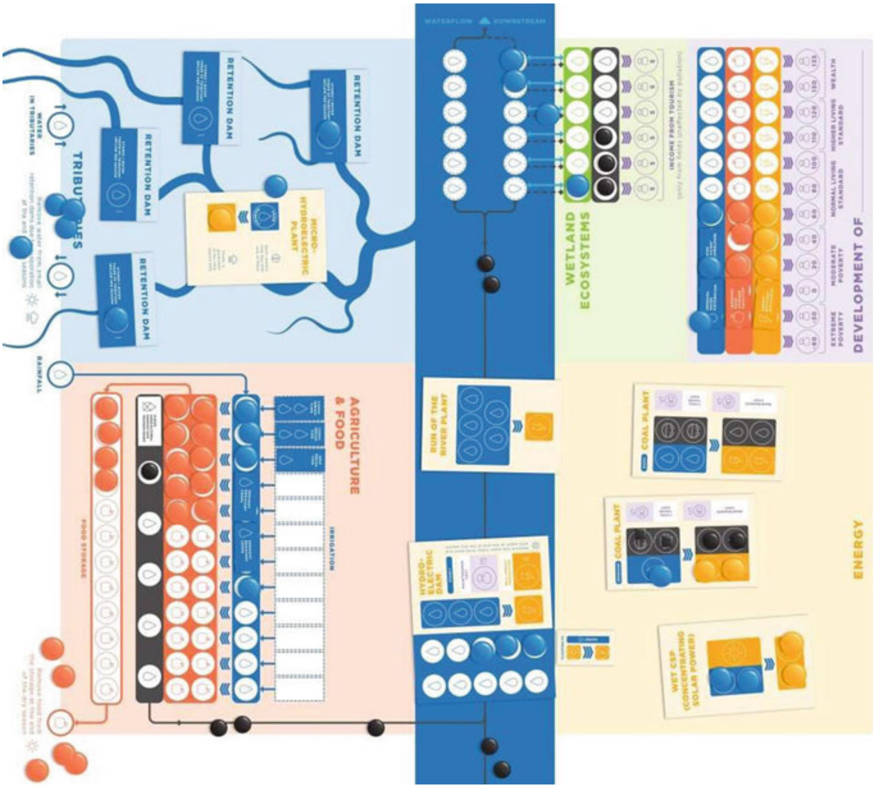

Fig. 2 Nexus Game board (only one country is shown) illustrating spatial relationships and technologies available in the game

the dry season. A rooftop PV, while slightly expensive, might be a better investment option in terms of water, energy, and emissions footprint. The game uses visual representations of these ‘flow’ relationships to help players gain an intuitive sense of water-food-energy input-output relations.

In addition to different energy production options, players are introduced to other resource-saving options such as demand-side management (for example, the promotion of more efficient residential electric appliances or drought-resilient crops). In the agricultural sector, players have options to improve production and storage capacities through measures such as canal and drop irrigation and reduction of food waste. To avoid information overload, only a small set of technological options are introduced each year, allowing players to progressively process measures to reduce water and energy footprint of their country (Fig. 2).

The game’s representation of the interdependency between upstream and downstream countries also prompts collaboration and coordination. Each player is given partial authority to decide on resource allocation within a defined ministerial mandate, and the game is crafted in such a way that a ‘siloed’ focus on the ministerial mandate, although possible, can lead to serious problems. For example, water storage and allocation decisions by the Water Ministry directly affect the resources available to the Energy and Agricultural Ministry, and technical options, such as irrigation, create additional dependency between the Energy and Agricultural Ministries. Sharing resources (and pollution) across national borders creates added tension and the need to engage in dialogue and negotiation. There are a number of channels in which players learn of lagged feedback loops, including the potential for pollution impact in the form of increased clean-up costs or reduced eco-tourism income, and the inter-temporal impact of food/water storage decisions.

The game imposes general restrictions on the players' roles, for instance, only the prime minister can negotiate and decide on international agreements, and each ministry is responsible for its investment decisions. At the same time, the process and mechanisms of negotiation, coordination, and collaboration are flexible and open to trial and error. This flexibility is one of the important mechanisms in which not only players learn to simulate open-ended negotiations of nexus resource issues, but researchers make observations on players' communication, collaboration, and decision-making styles.

Discussion

As a simple and stylised representation of reality, the *Nexus Game* represents the challenges facing a transboundary river basin. The game is designed to simplify many aspects of the real-world problems, such as urban-to-rural water diversion and different agricultural production systems (combination of crop varieties, etc.). As such, the game falls short of providing a comprehensive representation of nexus issues in the SADC region, nor in-depth technological details of nexus trade-offs and solutions. Extensive scientific information on these topics is available from more conventional means, such as integrated assessment models and technological feasibility studies (Conway et al. 2015; Entholzner and Reeve 2016).

In spite of these limitations, the key value of the *Nexus Game* lies in its mimicry of a negotiation process, which can be compared to a systems optimisation problem that aims to find the optimal allocation of water and monetary resources. When a system is complicated but reducible to a few key relationships, then achieving the optimal solution is a matter of knowing all parameters and functional forms. However, diverse preferences, value judgments, and worldviews as well as other interpersonal dynamics make it hard for participants to agree on a joint strategy. This aspect is further highlighted in the *Narubu Game* discussed below, which brings in multiple frames of the problem that preclude the identification of one "optimal" solution. Achieving optimality is also difficult under the *Nexus Game* 'because the authority to decide' is divided and delegated among multiple players who may have different perspectives on desirable futures. No person is, hence, fully in charge. Instead, negotiation and collaboration are necessary.

The negotiated solution is also complicated by strategic interests, decision heuristics used by players, alternative interpretations of the problem and solution space (as in the *Narubu Game*), different willingness/affinity for collaboration, and simple misunderstandings and misinterpretations. The game plays shed light on the human

Table 3 Major characteristics of socio-ecological systems adopted in the Narubu Game

Resource Systems	• A flood and drought-prone river basin in Southern Africa • Dam expansion project is ongoing, which when completed is expected to double sugarcane irrigation and urban water supply • Alternative projects include investments in wetlands and forests, as well as water conservation
Resource Units	• Highly variable water supply characterised by wet and dry season rainfall
Governance Systems	• Floodplain and water resource development is on the top of the development agenda • A River Basin Commission will advise on government policy. The Commission is carrying out a stakeholder participatory process to produce recommendations • There is a fixed budget that can be used for the policy options
Users	• Stakeholders in the participatory process are pluralistic, characterised by distinct worldviews (hierarchical, individualistic, or egalitarian)

elements, largely ignored by conventional technological assessments (Parson 1996a; Geels et al. 2016). The more value-laden aspects of collective decision problems are extensively articulated in the design of *Narubu Game* discussed below.

The *Nexus Game* is under further development along with accompanying instruction materials, such as lectures and reading materials, highlighting SADC nexus issues and the scientific basis of the technological solutions.

3.2 The Narubu Game of Many Voices

The *Narubu Game of Many Voices* (*Narubu Game*) illustrates the inherent difficulties of framing and solving complex water issues in a multi-stakeholder context. In contrast to the *Nexus Game*, which highlights the complexity of cross-sectoral decision-making, the *Narubu Game* takes place within a single sector policy arena, flood and drought risk management, with ramifications throughout the region and economy (Table 3).

The goal of the *Narubu Game* is to build an appreciation for the fact that wicked problems, which characterise water management in Narubu, have no single best solution but rather different solutions depending on how the stakeholders frame the issues and interpret the science. The multiplicity of problem definitions, along with divergent solutions proposed, typically do not stem from scientific uncertainty, but from what Rayner (2006) refers to as contradicting certitudes. That is, stakeholders downplay uncertainty in the science, and state uncertain evidence as though it is certain, to bolster their policy advocacy arguments. Since no solution is best from all perspectives, a socially accepted or robust solution can only be that which is agreed upon by the stakeholders.

The Game was developed and played as part of EU-AU-IIASA Evidence and Policy Event Master Class with the theme, "Why do experts speak with many voices?", which brought together approximately 100 participants dedicated to the field of water-energy-food nexus including policymakers and scientists working at both European and African national and regional institutions (JRC 2016).

Game play

The Ng'ombe River Basin is situated in the fictitious Republic of Narubu, which is characterised by its picturesque agrarian landscape of large sugarcane farms, small subsistence vegetable farms, and small-scale fisheries. In recent years, the country has enjoyed relatively high economic growth, owing both to its political stability and favourable export market conditions afforded by the growing demands for sugar in emerging economies. However, the growth has not benefitted everyone in the basin, and malnutrition is rampant especially among children.

The government is concerned that floods and droughts may be exacerbated by climate change and further threaten the livelihoods and food security of its population. The need for action and the limited budget have prompted the Narubu government to consult the Ng'ombe River Basin Commission (NRBC), a regional body in charge of facilitating consultation and collective management of the Ng'ombe River Basin. The NRBC recommends the establishment of a citizen participatory process aimed at advising on options for combatting flood and drought in the basin.

Stage 1: Establishing the contending policy frames

The *Narubu Game* simulates the citizen participatory process, where players (citizens in the process) are asked to play one of three roles corresponding to the hierarchical, egalitarian, and individualistic worldviews as postulated by the theory of plural rationality. The hierarchical voice is pro-control. It talks of "wise guidance" and insists that problems, such as flood and drought risk management, demand expertly planned solutions. This translates into top-down planning by government authorities with their network of experts. The individualist voice is pro-choice and pro-market. It calls for deregulation, competition, the freedom to innovate and take risks, and for "getting the prices right". It also calls for the explicit recognition of trade-offs among competing uses of resources, requiring attention to the costs and benefits. The egalitarian voice is strident and critical. Deeply sceptical of both the individualist notion of trade-offs (especially when lives and other "sacred" values are at issue) and the hierarchy's claim that their experts know what is best, this voice argues for a more holistic, moralistic, and cooperative approach to flood and drought risk management.

The players join one of three groups according to their leanings toward the hierarchical, egalitarian, or individualistic worldviews (as elicited with a short questionnaire). Each group is provided a "preferred" option for dealing with flood and drought risk, and the players can shape this option in their internal discussions. Table 4 summarises preferred policy options as advocated by the three contending voices.

Table 4 Stakeholder groups and their preferred flood and drought risk management options

Stakeholder groups	Preferred policy packages or options
Hierarchical (pro security and growth)	*First priority* Complete Kokuro dam Expand irrigation system *Second priority* Long-term weather forecasts with early warning system Education: entrepreneurship and flood resilience
Egalitarian (stewardship of water)	*First priority* Restore upstream wetlands and forests *Second priority* Subsidise small scale agriculture Flood warning system and improved systems for communicating long-term weather forecasts Education: entrepreneurship and flood resilience
Individualist (rational choice)	*First priority* Consideration of the costs and benefits of investments in the Kokuro dam and irrigation scheme, forestation, and wetlands Water pricing through public investment in monitoring systems *Second priority* Support for education (entrepreneurship and flood resilience) to empower individuals to choose alternative livelihoods and reduce risk

Stage 2: Establishing the science to support the policy frames

The players are given time to discuss their preferred option and are asked to choose a leader to argue for its implementation. To support their case, each group receives a “fact sheet” as described below:

Hierarchical group: This stakeholder group has a strong preference for the completion of the Kokuro dam, which will provide sufficient water to the large sugarcane farms and ensure Narubu’s economic growth. A large dam gives the government more predictability and control over the country’s water resources (the hierarchical voice is *pro-control*). The most ‘rational’ approach, according to this voice, is to manage water resource fluctuation. This can be achieved by closing the ‘water gap’ with the Kokuro dam, as predicted by state-of-the art hydrological models. There is no shortage of evidence to support arguments for this option. The group was provided scientific information on the future water gap as shown in Fig. 3. Hierarchist players learn that if future water shortages are to be avoided then additional sources of water are urgently required to serve the rapidly expanding new areas and meet a rapidly increasing water demand that is predicted to increase four-fold in only 12 years’ time.

Egalitarian group: The egalitarian group is deeply sceptical of the Kokuro dam, which will benefit mainly the large farmers and do little, if anything, to deal with the grave problems of feeding the poor; moreover the dam has serious downstream

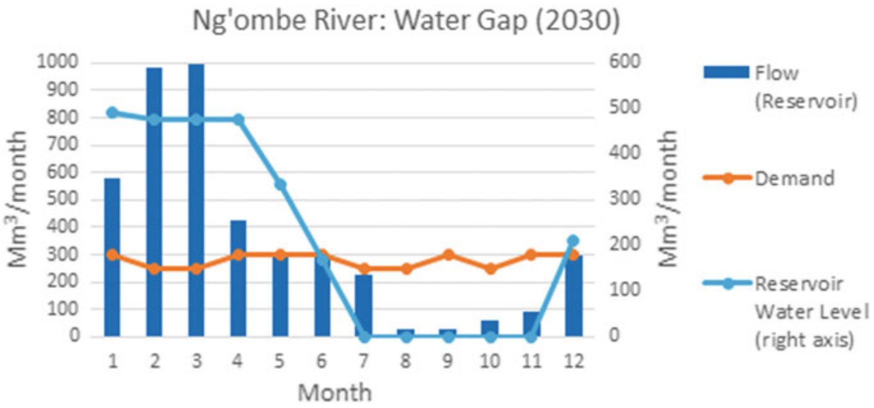

Fig. 3 Example of scientific information provided to hierarchical players ('gap' analysis). *Note* The gap increases in the future scenarios without an extension of the current dam

impacts on fisheries and ecology. This group argues for a more holistic, moralistic, and natural approach (the egalitarian voice is s*trident and critical*). The preferred policy package includes switching from water intensive sugarcane production to small-scale subsidised farms that supply local and healthy produce. The science this group receives for bolstering its arguments includes statistics on water and income distribution, poverty of the region, and the downstream ecological impacts of the dam. Egalitarian players argue that by reducing the sediment deposited downstream and eventually the delta, fish habitat is endangered and fisheries decline. The mono cropping of sugarcane leads to eroded soils, and the application of fertilisers risks serious water pollution.

Individualistic group: The individualist voice prefers markets over hierarchy, and recognises trade-offs among competing uses of resources. It calls for rational choice taking account of the costs, benefits, and alternatives (the individualist voice is *pro-choice and pro-market*). The science provided to this group documents the costs and benefits of the policy packages, including the economic, social, and environmental costs. This group learns that the Kokuro dam, in comparison with 'soft' measures like wetlands and deforestation, is less cost-effective in providing water and revenue. This group advocates water conservation through water pricing.

Stage 3: Argumentation and compromise

The groups appoint leaders who argue strongly for the group's preferred option, making use of the science provided to them. In the master course the game was played in eight repetitions (each with different players). The discourse became lively and contentious. Once each group has argued its case, the players are asked to seek a compromise. The compromise is aided with a "budget" board game, which gives each player a part of the full budget to allocate to the different policy options. No one group can achieve all its options without the support and budget of a second group (Fig. 4).

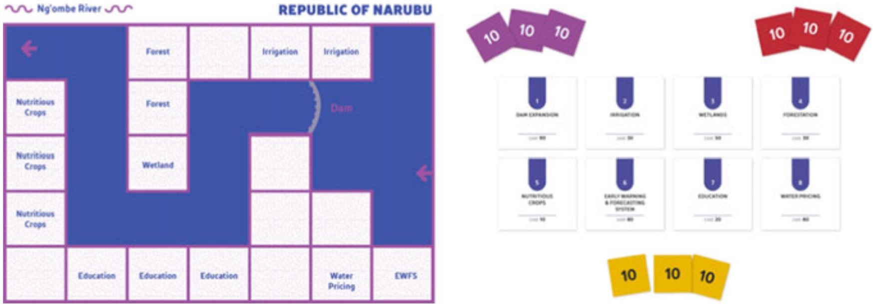

Fig. 4 Narubu Game play and investment options

In the eight repetitions, the arguments continued throughout the negotiated settlement. Particularly the hierarchical and egalitarian groups could not reach a common understanding or compromise; the individualists, alternatively, found partners either in the hierarchical group or egalitarian group, who were willing to support water pricing for reciprocal support of the Kokuro dam completion or wetland/forests, respectively. All groups could agree on allocating resources to educational programmes and early warning systems.

Debriefing and discussion

After the bilateral compromises were reached, the players in each group were asked if they would support the negotiated solution as a recommendation to the Ng'ombe River Basin Commission. In no case did all the groups agree to support. They did not reach then what the theory of plural rationality calls a “clumsy solution” where all voices support the compromise. This is illustrative of the policy stalemates faced by many such issues in the real world, and showed the need to continue negotiations (time was very limited in the game plays) and devise improved compromise packages.

From the comments in the debriefing sessions, the players appeared to have grasped the messages of the game. Wicked problems do not have single “best” solutions, only negotiated settlements, and the supporting science is shaped to reflect the contending frames and worldviews of the voices in the policy arena. According to one participant, the game made him realise that evidence-based policy is not about making the “best or optimal” solution given the science, but about listening to the voices (backed by different aspects of the science) to reach robust solutions that are accepted by the stakeholders. Many understood that this is how science-to-policy typically works in a democratic society.

3.3 *Forest Governance Game (Forest Game)*

The *Forest Game* takes the form of a repeated common-pool resource game, where players decide on sustainable harvesting strategies for shared forest resources. The

Table 5 Socio-ecological systems adopted for the Forest Game

Resource Systems	• A forest system which supports the livelihood of the local population, and a hydrological system characterised by periodic floods • The forest is used for two purposes: to earn income by harvesting timber and to prevent floods
Resource Units	• Trees which mature in one or three rounds (depending on game settings)
Governance Systems	*Forest Game (experimental)* No governance, i.e. no rules *Forest Game (deliberative)* Players classified according to their worldviews Three governance regimes are possible: • Hierarchy with rules on harvesting • Market with privatised forest plots • Egalitarian with equal distribution of forest income (players can vote to establish governance regime)
Users	• Stakeholders are pluralistic, characterised by distinct worldviews (hierarchical, individualistic, or egalitarian)

main purpose is to shed light on behaviours and governance rules that lead or resolve the tragedy of the commons. A somewhat unique feature is that the moderator has the flexibility to decide on specific game options (e.g., players' actions, available policies) to be represented. Unlike the *Nexus Game* and the *Narubu Game,* both of which are developed only for capacity building, the *Forest Game* is also used for experimental economics research. Table 5 shows two game settings, the first (experimental) played repeatedly at Vienna University, and the second (deliberative) played in one pilot run by participants in IIASA's Young Scientists Summer Programme. The *Forest Game* is also used regularly as an educational and awareness raising tool, played both in online sessions and workshops.

Resource sustainability and policy/governance stability are at the heart of the *Forest Game*. Using forest management as the focus, the games give participants a chance to reflect on the need for, and means to encourage collective action to avoid overharvesting by individuals with plural worldviews and motivations. The game thus addresses the social dilemma of self-interested behaviour leading to overharvesting on a common-pool resource.

Forest Game (experimental) has no imposed regulations on harvesting, and players confront the dilemma presented by the 'tragedy of the commons'; if each player maximises his harvest, the forest will be overexploited and collapse. Trees not only provide income, but also protect the players against floods. *Forest Game (deliberative)* provides a richer environmental context (more elaborate forest dynamics and additional actions for players) as well as brings simplified governance regimes linked with the three worldviews postulated by the theory of plural rationality: hierarchy, market/individualism, or egalitarian. With an initial questionnaire, the players are classified with regard to their worldviews, and their game play is later correlated with this classification.

Players of *Forest Game (deliberative)* can choose the governance regime: hierarchy, market/individualism, or egalitarian. The regime can be voted out and replaced by another. The idea is to explore the stability of any one regime given players with diverse worldviews, and ultimately the players can negotiate a regime that combines elements of hierarchy, market, and egalitarian rules. The game is thus constructed to explore the general hypothesis that stability (i.e. success or failure) of common pooled resource policy rests on the degree to which plural perspectives—as predicted by the theory of plural rationality—are integrated to provide multiple incentives needed to discourage free-riding behaviours.

Alternative versions of the *Forest Game* are played to test various hypotheses regarding institutional stability and collective action. Hypotheses tested are:

In the absence of institutions governing collective harvesting decisions, individual harvesting decisions (measured by the number of trees harvested) correlates with alternative worldviews as postulated by the TPR.
In the presence of a fixed governance regime, the level of player satisfaction regarding alternative policies correlates with alternative worldviews as postulated by the TPR.
In the presence of a dynamically changing governance regime, the dynamic patterns of policy change chosen by a group correlates with alternative worldviews as postulated by the TPR.
In the presence of a dynamically changing governance regime, inclusive governance and stable policies correlate with sustainable forest management outcome.

Both versions of the game blend case-study insights from diverse common-pool resource management contexts ranging from water governance in Iran (Yazdanpanah et al. 2013, 2014), oil exploitation in the Niger Delta (Umejesi and Thompson 2015), REDD+ in the Democratic Republic of Congo (ibid.), pilot whaling in the Faroe islands (Singleton 2016) among others.

Game play

Forest Game (experimental)

This version of the game starts from timber harvesting decisions made in the first of 20 years, for which the commonly managed forest—shared by five players—is available for logging. The common pooled forest is represented by an 8 × 10 matrix, from which each player may obtain 0.10 Euro for each timber harvested. For each round, participants were given one minute of harvesting time, during which they decided how many trees to harvest and how many to leave standing. The harvesting period is followed by another minute of a ‘result’ period during which players learned of their own and other players’ payouts. At the beginning of a following period, a part of forest regenerated: for each tree left standing at the end of last period, a new tree is added to forest (up to the maximum capacity of 80 trees). In addition, at least five trees regenerated in each period, regardless of the number of standing trees observed. All these parameters can be set flexibly by the game moderator depending on an experimental or educational design.

In addition to serving as a source of income for players, the forest can also serve as a natural defence against floods. Besides the motivation to maintain a sustainable income base from the forest, flood prevention further incentives for players to conserve rather than to cut trees. In each round, rainfall occurs to a differing extent (between 0 and 50 rainfall units). Each standing tree regulates this rainfall by one unit, i.e. the flooding potential of rainfall is reduced by the number of trees standing. A flood occurs if rainfall severity is above zero, after taking account the forest's regulating capacity. The flood damage is spread evenly across the players or unevenly depending on alternative experimental settings. This additional ecosystem service—flood protection—provided by the forest was used in the experiment to test if this additional co-benefit would result in more sustainable harvesting decisions (Bednarik et al. forthcoming).[6]

Forest Game (deliberative)

Forest Game (deliberative) is based on the assumption that in a democratic policy deliberation at least three different discourses can be recognised. This assumption is linked with the hypothesis that governance regimes for the collective management of common resources will be unstable unless they reflect the plural voices of stakeholders engaged in their use. To explore this hypothesis, the players can vote out regimes that run counter to their worldviews. Three governance regimes are tested:

Hierarchy, which imposes a limit on harvesting;
Egalitarian, where harvesting income is shared equally among all players; and
Market/Individualism, where the forest is privatised and each player is given an exclusive logging right to a certain area of the forest.

An important difference with respect to the experimental version of the game is that players maintained full and unconstrained communication among themselves, as opposed to the experimental version, in which only chat through a computer was allowed.

Forest Game (deliberative) was played by the participants of IIASA's Young Scientist Summer Programme in 2015 (Fig. 5). For each round, participants use what is called 'action points' to perform any of the following three activities: (i) logging (which yields revenue); (ii) tree-planting, and (iii) monitoring to prevent illegal logging activities. In the harvesting period, players individually decide how many trees to harvest and how many to leave standing. This harvesting period is followed by a 'result' period during which players learn of their own and other players' payouts. During this phase they can also vote for a preferred policy and a policy which garners the highest number of votes will come to effect in the following

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[6] There is an ongoing effort to expand the experimental setting to include specific governance regimes and their interactions with the participants' worldviews. To this end, players are also classified using a short questionnaire that determines their identification with the TPR worldviews: hierarchy, individualism, and egalitarianism.

Fig. 5 A Forest Game session during the IIASA's 2015 YSSP Programme

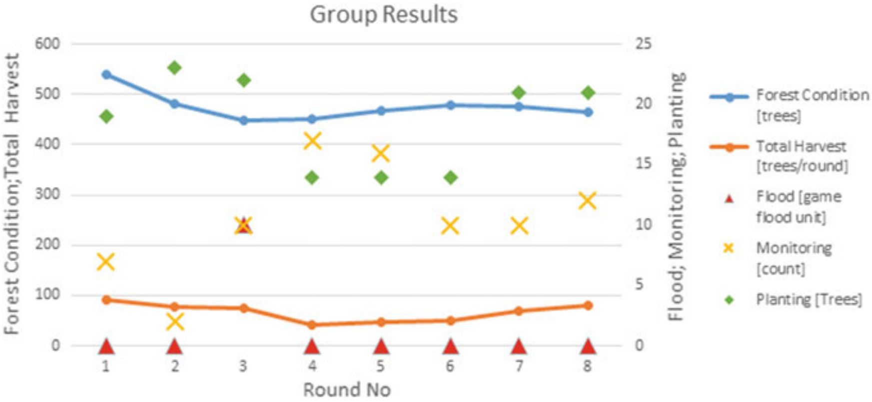

Fig. 6 Forest Governance Game (deliberative) group level results

round. Before each harvesting period, a part of the forest is regenerated: in this setting, a tree takes three years to mature. Figures 6 and 7 show the result of one game session.

During the first two rounds the harvest rate exceeded the regeneration rate. All players quickly realised that the harvest need was too high and would lead to forest collapse (i.e. a tragedy of the commons); however their collective effort to agree on a limit was not successful as one player attempted to free ride. In response, players collectively increased their monitoring activities. As a result, harvesting stabilised for a few periods followed by a slight decrease in the level of collective monitoring and rebound in harvesting rate. We also observed that participants discussed the policy

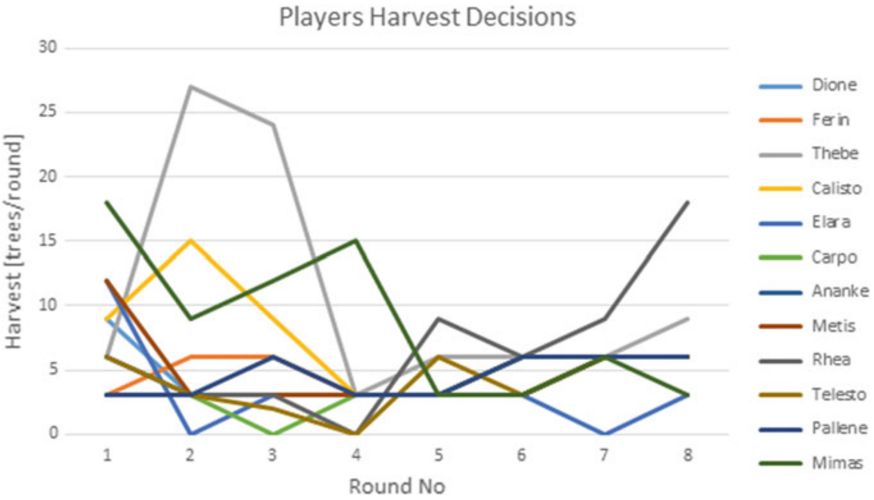

Fig. 7 Forest Governance Game (deliberative) rates of harvest by individual players

rules extensively, proposing specific governance designs that were not provided by the game software. Participants proposed and agreed on additional rules (e.g. monitoring responsibilities) to better shape the game outcomes. Even in a relatively short experiment of eight rounds, the game simulated dynamically evolving individual and collective behaviours.

In this game play, the players adopted the egalitarian regime of collective sharing of the harvesting revenue, and this regime was stable (not voted out) throughout the eight rounds of the game. However, we have observed that although egalitarian discourse was dominating, the individualistic discourse was also present: one of the participants at one point, for example, attempted to challenge other players saying: “we could be equally poor or equally rich” with an attempt to reject income sharing adopted by the group. Hierarchical discourse did not manifest prominently, however, which we believe to be due to a self-selection bias, both with respect to the whole YSSP programme and to the game itself. We hypothesised that a dominating worldview will be undermined by participants with different worldviews, but this was not confirmed, plausibly due to a high group uniformity observed in this particular game play. This was our conclusion drawn from this initial pilot run, and more games will be played upon recruitment of participants with a balanced mix of worldviews.

Discussion

The *Forest Game* versions illustrate how the ‘tragedy of the commons’ may or may not be averted through different regimes for managing common pool resources. The pluralistic voices represented in *Forest Game (deliberative)* are in fact a crucial foundation for sustainability. How society chooses among alternative policy instruments, such as top-down regulations, market-based instruments, or bottom-up community-based initiatives, can have a significant bearing on the effectiveness, acceptability, and stability of institutions. As Holling (2000) writes:

> Sustainable designs driven by conservation interests often ignore the needs for an adaptive form of economic development that emphasizes human economic enterprise and institutional flexibility. Those driven by economic and industrial interests often act as if the uncertainty of nature can be replaced with human engineering and management controls, or ignored altogether. Those driven by social interests can act as if community development and empowerment of individuals encounter no limits to the imagination and initiative of local groups. Each view captures its prescriptions in code words: regulation and control; get the prices right; empowerment; stakeholder ownership. These are not wrong, just too partial. Investments fail because they are partial.

From this perspective, an inclusion of diverse actors from the government, business, and civil society sectors is crucial not only because a balanced representation of 'interests' is needed, but also because a balanced representation of 'perspectives' is needed so that differently motivated people—within and across these sectors—work collaboratively for the achievement of the SDGs. This observation, increasingly validated empirically (Verweij and Thompson 2011; Linnerooth-Bayer et al. 2016; Scolobig et al. 2016), has significant implications for stakeholder engagement in nexus issues. Given stakeholders may respond differently to different policy incentives, nexus and SDG governance using any single instrument—regulation and standards, market-based instruments, or conservation alone, for example—would unlikely garner wide public support necessary. Hence, active participation of all parties are necessary as articulated in the SDG Goal 17 which aims to 'revitalise the global partnership for sustainable development.'

4 Concluding Remarks

Achieving the 17 goals of sustainable development challenges scientists, policymakers, and stakeholders to respond to interdependent nexus policy issues, and to rethink the way societies are organised for this response. Navigating a social transformation will require knowledge of interlinked resources systems, such as soil, water, energy, and waste, and a sound grasp of the diverse and dynamic ways in which our formal institutions, markets, and norms shape collective behaviours. Importantly, a social transformation in the management of collective policy issues will require buy-in from the many institutions and individuals concerned, and for this reason we need new approaches for involving stakeholders in nexus policy issues. Understanding what motivates our actions, and why, are important first steps in making collaboration possible.

In this position paper, we described three smart games, each serving as a space in which players (stakeholders) and researchers jointly explore alternative solutions to addressing complex resource management issues. The *Nexus Game*, developed in the context of the Southern African countries, highlights the dependency of decisions made in separate disciplines of water, energy, and agriculture. Finding an 'optimal' resource allocation is difficult in such an interdependent system, especially due to actors having separate but overlapping responsibilities, and alternative interpretations regarding the issues and goals. The *Narubu Game*, developed as a part of capacity building activities for science-policy, highlighted how policymaking using 'best science' is hardly as straightforward as it seems, particularly when "science" is selected to serve fundamentally distinct interpretations of the issues (or 'worldviews'). The *Forest Game* highlights how different institutional arrangements to prevent free-riding may have different longevity and effectiveness depending on how well such institutions accommodate the competing worldviews and interests of the stakeholders.

As illustrated by these games, addressing the interdependent drivers of and constraints on sustainability in a nexus context is not trivial because of the interdependency of the issues, the diverse frames of the problem and its solution, the wide-ranging distributional consequences, and perhaps most importantly, the heterogeneity of institutions and individuals with their plural concepts of rational action.

Simulation games are particularly apt in encouraging collective learning. A game is a playful forum for participants to articulate their opinions, to elicit the perspectives of others, and to build confidence and skills needed to negotiate a solution in contentious and uncertain situations. Of course, there are other participatory methods that perform complementary functions such as participatory modelling and scenario-based analysis, in which experts may assist in stakeholders' learning of scientific information, alternative policy options (see for example Van der Heijden 1996; Foran et al. 2013; Smajgl et al. 2015; Smajgl 2018, Chapter "Participatory Processes and Integrated Modelling Supporting Nexus Implementations").[7]

Similar with other stakeholder engagement methods, 'scaling up' these types of participatory process will likely pose a challenge, though a potential for 'scaling across' (i.e. learning through multiple applications of games in different contexts at a similar scale) will likely be high. As with analytical modelling, predictive claims of serious games together with an overgeneralisation of gaming insights from a handful of applications are common pitfalls to be avoided when using games in diverse stakeholder contexts (Parson 1996b). It is expected that gaming observations regarding preference and behaviours will likely deviate from those made in richer real-world contexts, and users of games should be aware of these limitations (Levitt and List 2007).

Unlike conventional instruction methods, gaming simulations provide a hands-on and flexible space for players to discover the lessons. Players' diverse interpretations of storylines and rules are hence a unique ingredient of what make games a dynamic, unpredictable, and self-discovering vehicle for stakeholder engagement.

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[7] It goes beyond the scope of this article to provide comprehensive evaluation of gaming versus other stakeholder engagement methods. However, we generally have in our experience applying these tools that methods such as scenario building activities provide a broader opportunity for stakeholders to evaluate futures (i.e. alternative pathways to achieving them and their consequences), whereas simulation games engage them more intensively (i.e, emotionally) in the process of achieving a particular path towards future. These methods are often complementary and can be used in an integrated manner.

These qualities distinguish a “complex system” from a “complicated system”, where the latter is defined as the sum of individual parts. Game plays encourage us to avoid the common pitfalls of systems-thinking:

> People who are raised in the industrial world and who get enthused about systems thinking are likely to make a terrible mistake. They are likely to assume that here, in systems analysis, in interconnection and complication, in the power of the computer […] is the key to prediction and control….. But self-organizing, nonlinear, feedback systems are inherently unpredictable. They are not controllable. They are understandable only in the most general way… We can’t find a proper, sustainable relationship to nature, each other, or the institutions we create, if we try to do it from the role of omniscient conqueror. (Meadows 2002)

Appreciating complexity in this way, we begin to see that the notion of nexus is not only a connection of nodes and paths: nor is it only about the interconnectedness of SDG goals and the co-benefits that an integrated solution may bring. It is also about the dynamic, and sometimes unpredictable, nature of our self-organising and integrated society that requires a pluralistic approach to collective problems, or regimes that combine authoritative control, market incentives, and bottom-up collaboration. Effective stakeholder engagement is hence crucial for the operationalisation of nexus, because by articulating and incorporating plurality in our policy design, and equipping us with the mindset to learn as we proceed, we can create social mechanisms that are reflective, tolerant, and adaptive.

As we have shown in this paper, a simulation game is a tool for aiding stakeholder participation in nexus policy issues. Simulation games can raise stakeholder awareness of and suggest solutions to the complexities of nexus problem solving: conflicting institutional mandates, social dilemmas, contending worldviews, plural interpretations of science, and the need for plurality in governance regimes. Systems thinking as encouraged in the games can help navigate the many challenges for operationalising the nexus concept, and as Koster (2012) puts it, ‘fun is just another word for learning’ (p. 46).

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Governance of Water-Energy-Food Nexus: A Social Network Analysis Approach to Understanding Agency Behaviour

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Abstract Research seeks to treat each resource embedded in the nexus as connected to the other resources. This approach is unique from other natural resource research agendas where the primary focus is on system efficiencies or examinations of a single resource. The nexus by emphasizing trade-offs places a premium on coordination. From a governance perspective coordination is not limited to decisions involving finances and allocation of trained human resources among different agencies organized both vertically and horizontally within a multi-level governance framework. Coordination could also be extended to include uses of data between public agencies, private sector and individuals. Due to nexus interconnectivity, we suggest here that social network analysis (SNA) is an appropriate tool that can divulge and highlight the relational complexities that exist within the nexus and among stakeholders that work with the singular elements of the nexus. We suggest that in the cases of organisations with a high institutional capacity by means of expertise, resources, and other assets, the Water-Energy-Food (WEF) network will be highly connected between resource areas in the overall network. Two network tie characteristics—density and centrality—are particularly important to understand a critical mass of interests within a multi-level governance framework. The paper concludes by arguing for the organisation of data covering different dimensions of the Water-Energy-Food nexus through the mechanism of an observatory that could potentially improve our understanding of thresholds of environmental resource use and the incentives required for public agencies to act in support of sustainable development.

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1 Introduction

In a recent paper on governance of the water-energy-food nexus three concepts of nexus nodes, thresholds, and critical mass were introduced (Kurian 2017). The paper emphasised that it is imperative that we develop an understanding of biophysical fluxes, public financing, and heterogeneity of institutional and biophysical systems, and the critical nodes at which they intersect to support the implementation of the Nexus Approach. We pointed out in this context that changes in legal and policy structures and institutions (rules) that guide their implementation, structural changes in the economy and society, and variability in the biophysical environment can lead to fragmented decision making due to non-alignment of rules within a multi-level governance system.

Decision making for management of water, soil, or energy resources is fragmented leading to sub-optimal environmental and social outcomes or rebound effects of policy, programme, and project interventions. On the other hand, when institutions (rules) regarding environmental resources (water, soil, or energy) are aligned with institutions relating to management of environmental services (water supply or wastewater) then resilience could be enhanced thereby mitigating the incidence, frequency, and intensity of environmental risks induced by natural or meteorological hazards such as droughts or floods. As research on water-energy-food (WEF) systems nexus governance has advanced in recent years (see Berardo and Lubell 2016; Berardo et al. 2015; Kurian 2017; Scott et al. 2015) the importance of understanding how the natural and human systems interact has become evident.

Despite the acknowledgement of the need to better understand human-environment interactions surprisingly little research has been devoted to explaining how decisions about WEF resources are made and how decisions in one domain affect decisions in others. The nexus by emphasizing trade-offs places a premium on coordination. From a governance perspective coordination is not limited to decisions involving finances and allocation of trained human resources among different agencies organized both vertically and horizontally in a multi-level governance framework. Coordination could also be extended to include uses of data between public agencies, private sector and individual agencies. The presence of a "critical mass of interests", often involving community and private stakeholders vested with decision making authority and discretion on issues of data sharing may determine the propensity for institutional "thresholds to public action" to be crossed in support of integrated, cross-sectoral, and harmonious interventions that advance the nexus approach in environmental governance.

Many methods have been created to examine the structural nature of a given social network. For example, a structural analysis can examine the extent to which an overall network is densely or weakly connected. It can also identify the most centrally connected nodes, or nodes that are connected to these central nodes, among other things. Although the map represents a primary way of visually depicting social networks, the method has been constructed with the benefit of a wide array of metrics that provide systematic statistical measures of the nature of the nodes and ties. In the description below, we make reference to some of the metrics that we would expect to accompany different possible hypothetical maps in WEF nexus governance networks.

Network science and network analysis have long been used as a method of examining relational data and have recently emerged as an important tool in policy and governance sciences (Berardo and Lubell 2016; Berardo and Scholz 2010; Berardo et al. 2015; Jasny and Lubell 2015; Lubell 2013). Socian Network Analysis (SNA) is usually associated with the creation of "maps" that depict types or strengths of relationships and transactions between and among people and organisations. Social networks are comprised of "nodes" and "ties," where the nodes are individuals or other social actors and the tie represents some relationship or transaction. The nodes and ties are compiled into an adjacency matrix and a graphical "map", which serve as the foundation of SNA.

While initially SNA omits all qualitative or descriptive information, recent developments allow network analysts to incorporate actor characteristics into the analysis (Borgatti et al. 2013). For example, a network comprised of individuals would benefit from integrating gender, age, and marital status. Within the WEF nexus framework, it may be useful to examine organisational size, age, geographic location, public-private ownership, natural resource domain, etc.

Another important aspect to network analysis in natural resource governance is outlining or capturing potential flows of resources and information (Bodin and Crona 2009). For instance, gatekeepers often use their strategic location as a network broker to attain power or exert control over some resource. This behaviour thwarts efforts to create efficient and sustainable communities. In addition to the individual connectivity characteristics, network analysis also measures aspects of the global, or overall, network. Measures of connectivity at the global level allow us to determine if the specific geographic area has a high or low level of connections, which will influence strategic cooperation and collaboration on projects dealing with policy implications on natural resources. Thus, network analysis allows for analysis of relationships at the node level as well as the network level.

SNA can thus potentially analyse and visualise multiple relational measures, i.e., density and centrality, to support hypothesis testing on the relationship between thresholds to public action and presence of a critical mass of interests involving public, private, and community stakeholders responsible for management of water, energy, and soil resources. For example, SNA can potentially illuminate the role of complex interactions between financing, technology, and leadership under predefined scale and boundary conditions. SNA of governance can potentially measure the extent to which decisions on water, or energy, or food/agriculture policy are coordinated or siloed. From a governance perspective, data visualization tools can map the density of ties and the extent to which ties between public agencies (for e.g. departments of water or agriculture) and between individuals within agencies are centred or biased towards one or the other. Further, knowledge translation tools such as scenario analysis and benchmarking can highlight possibilities for trade-offs to be managed through an integrated examination of both bio-physical and institutional thresholds across the continuum of environmental resources, services and risks (Kurian et al. 2016b).

From a research perspective knowledge translation is key to bridging the gap between science and practice through innovative uses of data. How can perspectives emerging from application of social network analysis to analysis of critical mass on interests help identify pathways for implementation of integrated and coordinated planning approaches and management strategies for management of environmental resources? This paper discusses prospects for organising data by specifying scale and boundary conditions to support construction of integrated indices as a knowledge translation tool. Integrated indices (or models) are amenable to conveying important information about organisational response and system performance. Moreover, integrated indices can enable scenario analysis and benchmarking of outputs, outcomes, and impact of policies, projects, and development programmes.

This paper represents an effort to advance a research agenda focused on WEF nexus governance. Here we propose the "social network analysis" (SNA) approach to investigating governance issues, arguing that SNA carries great promise for both advancing a governance research agenda and improving the efficiency of WEF nexus decisions themselves. In this paper, we provide an outline of how SNA can be productively brought to bear on WEF nexus governance issues, and a proposal for how such analysis would be accomplished through innovate methodological innovations in data aggregation, collection and dissemination. This paper therefore, has three objectives: (a) discuss the role of critical mass of interests and thresholds to public action, (b) outline use of SNA to study the role of networks among agencies and individuals and their effect on WEF governance, and (c) discuss the implications of such an analysis for organisation of data and analytical tools that enable knowledge translation in support of evidence-based decision making.

2 A Critical Mass of Interests for Management of the Water-Energy-Food Nexus

Nexus research thus far has emphasised the importance of "biophysical" thresholds that once crossed could make an environmental problem critical. For example, if temperature rises beyond a certain threshold, all factors remaining the same, the chances of an outbreak of forest fires could increase. If *E. coli* levels in water supplies rise beyond a certain threshold, then the risks of a cholera epidemic could rise exponentially. If use of essential resources is beyond the Earth system's safe operating space (Rockstrom et al. 2009), unacceptable environmental deteriorations threatening human development become likely, e.g., in the case of the Nitrogen Cycle there is an urgent need to re-engineer it in order to curb the environmental footprint (see chapter "The Urgent Need to Re-Engineer Nitrogen-Efficient Food Production for the Planet" by Pikaar et al. 2018). What nexus research has not examined so far is the question: what institutional thresholds need to be crossed for governments to intervene in public interest? Institutional thresholds in this context refer, for example, to a situation where laws and policies on water quality or biodiversity are backed by capacity of staff to interpret and apply rules that ensure compliance with a particular legal or policy guideline. This is the challenge confronting social scientists and development practitioners confronted with the task of mainstreaming nexus perspectives in the design of programme, policies, and projects (Kurian 2017).

Interdependence among environmental resources makes collective action imperative for management of environmental risks (Marwell and Oliver 1993). Two examples of environmental risks are water quality and soil degradation. Deterioration of water quality and soil degradation may be caused by a range of factors that include deforestation, land use change, and infrastructure construction. These drivers of environmental risks are influenced by human and agency behaviour. For example, subsidies for infrastructure construction may lead public agencies to build water supply treatment plants or groundwater pumping wells. On the other hand, privatisation of forest lands and attractive prices for timber products may encourage land owners to prioritise short-term profits over the longer-term environmental benefits of conserving forest cover.

Public interventions aimed at preventing agency and individual behaviour that prioritises individual profit over longer-term environmental benefits must acknowledge the common pool nature of a number of environmental resources such as, for example, forests and river systems the world over. The common pool nature of such resources that are most prone to misuse are characterised by the presence of costly and sometimes complex rules (institutions) that are required to exclude people from overharvesting resources. On the other hand, the absence of rules can also make it difficult to exclude people from overharvesting resources. Further, for every resource unit that is extracted there are implications in terms of the time it takes for the unit to be replaced through natural growth processes. Thus, collective action is required for these two reasons: (a) to ensure there is alignment of rules within a multi-level governance structure and (b) there is a balance between the distribution of interests and resources among the main users of a given environmental resource that is under risk of overexploitation (Marwell and Oliver 1993).

Since a large number of the world's environmental resources that are prone to degradation (water, soils, forests) are under governmental control, their common pool nature makes collection action imperative both at the level of agencies and resource users (Ostrom 1990). This is why we argued that an examination of "thresholds to public action" must consider the role of critical mass of interests since it can predict prospects for collective action involving stakeholders drawn from public, private, and community groups (Kurian 2017). The presence of a critical mass and its ebb and flow can be influenced by changes in legal and policy structures and structural changes in economy and society (example: prices in markets for certain agricultural products or public-private partnerships). The presence of a critical mass may also reflect the alignment of rules among different levels of government often involving public, private, and/or community stakeholders (e.g. departments of forestry, agriculture of private water providers). However, fleeting the reality of a critical mass, it is imperative that we understand the conditions that make it possible for its emergence in the first place. This is because the emergence of a critical mass can potentially be responsible for big and long-lasting institutional change that affects prospects for the

Nexus Approach. As a result, we posit in this paper that SNA has much to offer in terms of our understanding of the role of connectivity and cohesion and frequency of ties between public agencies (ministries and departments) and between and among officials in public agencies and representatives of community resource user groups.

3 Social Network Analysis to Study Water-Energy-Food Nexus Governance

Nexus research has highlighted three dimensions of governance that are key to implementation of integrated approaches to environmental planning and management: (a) distribution of environmental risks, (b) externalities, and (c) institutional capacity (Kurian 2017). This perspective is different from prior governance analysis that focused on a descriptive analysis of laws and policies and provided in many cases a justification for transplanting frameworks in the hope that good practices in one location will work in another context irrespective of differences in institutional trajectories. Below we discuss a few examples of environmental risks and institutional capacity to appreciate the role of SNA in advancing our understanding of a critical mass of interests in nexus governance.

3.1 Environmental Risks

Sustainable management of environmental resources (e.g., water, soil and air) requires a holistic approach not only between the individual resources but external drivers such as climate hazards. The quality and availability of environmental resources is highly dominated by human activity and climate variability and change. Compared to developed countries, the impact of climate change, in addition to fast population growth and urbanization, is significantly higher in developing countries due to their low capacity to manage and adapt to the change. In Africa, particularly East Africa, the majority of people (>80%) are mainly dependent on agricultural production and the sector adds about 50% to the country's GDP (FAO 2014). In addition, the land for agriculture is mainly dominated by smallholder farmers, and the access to advanced irrigation system is limited to specific regions. This condition makes the impact of climate change and variability more severe in areas where the majority of residents depend on agricultural production. For example, a failure in two rain seasons in East Africa would leave millions of people food insecure and in need of emergency assistance (ActionAid 2011, 2016). Therefore, water availability as a result of climate variability and poor management significantly affects both agriculture and the energy sector. In addition to the poor management of environmental resources in East Africa, the impact of climate change is projected to increase with rising temperatures and decreasing rainfall (Niang et al. 2014), which requires development of sustainable adaptation options. For this purpose, high quality data with higher resolution (spatial and temporal) is required as input to sector models to manage water for agriculture and energy use and to develop sustainable adaptation strategies. However, this type of data is not freely available and sometimes it is even impossible to find site-specific data from local meteorological organisations.

3.2 Institutional Capacity

An underlying theme of WEF nexus research is the idea that connections and trade-offs must be better understood, and that decisions that affect the uses of one resource must take into consideration the impacts on the others (Scott et al. 2015). Indeed, the implicit goal of WEF nexus research is, arguably, coordination of these decisions such that the connections or trade-offs are minimised. We therefore suggest that effective governance of the WEF nexus requires a high level of cooperation and coordination among decision makers, stakeholders, and managers (Ansell and Gash 2008). Conversely, decisions made in one domain with no regard for impacts in the others inevitably yield sub-optimal results.

Specifically, analysis has turned its attention to understanding some of the conditions under which nexus governance networks are more or less connected. Are there examples of food-energy-water governance networks that are highly connected? What makes these networks connected when others are much less so? Theories of nexus governance have not advanced to the point where comprehensive statements about these conditions can be made, but this paper proposes building on existing works to advance this task. Here we choose two specific characteristics that are thought to distinguish highly connected nexus governance networks from poorly connected networks, both developed by Kurian (2017). The first of these is the institutional "capacity" of organisations and agencies to work with others. We hypothesise that when organisations in a governance network possess high capacity (high amounts of resources, expertise, and other assets) they will be part of a governance network that is well-connected. This could lead to effective enforcement of rules within a multi-level governance system and improve prospects for "thresholds to public action" to be crossed in support of integrated and coordinated actions in environmental planning and management. On the other hand, when organisations in a network possess low capacity, they will be part of a governance network that is poorly connected as outlined below.

3.3 Application of SNA

An important use of SNA is to determine in any WEF nexus system the degree to which coordination actually seems to occur. Our expectation is that in most WEF systems, there is little or no coordination. We would expect to find that there are three individual networks representing the three domains of food, energy, and water, and that these networks are largely disconnected from each other. Figure 1 captures the hypothetical image of a very compartmentalised or siloed version of the nexus governance network. There are three network domains in the figure, one representing governance of water, another of food, and the third of energy. The blue squares would represent specific organisations within a defined geographic governance area and the red circles would represent categories of organisations. For example, we show a hypothetical organisational category called "Wastewater Governance," with two specific organisations, "Clean Water" and "Wasted H_2O", key to this category of governance. The point is that when SNA is applied across all three domains, we expect to find very few interconnections.

The siloed nature of the nexus governance network depicted in Fig. 1 highlights the idea that the organisations and people involved do not frequently communicate, collaborate, or cooperate across domains. There are some interactions that are present within the nexus domains, but there is little interaction between domains. Empirically, a local nexus network could be even more disconnected than what is shown in Fig. 1, as there are some organisations in each division that correspond to two organisation category types.

Note 1 For Fig. 1, we are primarily interested in node centrality and network cohesion. These values will reveal (a) which nodes are highly connected to other nodes and (b) to what extent the network as a whole is connected or disconnected, or a general measure of connectedness. Actor centrality reveals which actors are the most connected to other actors. This would indicate which actors would serve as suit-

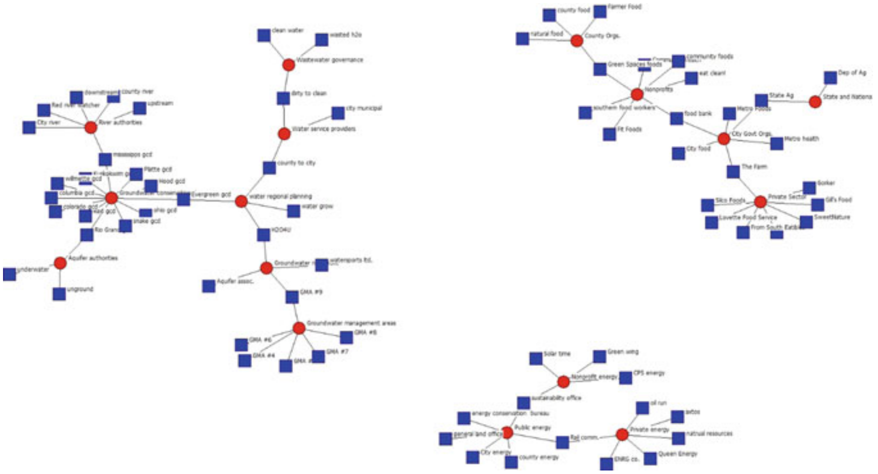

Fig. 1 Example of WEF governance network that is "siloed". There are three network domains in the Figure, one representing governance of water, another of food, and the third of energy. The blue squares would represent specific organizations within a defined geographic governance area and the red circles would represent categories of organizations

able access points for policy interventions. In a highly connected network we would expect to see high levels of network density which is expressed as a ratio of the total number of ties present to the total number of ties possible. Density ranges from 0 to 1 where highly connected networks have values closer to 1 and disconnected networks have values closer to 0. Density informs on how well connected the different portions of the network are. Another simple metric of connectivity between nexus domains is a count of number of network components. Components are the number of disconnected, or siloed, portions of the network. This is easily identifiable by the number of connected groupings. In Fig. 1, for example, there are 3 components. When nexus networks are siloed we would expect to see a large number of components.

Note 2 Overall network density will provide information on the extent to which the observed level of connectedness is high or low in comparison to the potential level of connectedness, or number of potential ties. When connectivity among the water-energy, and food domains is high, the high value of density suggests that, overall, the network is densely connected. This phenomenon is ideal when implementing nexus policy or interventions in the nexus.

Note 3–4 For Figs. 3 and 4 we would compute connectivity measure using network attributes. We assign a binary indicator of which network domain the organisation pertains to. We then examine the rates of connectivity between network components. In a network where institutional capacity is high, we expect to see high levels of between-group connectivity. Similarly, in Fig. 4 we would expect to see low levels of connectivity between groups as institutional capacity is low.

Figure 2 shows what a highly connected nexus governance network might look like. Here, organisations from each domain of the nexus seem to interact and cooperate, or are in communication with organisation types in the other domains. There is much interaction between and within the nexus domains. From a nexus governance perspective, this hypothetical connected structure is presumably desirable in order to achieve high levels of resource efficiency. High levels of connectivity imply sharing of information, resources, and strategies to increase efficiency and sustainable practices. Similarly, consideration of trade-offs between resources (the subject of specific questions posed to all stakeholders) is likely to be present in highly integrated networks. In a highly connected network the transaction costs of resource trade-offs are expected to be reduced because there is more information and resources flowing through the network.

Increasingly, analysis of nexus governance networks has sought to move beyond the network descriptions depicted in Figs. 1 and 2. When organizations in a governance network possess high capacity they will be part of a governance network that is well-connected, as depicted in Fig. 3. We would expect that eigenvector and closeness centrality, as well as density in the map in Fig. 3 to be high, or show that network actors are well connected to other network actors. When organizations in a network possess low capacity, they will be part of a governance network that is poorly-connected, as depicted in Fig. 4.

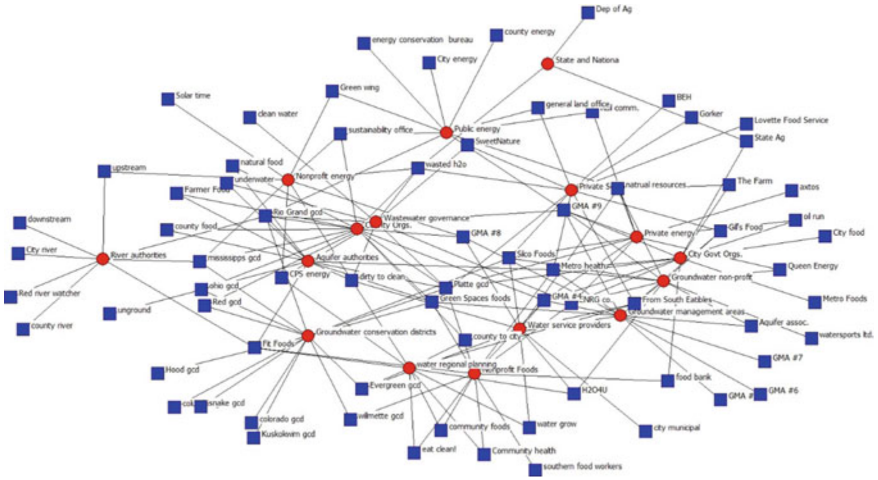

Fig. 2 Example of WEF governance network that is "coordinated"

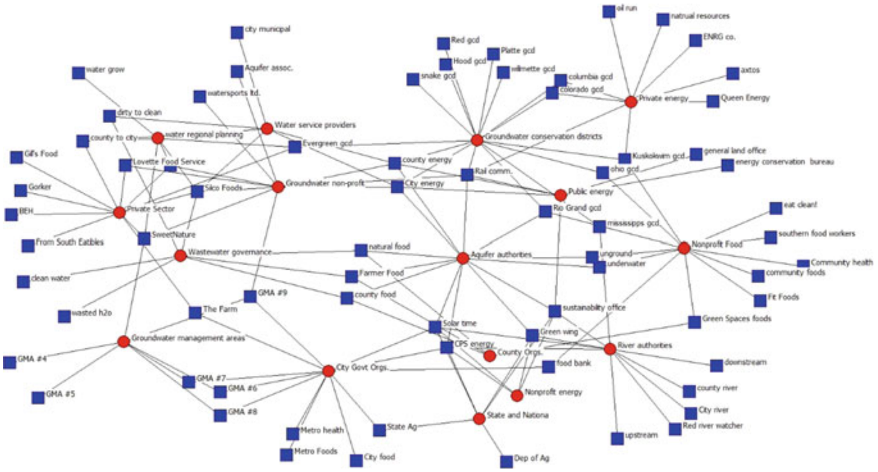

Fig. 3 Example of WEF governance network with "high capacity" institutions showing high levels of between group connectivity

4 Organisation of Data and Analytical Tools that Enable Knowledge Translation in Support of Evidence-Based Decision Making

Network science recognises the inherent and complex interdependencies that create the WEF nexus and provides means to examine relationships not only between individuals but also between individuals and organisations or institutions. The traditional

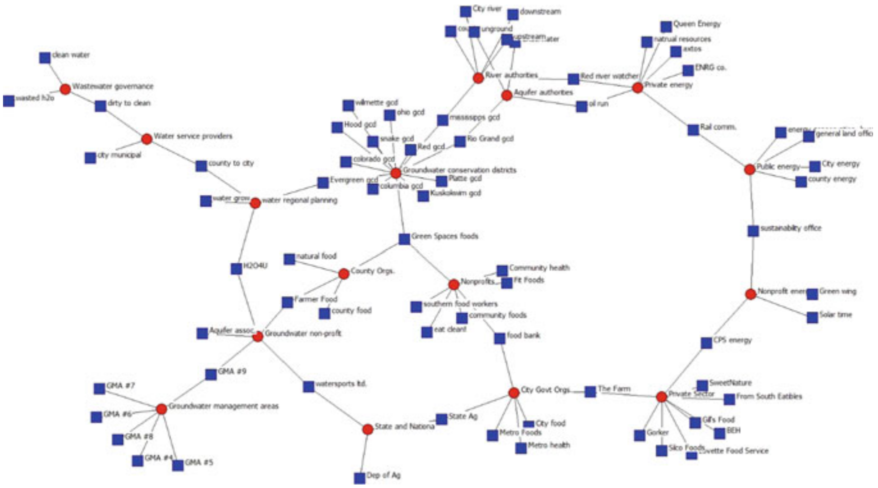

Fig. 4 Example of WEF governance network with "low capacity" institutions showing low levels of between-group connectivity

approach to policy analysis and governance focuses on examining a single policy, policy domain, or phenomena at a single point in time. This approach treats multiple processes that occur simultaneously as a function of some decision-making agenda or leaves them wholly unresolved. In contrast to the singular approach, Lubell (2013) updated the Ecology of Games (EG) framework to address the institutionalised nature of policymaking. Essentially, the theory argues that there are multiple policy actors and organisations that participate in the decision-making process, all existing within one geographically defined policy area. A policy game consists of policy actors that participate in a "rule-governed collective decision making process called a policy institution" (Lubell 2013, 538). Perhaps more importantly, the EG approach suggests that actors may well be engaged in policymaking in more than one domain simultaneously. To understand the decision making "game" for a given policymaker or organisation, the roles that that policymaker plays in all domains is required (see also chapter "Games for Aiding Stakeholder Deliberation on Nexus Policy Issues" by Mochizuki et al. 2018). The EG framework and network analysis provide new insights to understanding governance strategies in the WEF nexus. It suffices to say here that SNA promises to provide a means to examine the complexity of decision making networks even across policy domains.

The EG framework applied to nexus governance seeks to understand how governance networks operate within domains and across domains (Lubell et al. 2010; Mewhirter et al. 2017). To achieve the kinds of efficiencies between water, energy, and food governance presumably requires a high degree of connectivity between networks (Scholz et al. 2008). If such connectivity exists, the EG framework posits that different decision making entities over water, energy, or food would ideally work simultaneously across natural resources within a geographically designated area. The question is whether or not these entities have any communication about what effect their behaviour will have on other natural resources of the WEF nexus, or if these governance bodies cooperate in their respective requirements and duties.

SNA is typically conducted with benefit of information about how connected different organisations, stakeholders, and decision makers are (Leach et al. 2002; Lubell et al. 2012). While there are many ways that decision makers and stakeholders from water, food, and energy can interact, we propose to examine two specific connectivity behaviours—interpersonal interactions and communications. For each individual involved in nexus governance, we would seek to determine how frequently interpersonal interactions and communications take place. For example, after assembling a comprehensive list of agencies, organisations, stakeholders, and decision makers in each policy domain, we would survey decision makers or agency informants and ask each of them a number of questions, such as:

- How often do you speak to a member of [water, energy, or food governance organisation or agency]?
- How frequently do you communicate with individuals from the following [water, energy, or food governance organisations] about specific projects?
- In the course of doing your job, how frequently do you come into contact with other employees from the following [water, energy, or food governance organisations]?

While the frequency of communication and interaction is a first step in identifying a connection within the nexus, SNA also seeks to take into consideration the content of individual communication. This is accomplished by asking about specific kinds of communications or interactions. For example, the decision maker or informant may be asked:

- How frequently do you have meetings with [water, energy, or food governance organisations] about how to best manage water resources?
- How often do you or your organisation collaborate with [water, energy, or food governance organisations] on energy conservation projects?

Have you or your organisation ever been involved with any of the following organisation on a local planning commission that focused specifically on food, water, or energy?

4.1 Operationalizing Key Metrics in the SNA Toolbox

The values from the survey questions are then used to create the network graph demonstrated. There are many metrics in the SNA toolbox that can be used to determine the extent of connectivity. Here, we highlight two of the most frequently used: centrality and density.

Centrality measures the extent to which individual nodes are connected to other nodes in the network. Degree centrality is a simple count of the number of network actors each node is connected to, or the total number of connections. Degree is able to be analysed as a directional (in-degree and out-degree) and non-directional, which have different implications in how information may flow through the network. Other measures of centrality, eigenvector, and closeness, for example, incorporate measures of the actors' connections into the measures. For example, eigenvector essentially measure the extent to which the focal actor is connected to other well-connected actors. Closeness measures how close, according to graph theoretic measures, each actor is to every other actor in the network. Both of these measures offer an effective measurement of how soon the actors may be made aware of information flowing through the network. All three measures will reveal how connected the actors are to their surrounding network.

Density is a more direct examination of the levels of connectivity in an interpersonal and global network. It is expressed as a ratio of the number of ties present to the number of potential ties. Density examines whether or not the actors' connections are also connected to each other. In other words, a network is densely connected if actor A is connected to actors B, C, D, and E, and actors B, C, D, and E are also connected to each other. If actors B, C, D, and E are not connected to each other there are low levels of network connectivity and high levels of brokerage or sparseness. This measure can also compute an overall density, or how connected the entire network is to each other. If all actors are connected to all other actors (a relatively rare occurrence) there will be high levels of connectivity in the overall network.

These SNA measures offer opportunities for unique insights into interventions and policy implementation for a given population of nexus actors. Without structural analysis and the accompanying visualization, it is difficult to capture and identify the construct of interconnections which may be necessary to determine a overall network of interaction. Indeed, research suggests that when individuals are asked to explain or create visual representation of connections in their own friendship networks, results are surprisingly distinct from the connections as they exist in reality (Krackhardt 1992). In short, people are often not fully aware of the interconnections within their own respective networks. This gap between actual and perceived networks would likely only be even greater in the context of inter-organizational networks. To further illustrate, consider the organization Green Spaces Foods (GSF) in Fig. 4. GSF (represented by the blue square) is connected to three categories of organizations. Based on the other organizations also tied to these three categories, it can be inferred that GSF is well connected to other organizations. Given that GSF is a well-connected actor, it is in a unique structural location to act as a hub for the diffusion of information or nexus cooperation strategies. In this sense, policy or management interventions could use the well-connected organizations as access points to address nexus issues more effectively given the connectedness of the network actor. Another possible situation that is common in network studies is that one organization or node that was originally thought of as unimportant is revealed to be vital to the overall connectedness of the network. For example, certain organizations will naturally stand out as prestigious, large, historically relevant, or for some other reason. Other organizations may be less predominant but still play an important role in connecting otherwise disconnected actors. SNA can inform decisions and policy makers which network actors are central or important to the network construct that may otherwise go undetected.

SNA within nexus networks also reveals unique and important points of information about the how siloed or connected the organizations are within each nexus domain. This is particularly important to nexus studies as examinations of cooperation within the energy, food, or water domains may not divulge how invested each domain is in the other two, or how conscious one domain is of their potential impact on the other two domains. Similarly, decision processes and policies should differ based on high levels of connectivity among nexus domains vs siloed and otherwise disconnected networks. Once network structures and key actors are determined, policy recommendations could reflect the structural makeup of the network. For example, a piece of legislation enacted in a highly siloed network (see Fig. 1) could reflect the disconnectedness and seek to bring organizations together to enhance cooperation. Without knowing the structural network of nexus connections, effective ways of strengthening the nexus may be difficult or impossible to prescribe. Decisions about energy will not likely take food and water related issues into consideration, or water decisions will not take food or energy into consideration.

In addition to the measures and concepts that are unique to network science, including those outlined above, quantitative outcomes of network structures are often used in conjunction with other methods. For example, the quantitative measures of network dimensions are often used as variables in more common multivariate statistical analyses to estimate the influences on different network characteristics, or to estimate the effects of different network characteristics on some other outcome variable. Each network measure (i.e., density or various centrality measures) measures a specific to the network actor characteristic. This allows researchers to examine the significance of the influence of network connections on a given outcome. While there are statistical challenges and pitfalls that need to be addressed (Borgatti et al. 2002), network analyses offer unique opportunities to test numerous hypotheses.

5 Beyond Network Descriptions: Making Possible an Explanation of Differences

An important characteristic of networks, also rooted in the work of Kurian (2017), suggests that the extent to which a given critical mass of interests within a multilevel governance framework produces effective resolution of critical trade-offs can be systematically measured. For example, Kurian (2017) develops an example of a "wastewater reuse effectiveness index" (WREI) that measures, for a given jurisdiction (usually a nation), an important policy outcome or result. What SNA promises to add to this analysis is the inclusion of a key explanation for why some jurisdictions seem better in producing high effectiveness while others produce less effectiveness. Our expectation is that better connected networks will produce higher levels of effectiveness. An example of this is shown in Fig. 5, meant to convey the expected patterns

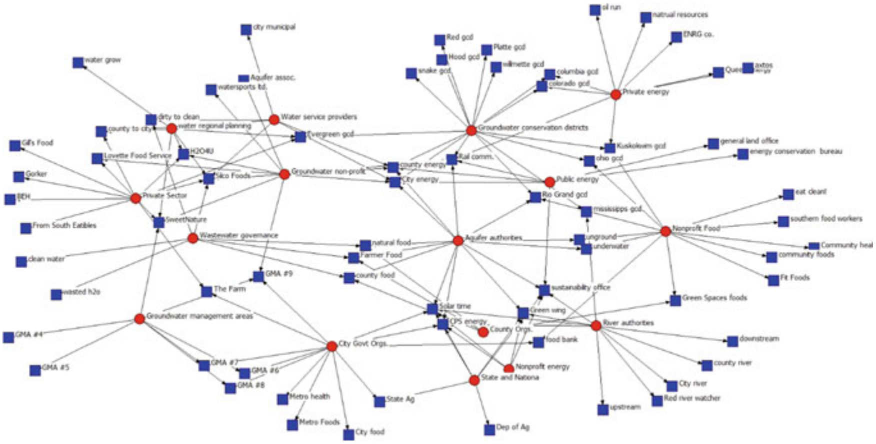

Fig. 5 Example of WEF governance network where WREI values are high

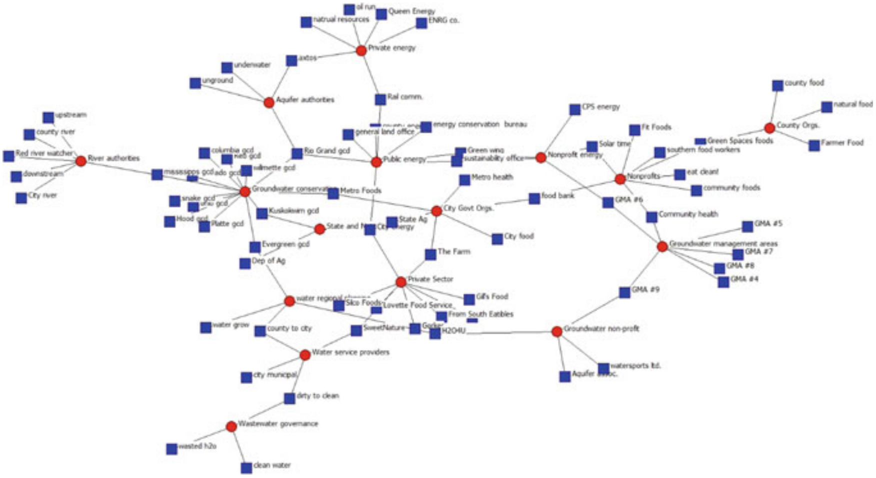

Fig. 6 Example of WEF governance network where WREI values are low

of nexus governance where the WREI values are high, i.e. where wastewater management is highly effective. In short, we expect that the nexus governance network will be highly connected (food, energy, and water governance are closely connected) where wastewater reuse is highly effective. The opposite expectation is depicted in Fig. 6, where a poorly connected nexus governance network is associated with low WREI values. The availability of good quality data in a cost-effective and time-sensitive fashion is crucial for network analysis to ascertain the key dimensions of a critical mass of interests within a multi-level governance framework (Mannschatz et al. 2015). This is an issue we examine in the following discussion.

Note 5 In addition to the metrics used in Figs. 3 and 4, we can identify within-group connectivity using network attributes as well as determine if there are any statistically significant connections between groups. Network attributes, like actor characteristics, are classifications of network actors. Within the nexus network, a basic and logical attribute would be to characterize each organization as part of the water, energy, or food domain.

5.1 Mapping Biophysical Processes in Data Scarce Regions

Data scarce regions are the most vulnerable to climate change and variability (Wilby and Yu 2013), which affects food security globally and particularly in Africa due to their technical and financial capacity to cope with the change. In addition, managing environmental resources (e.g., water and soil) becomes more challenging in data poor regions. In recent decades a number of global and semi-global data sources (remote sensing, reanalysis, and output from global and regional climate models) have become available with higher spatial and temporal resolutions and coverages that can be used as input for sector models to manage environmental resource even in very complex topography and remote areas (e.g., Sheffield et al. 2006; Chaney et al. 2014; Funk et al. 2015). Also tools for data visualisation are becoming increasingly sophisticated to support stakeholders and decision makers (Mannschatz et al. 2015). However, before using the data as input for different sector models to manage resources, each product needs to be evaluated with ground observations. Spatially and temporally limited ground observations from meteorological stations are available at the meteorological organizations of the respective countries and National Climate Data Center (https://www.ncdc.noaa.gov/). For purpose of evaluation with ground observations, the global and semi-global data sets are first spatially downscaled to regional and point scale using statistical software such as R (R Core Team 2012) and Climate Data Operator (Schulzweida et al. 2009). Both R and CDO help manipulate, clean and merge daily data products to create long time series for evaluation. A number of statistical parameters are used to evaluate the accuracy of each data product such as using the coefficient of determination, correlation coefficient, Root Mean Square Error (RMSE), Mean Square Error (MSE), bias and relative bias, probability of detection (POD), and False Alarm ration (FAR). Finally, based on the outcome of this evaluation, the most accurate data sets are selected and can be used for further analysis and input for regional and local scale sector models. An important output of the data evaluation procedure could be a synthesised data set incorporating several data sources.

5.2 Working with Integrated Indices

Our experience of working with UN agencies, national governments, and universities to develop a prototype WREI methodology highlighted several shortcomings of research projects that aimed to achieve practical relevance (Kurian et al. 2016a). For one, implementing agencies work with limited data covering a limited number of aspects; for example, ambient water quality. However, to better understand the scope for implementation of nexus perspectives in planning and management of environmental projects, attention to institutional and socioeconomic factors is critical. For example, factors such as politician's awareness, cost-recovery, decentralisation, and willingness of consumers to pay for services need to be accounted for. This is where integrated indices can play an important role in supporting an improved understanding of the role of a critical mass of interests in environmental management. SNA through its focus on density of ties among individuals both within and across organisations (spanning public, private, and community entities) can go a long way in improving our understanding of the conditions under which a critical mass of interests emerges to act in support of environmental management that is integrated, equitable, and sustainable. This would necessitate a deliberate attempt to engage with databases, trend and sensitivity analysis of select data sets to generate hypotheses, and validate and recalibrate the models based on in situ data collection.

5.3 The Use of Observatories

As we have seen so far, access to quality controlled and accurate data sources is crucial for purposes of managing environmental resources at regional and local level, projecting future climate using climate models, developing scenarios, and computing site-specific thresholds. Observatories can produce site-specific information (e.g., rainfall and temperature), develop scenarios, define thresholds, and visualise results for different purposes such as decision-making process. Observatories (Kurian et al. 2016a, b) help researchers to easily access refined data sets for their area of interest without learning the large data set processing tools such as multiple packages in R, CDO (climate data operator), or NCO (NetCDF operator), which saves time and resources. Taking a hydrological model, for example, and by retrieving location-based minimum and maximum temperature and rainfall data from an observatory, one can make a watershed-based soil-water budget analysis and develop scenarios. Access to data also enables researchers to compute different extreme indices by defining their own or improving existing thresholds for managing environmental resources more sustainably, which requires high quality data sets. In addition, observatories can also support the refinement of environmental models through reusing or expanding the uses of data for a given geographical context (Kurian et al. 2016b).

Observatories can go a long way in facilitating the development of integrated indices. This is possible by making available a diversity of models (e.g., biophys-

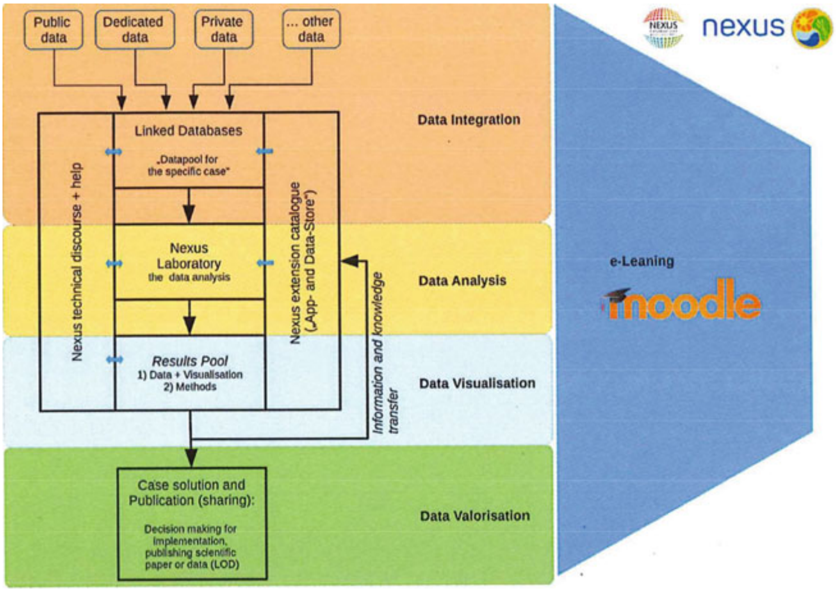

Fig. 7 Stylized workflow for an observatory

ical models of climate but also institutional models of agency behaviour) and/or by facilitating the selection of the most suited and appropriate model/set of models (Mannschatz et al. 2016). Further, observatories can enable the generation of research hypothesis that borrow on perspectives from a variety of disciplines to construct a nexus index. This process would necessitate engagement with a broad variety of literature covering biophysical processes, institutions, and natural resources management for which online learning tools may be made available (Fig. 7). An important outcome of transdisciplinary research effort would be an engagement with both quantitative and qualitative research instruments, agent-based modelling approaches, and methods with the potential to support knowledge translation through robust use of scenario analysis, benchmarking, and data proxies in research (Foran 2015). However, a pre-requisite for an effective observatory is the development of a typology that can guide data application (see Box 1).

A robust typology would clarify the following issues: (a) trade-offs for biophysical and institutional domains for along the continuum of resources, services and risks and (b) thresholds for bio-physical and institutional domains along the continuum of resources, services and risks. For specific threshold analysis the types of data sets ranging from project data, research data and profile data needs specification with the goal of developing integrated indices. Finally, when the combined power of science (e.g. climate sense), computing (e.g. linked databases) and outreach (partnerships for data sharing) are established outcomes for science and nexus implementation can emerge, thereby lowering the time and costs of research and improving the chances of evidence-based decision making (Mason 2016).

Box 1: Identifying nexus typologies: The opportunity for methodological synergies

Science can inform nexus practice

After the Bonn 2011 Nexus Conference, the conference website was turned into the Nexus Resource Platform, which was to unite the globally scattered content on the nexus. The relaunch in 2016 by the GIZ-hosted Global Nexus Secretariat pursues this approach further by creating a neutral and inclusive nexus branding to ensure that all parties can join and create or co-create content for the Nexus Resource Platform. The next step will be to move beyond text-dominated content and extend the Nexus Platform to facilitate scientists and practitioners to develop, publish, and share data-driven nexus analyses and visualisations. This extended platform will be called the Nexus Observatory (NO). It shall stimulate scientific and technical nexus discourse and individual as well as collective learning.

What issues does the Nexus Observatory address?

Web-based collaboration platforms are already established as tools for cooperation. The multidisciplinary character of the Nexus Approach and its ambitions to systematically integrate the sectors creates an additional challenge: to cope with cross-sectoral coherence and to identify synergies and fair trade-offs to ensure a reliable supply of water, energy, and food. This challenge will be addressed by the Nexus Observatory. Furthermore, evidence-based nexus research and implementation require a common understanding of the different nexus sectors in the whole team. To foster this, it is not enough to exchange results but necessary to co-create, understand, and reflect on the other team members' work. The Nexus Observatory shall create the environment for joint evidence-based nexus research and implementation as well as nexus learning.

Structural Design: Nexus typologies

UNU-FLORES and GIZ will search and analyse use cases from scientific and project backgrounds to develop a suitable design which: (a) is oriented at existing open source analytical software solutions that facilitate collaboration and (b) addresses the structural challenges of the nexus. The major additional feature and added value will be a structural design that is derived from a nexus typology developed by UNU-FLORES. The typology structures the Nexus Approach and thereby limits complexity and identifies similarities between research approaches. This facilitates exchange and collective learning. It will also structure data sets, analytical methods, and results in a practical way.

For a typology such as “Nexus Governance” or “Desalination”, the Nexus Observatory will organise data repositories, methodological inventories, and analytical results accordingly. This is relevant because the Nexus Resource Platform addresses practical implementation with equal importance to scientific research. Practitioners will be able to easily find a typology related to their task and have access not only to scientific information but also to (sample) data and applicable methods (code) that can be utilised with little extra effort.

6 Conclusions

Nexus research seeks to treat each resource embedded in the nexus as connected to the other resources. This approach is unique from other natural resource research agendas whose primary focus are on system efficiencies or examinations of a single resource. The nexus by emphasizing trade-offs places a premium on coordination. From a governance perspective coordination is not limited to decisions involving finances and allocation of trained human resources among different agencies organized both vertically and horizontally in a multi-level governance framework. Coordination could also be extended to include uses of data between public agencies, private sector and individual agencies.

Due to nexus interconnectivity, we suggest here that social network analysis (SNA) is an appropriate tool that can divulge and highlight the relational complexities that exist within the nexus and among stakeholders that work with the singular elements of the nexus. From a governance perspective, data visualization tools can map the density of ties and the extent to which ties between public agencies (for e.g. departments of water or agriculture) and between individuals within agencies are centred or biased towards one or the other. Further, knowledge translation tools such as scenario analysis and benchmarking can highlight possibilities for trade-offs to be managed through an integrated examination of both bio-physical and institutional thresholds across the continuum of environmental resources, services and risks

We offer several instances that illustrate under what conditions the network of WEF stakeholders may become more or less cohesive and connected. Specifically, we suggest that organisations with a high institutional capacity by means of expertise, resources, and other assets, the WEF network will be highly connected between resource areas in the overall network. The opposite is true for organisations with lower institutional capacity. We also provide an example using a wastewater reuse effectiveness index (WREI) and similarly suggest that where wastewater reuse is highly effective we would expect to see a highly coordinated and cohesive overall network. The opposite is expected when WREI values are low.

In addition to the examples provided above, we also highlight some potential questions for stakeholders that will begin to focus on the underlying nexus network structure. We emphasise that two network tie characteristics are particularly important to understand. Patterns, types, and content of communications and between resource interactions will provide a wealth of information about how the WEF network is organised and how resources are managed. Overall, we suggest that social network analysis may provide one explanation as to why some jurisdictions are highly effective at managing WEF resources and others are not. We emphasized in this connection that observatories have the potential to mine data on WEF interactions to support development of a robust typology to guide nexus oriented analysis.

The organisation of data covering different dimensions of the WEF nexus using the mechanism of an observatory could improve our understanding of thresholds of environmental resource use and the incentives for public agencies to act in support of sustainable development. In this connection we argued that data from a variety of sources—remotely sensed and in situ—will play an important role in analysing differences between networks. We discussed the challenges of mapping biophysical differences in data scarce regions and their potential role in developing and improving upon models of environmental resource use. We point out that integrated models have the potential to bring together data covering biophysical, institutional, and socioeconomic aspects as in the case with WREI.

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Integrated SDG Implementation—How a Cross-Scale (Vertical) and Cross-Regional Nexus Approach Can Complement Cross-Sectoral (Horizontal) Integration

Holger Hoff

> *Your magic joins again*
> *What custom has divided*
> Ode to Joy, Beethoven

Abstract The growing demand for food, energy, and water, the resulting pressure on natural resources and the environment and the persistent lack of human securities in many parts of the world, require new integrated approaches in management and governance. Integration is not only required horizontally across disciplines and sectors, but also vertically across levels, scales and across regions. Implementation of a vertical Nexus Approach is to be achieved through mainstreaming, i.e. through entry points such as national and regional development plans, strategies and policies to which it can add value. In particular, the call for integrated implementation of the SDGs requires a horizontal and vertical Nexus Approach for achieving coherence across sustainability goals and targets across levels, scales and across regions. For example, the "global level of ambitions" to which the 2030 Agenda refers can be specified and quantified with the help of the Planetary Boundaries (PBs). For mainstreaming the PBs into say,—national—policy and decision making, they need to be downscaled and allocated to the individual countries, so they can serve as benchmarks for national environmental performance and can be integrated with bottom-up sustainability criteria, e.g. national environmental standards. Transdisciplinary approaches are required, for co-designing and co-generating relevant knowledge by scientists and policy and decision makers. This also involves normative decisions about fair allocation of natural resources, emissions and burden sharing among nations and eventually institutions for the global governance of natural resources.

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1 Introduction: Which Nexus and Why Do We Need It?

Nexus (in Latin) means “interlinkage”. Given the multitude of interlinkages (“everything is linked to everything else”) the emphasis of the Nexus Approach is on **critical interlinkages** (critical in the respective context), e.g., among and between different natural resources, human securities, and sectors such as agriculture, energy, water or environment. Addressing these critical interlinkages requires integrated management and governance. Such an emphasis on integration is not new. The intensive discussion of the Nexus Approach since the Bonn Nexus Conference in 2011 is to a large extent a revival of earlier attempts to establish integrated or systemic approaches, such as in Integrated Water Resources Management (IWRM), Integrated Natural Resources Management (INRM), Integrated Coastal Zone Management (ICZM), landscape and ecosystem-based approaches, etc. This has led some authors to conclusions such as that the Nexus Approach “may not be more successful than earlier, similar attempts to achieve integration and policy coherence”, or even that the “notion of a water-energy-food nexus is possibly somewhat misplaced” (Wichelns 2017). What such a critical assessment ignores, is the fact that the Nexus Approach (not strictly limited to water, energy, and food) is addressing a wider range of natural resources, sectors, and institutions in a more comprehensive and balanced manner (providing a level playing field) compared to previous integrated approaches. Also, importantly, the nexus has become a successful communication tool, promoting very effectively the much needed integration in management and governance, also across the biophysical and socioeconomic domains and eventually across the environment-related and development-related sustainability goals. Indications of this success is the rapidly growing number of scientific papers, special journal issues and conferences dedicated to the nexus over the past 5 years and subsequently also the adoption of the Nexus Approach by research and development agencies. For example, the Arab or MENA (Middle East–North Africa) region is most vulnerable in terms of water (and land) scarcity and climate risks. Accordingly the League of Arab States has adopted the Nexus Approach as a key element for sustainable development and has launched its own nexus initiatives in close cooperation with development organizations such as the German GIZ and UN organizations such as ESCWA (Economic and Social Commission for West Asia) on nexus mainstreaming.

This all indicates that too narrow definitions of the nexus (e.g., water-energy-food) or too rigorous formalisation of the nexus (as requested by Wichelns 2017) may not be very helpful in practice and/or lead to new criticism, see e.g., Cairns and Krzywoszynska (2016). They suggest, for example, that the nexus might be too apolitical or not sufficiently accounting for justice or other social science aspects. While this may be true for some of the attempts to operationalise and apply the nexus, such criticism should be used constructively for co-developing and adapting the Nexus Approach by scientists, policymakers, and practitioners, to make it more applicable and useful. The harsh realities in many regions of the world in terms of environmental degradation, dwindling resource bases, increasing demand-supply gaps, and more pressing human (and subsequent political) insecurities, definitely call for more integrated approaches in management and governance. In the MENA region for example, strictly sectoral planning in the water sector is creating the world's largest desalination capacity, partially in response to the pressures of climate change. This is causing enormous energy demands, met almost exclusively by fossil fuels. Not only does such a water policy increase the region's dependence on fossil fuels, it also fuels climate change. An integrated approach across water and energy would promote more aggressively the use of renewable energy in desalination.

The co-development of relevant knowledge and putting the Nexus Approach into practice can add value to and complement (but not substitute) sectoral approaches and improve overall outcomes in policy- and decision-making, across sectors and scales. Integrated or nexus approaches become ever more important in the Anthropocene (Hibbard et al. 2007) with its rapidly increasing resource demand and environmental pressures. As part of the "Great Acceleration" (Steffen et al. 2015), mankind increasingly interferes with the environment at all scales up to the global scale, risking to transgress critical thresholds, causing "regime shifts" to new states, disrupting the functioning of the Earth system at the largest scale and losing its capacity to sustain human development and well-being. A prominent example is the the loss of biodiversity and ecosystems and their services (and the likely consequences for climate and the hydrological cycle), due to the disconnect of much stronger sectors such as energy or water or housing from the environmental sector. A Nexus or Landscape Approach would emphasize the benefits of "soft infrastructure" (provided by ecosystems) e.g. in terms of decentralization, diversity and resilience, complementing "hard infrastructure" (made from concrete and steel).

Precautionary limits, within which the Earth system and its sub-systems should remain, have been spelled out from a science (and environment) perspective in the Planetary Boundaries concept (see below). But motivation for a Nexus Approach can also be found at a smaller scale such as non-sustainable local resource degradation and exploitation, as well as widespread human water-, energy- and food-insecurity. The potential of a Nexus Approach to increase overall resource use efficiency and with that decouple human well-being and development from resource use and environmental pressure (as expressed in UNEP's Green Economy definition) becomes even more important under these conditions and trends. In the MENA region for example, resource use efficiencies remain very low, despite the pressing scarcity of water and land. A Nexus Approach in which water, land and energy planning, governance and management are coordinated could increase these efficiencies. Increasing water use efficiency in agriculture only to global average efficiency would bring enough water savings to allow the production of half of the current food imports within the region (Sadik et al. 2014).

Good agreement has been reached over the past few years on some key elements of a Nexus Approach: it focuses on critical interlinkages, promotes synergies and co-benefits (and hence emphasises the opportunities of integrated approaches), e.g., through improved policy coherence, through integrated management, and cascading use of natural resources, recycling of waste and by-products and by this increasing overall resource use efficiency—in line with the principles of a circular economy. At the same time the Nexus Approach identifies and quantifies trade-offs and negative externalities—and hence, risks—associated with strictly sectoral or silo approaches and helps to negotiate and avoid them (Hoff 2011). Implementation of the Nexus Approach is slow, but there are promising examples which need to be highlighted, replicated and upscaled. One example is the Sahara Forest Project in Qatar and Jordan (www.saharaforestproject.com), which uses those resources available in (almost) unlimited quantities in the region, i.e. sun, seawater and desert land and turns these into fresh water and biomass, with the help of solar desalination, solar cooling, and greenhouses. Such a multi-functional production system is based on the principles of recycling and reuse and emphasizes the role of the biosphere in sustainable production. Essential elements for the implementation of a Nexus Approach are (i) subsidies and other financial incentives which are oriented along sustainable production and consumption (e.g. not subsidizing the overexploitation of water or the continued use of fossil energy), (ii) new integrated curricula in education and training, and (iii) changing mindsets, behaviours and political will to overcome the strong sectoral vested interests.

Globalisation not only intensifies interlinkages among and between sectors, resources and scales, but also among regions, in particular through trade. European and other industrialised countries increasingly import raw materials and biomass-based goods and services from other regions and with that they externalise environmental and socioeconomic impacts of their consumption patterns to sometimes far away regions. Globalisation and the more interconnected world spread risks geographically and add new and more complex and sometimes global risks, e.g., human and environmental security risks, but also health risks, cyber risks and (geo-)political risks (Scheffran 2008). These new risks can no longer be addressed sufficiently by conventional sectoral or single-scale approaches only. (Risk) management and governance at all scales, up to a global scale, need to take on board the Nexus Approach for improving hard (conventional political) and soft (human and environmental) securities.

The main emphasis of this paper is on **vertical critical interlinkages**. While horizontal interlinkages across resources, sectors, and disciplines, have been recognised for some time, critical interlinkages also exist in the vertical dimension, across hierarchical levels, geographical scales, and also across regions. For example, local emissions of greenhouse gases cumulatively drive global climate change, while global climate targets should guide national emission reduction commitments. Non-sustainable local land uses may cause resource degradation and loss of biodiversity and with that cumulatively reduce the Earth system's resilience, while at the same time local resource use may be affected by international mechanisms and global teleconnections such as trade or foreign direct investment. IT solutions and networks pushed by individual companies quickly go global and determine behaviour and values globally and with that sometimes overriding and making obsolete local and national norms, regulation and legislation. Accordingly, local, national, regional, and global action, management, and governance need to be aligned towards coherent cross-scale sustainability goals and approaches. Bottom-up and top-down approaches need to be coordinated or integrated. Science can provide quantitative evidence for such a **vertical Nexus Approach** and its operationalisation. By identifying, specifying and communicating uncertainties and potential surprises, science can also promote the precautionary principle in policy- and decision-making. Various integrated and sometimes globally consistent data sets, models, and tools are available towards that end. The Planetary Boundaries themselves present an integrated approach, emphasizing the interlinkages and feedbacks among the different boundaries within the Earth system. The UN System of Evironmental-Economic Accounting (SEEA) presents an integrated global data system. The Water Evaluation and Planning—Long Range Energy Alternatives Planning (WEAP-LEAP) nexus tool for integrated water-land-energy scenario assessments (Karlberg et al. 2015), was applied e.g. in Ethiopia, where it revealed that a nexus approach could generate much larger overall benefits than business-as-usual or the current national development plans and strategies. However despite these promising advances, there is still a severe lack of integrated cross-sectoral and globally consistent data, knowledge and practice, hindering the replication and upscaling of Nexus Approaches.

2 Supporting Integrated Implementation of the SDGs Through a Vertical Nexus Approach

The Nexus Approach can be operationalised and implemented by way of mainstreaming, i.e. aligning it with and thereby adding value to ongoing or planned activities, policies, strategies, etc. There are numerous entry points for mainstreaming the Nexus Approach at all levels and scales. Such entry points for nexus mainstreaming include for example national bio-economy or green-economy strategies, energy or agricultural transitions, and also land, water, and environmental planning. All of these issues not only require horizontal coherence across sectors or disciplines at one hierarchical level or geographical scale, but their effectiveness and sustainability also depends on vertical coherence across levels and scales. A practical example which has been pursued by the German government was the mainstreaming of a vertical Nexus Approach into the planned German Nitrogen Strategy, which required coordination of nitrogen-related strategies, goals, and targets at sub-national (*Länder*), national, regional (EU) and global (e.g., Planetary Boundaries) level—see Box 1.

One of the most prominent entry points for nexus mainstreaming anywhere in the world are the Sustainable Development Goals (SDGs) and the call for their integrated implementation. Integration and universality are core principles of the 2030 Agenda and the SDGs. While integrated implementation implies the achievement of one goal/target not at the cost of another (see Nilsson et al. 2016 for synergies and tradeoffs among SDGs), universality refers to the need for implementing the goals and targets everywhere and also across regions (see section on Sustainable Consumption and Production below). Accordingly, critical interlinkages among and between the different environmental and developmental goals and targets need to be actively addressed for successful SDG implementation. This was already recognised in the final communiqué of the 2015 Dresden Nexus Conference: “applying a Nexus Approach is the key…for achieving the SDGs”.

Besides the horizontal coherence across goals and targets, vertical (cross-scale, cross-level), and cross-regional coherence is also essential for successful implementation of the SDGs and the 2030 Agenda. Towards that end, the 2030 Agenda requests “each government setting its own national targets guided by the global level of ambition”. Vertical coherence here means that local and national SDG implementation has to be aligned with global ambitions or global and supra-national sustainability goals (while at the same time, global goals must not compromise local and national sustainability goals). This explicit request to national governments for integrating global sustainability criteria and goals in their national policymaking is also a response to the Anthropocene situation, in which the aggregate effects of human action have become a driving force of non sustainable change at global scale, including potential modifications of the Earth system and its function as life support system for humanity. Identifying critical hotspots in the Earth system and addressing sustainability at the global scale require large-scale quantitative environmental sustainability boundaries, which delineate a safe operating space for humanity. This is what the Planetary Boundaries concept is aiming at.

3 How Can the Planetary Boundaries Support a Vertical Nexus Approach?

The Planetary Boundaries can help to specify and quantify the “global level of ambition” to which the 2030 Agenda refers. The nine Planetary Boundaries (PBs) delineate a safe operating space from an Earth system perspective, in terms of global limits to resource use, emission of harmful substances, and other environmental pressures (Rockstrom et al. 2009; Steffen et al. 2015). Control variables include, for example, atmospheric CO_2 concentration (for the climate boundary), species extinction rate (for the biosphere boundary), forest cover (for the land boundary), consumptive water use (for the water boundary), and anthropogenic nitrogen fixation (for the biogeochemical flow boundary). Note that respecting a Planetary Boundary at global level (for example, the Planetary Boundary for water is not yet transgressed) does not necessarily mean that local water use is sustainable, as demonstrated by the depletion of groundwater aquifers in many parts of the world. By introducing quantitative global-scale environmental boundaries into sustainability discourses and institutions, the Planetary Boundaries can guide a vertical Nexus Approach (“think global—act local”) e.g., in SDG implementation. An example is the 2 °C climate target (recently further strengthened by the Paris Climate Agreement), from which maximum allowable total greenhouse gas emissions can be derived. The Planetary Boundary for climate has been set at the lower limit of the uncertainty range for staying below 2 °C global warming. Similarly the other Planetary Boundaries also delineate a global safe operating space in their respective environmental domain. The aggregate sum of all national environmental pressures, emissions, or resource uses should remain within that safe operating space, in order to avoid the transgression of critical thresholds, which may endanger the functioning of the Earth system in its current stable state. This safe global operating space can also guide SDGs implementation: total aggregate effects of the worldwide implementation of all goals and targets need to remain within each of the nine Planetary Boundaries. Vertical coherence means to fulfil the ambitions of the SDGs locally, nationally, and regionally, while at the same time staying within the global safe operating space as delineated by the Planetary Boundaries. For example, the many national bioenergy and bioeconomy and food security strategies in their sum must still respect the Planetary Boundaries for land (defined by minimum remaining levels of forest cover) and for Water (defined by maximum water withdrawals). Applying the precautionary principle inherent to the Planetary Boundaries to the Nexus Approach means to account for potential negative interactions and feedbacks among the different boundaries when quantifying and applying them.

Given that the Planetary Boundaries are systemic boundaries, with reference to the Earth system, their definition accounts for critical (horizontal) interlinkages between the different system components, e.g., the biosphere, hydrosphere, and atmosphere, and the resulting Earth system dynamics (Friedrich 2013). With that, the Planetary Boundaries can also support horizontal integration and coherence or a horizontal Nexus Approach across environmental sectors and environmental SDGs (goals and targets).

In order for the Planetary Boundaries to support vertical (and horizontal) policy coherence and to serve as sustainability boundaries for national environmental pressures and resource uses associated with SDG implementation, the PBs need to be downscaled and made spatially explicit. Given that not all Planetary Boundaries are equal, there are different downscaling mechanisms: truly global boundaries, e.g., the climate or ozone boundary, refer to global commons. For those boundaries it does not matter where on Earth the emission of harmful substances occurs and accordingly the global boundary values can be downscaled and allocated equally across the globe. For other boundaries, such as the land, water, or biogeochemical flow boundaries, local context matters and needs to be taken into account when downscaling the respective Planetary Boundary. Moreover, for all PBs the allocation of the global safe operating space to individual countries also contains normative elements—much like the Planetary Boundaries themselves, which are defined by "acceptable risks". Such acceptable risks need to be negotiated at global level and allocated and eventually accepted at national (or other) decision making level. An example is the climate boundary or the 2°/1.5° target which took decades to become accepted by the global community and (almost) all countries. Depending on the normative choices and justice or equity criteria chosen (see Sect. "5" below), PB downscaling can result in different possible allocation of the safe operating space to individual countries. Once the respective boundary is downscaled to the national, regional or other sub-global level, it can serve as a benchmark to which actual environmental performance, or the expected change in performance in response to a policy or management intervention, can be compared—an example is provided in Box 1 below for the Planetary

Boundary on nitrogen (see also chapter "The Urgent Need to Re-engineer Nitrogen-Efficient Food Production for the Planet" by Pikaar et al. 2018).

Box 1: Is Germany's national performance consistent with the Planetary Boundary for nitrogen?

Nitrogen is primarily used for increasing agricultural yields to meet the rapidly growing demand for food and other biomass-based products (Sutton et al. 2013; Alexandratos and Bruinsma 2012). Sufficient food and biomass production (and accessibility) are underlying several SDGs, e.g., SDG 2 on food security (and sustainable agriculture) and SDG 7 on sustainable energy for all, implying an intensification of biomass production. While the use of nitrogen is essential for meeting these and other SDGs, there are also serious side effects when excess nitrogen enters the different environmental compartments, where it may compromise goals and targets such as SDG 6.3 on water quality, SDG 12.4 on chemicals in air, water, and soil, or SDG 15.5 on natural habitats. Besides the need for horizontal integration of nitrogen use and management across the different SDGs, there is also the need for a vertical Nexus Approach, negotiating and reconciling local, national, regional, and global wanted and unwanted (side-) effects of nitrogen use.

The Planetary Boundary for nitrogen sets a global limit for the intended anthropogenic nitrogen fixation (including additional biological fixation and fertiliser use). It has been set at 62 million tonnes per year (de Vries et al. 2013; Steffen et al. 2015), which is only about half of the actual rate. So there is a need for drastic reductions in the production of reactive nitrogen from an Earth system perspective. In order for this PB to guide national SDG implementation and policymaking in general, it needs to be downscaled. Allocating the global value of 62 million tonnes equally across all global cropland results in a safe application rate of 41 kg per hectare and year. Under that allocation scheme, Germany would be "entitled" to a total nitrogen application of 0.5 million tonnes, in order not to contribute more than its fair share to the total allowable pressure on the nitrogen PB. Germany's actual current application, however, amounts to 2.3 million tonnes. The full implementation of the European emission ceilings directive for nitrate would only lower this application to about 1.8 million tonnes. Implementation of the strictest currently discussed national limit (Faulstich et al. 2015) would bring down national application to about 1.5 million tonnes, still 200% above the downscaled PB (if using equal-per-area or equal-per-capita allocation of the global boundary value). When accounting also for consumption-based external pressures, i.e. external application of nitrogen in other regions and countries for export production for Germany (Germany being a net importer of biomass and agricultural products), Germany's national responsibility for the current transgression of the nitrogen-PB increases even further (Oita et al. 2016; Eggers 2016).

So the nitrogen PB provides new quantitative information on environmental sustainability, which can inform vertically coherent SDG implementation from an Earth system perspective, in line with the SDGs universality principle. From that global perspective, much more ambitious reductions in nitrogen application would be required than from a strictly national perspective. Such stronger emission reductions for meeting (downscaled) PBs would have to go beyond agriculture (which is responsible for about ¾ of total production and release of reactive nitrogen), and also include other sectors such as energy, transport, and industry sectors (Hoff et al. 2017). Note that vertical coherence not only extends upwards from national to global scale, but also downwards to smaller scales, at which nitrogen (and other natural resources) is managed and governed, e.g., *Länder* in the case of Germany.

We can conclude here, that such initial assessment of national pressures on the Planetary Boundaries and limits to be set from a global Earth system is useful to support vertical policy coherence and vertically integrated (universal) SDG implementation. Even though there still is (and will be for the foreseeable future) significant uncertainty about each of the boundaries, and downscaling algorithms and fair allocations of the global safe operating space need to be broadly debated, the currently available knowledge should already now be communicated to policymakers, because it provides valuable new information on the "global level of ambitions" mentioned in the 2030 Agenda. Moreover, this can trigger science-policy dialogues (see section below) from which also the further development of the Planetary Boundaries themselves can benefit.

4 An Inter-regional Nexus Approach in Support of Integrated SDG Implementation and Sustainable Consumption and Production

Globalisation results in stronger horizontal, vertical, and cross-regional interlinkages, in particular through more trade and longer and more complex supply chains from the location of primary production via several processing steps to final consumption (so-called "teleconnections"). Currently a quarter of all food production is traded internationally—up from only 15% some 30 years ago (D'Odorico et al. 2014). Underlying natural resource inputs for producing these export commodities, e.g., water and land for agricultural production, are increasing along with the production increase (e.g., Dalin et al. 2012).

By globalising supply chains, by sourcing more goods and services from abroad, and by externalising the resource use and environmental pressures associated with their consumption patterns and lifestyles, countries also affect the sustainability and the implementation of SDGs in other countries and regions. In particular, industrialised countries with their above average per capita consumption levels and strong imports are responsible for large external environmental (and socioeconomic) footprints, which can prevent other countries from achieving their sustainability goals and targets. Referring to these effects, the 2030 Agenda requires "to protect the planet …through sustainable consumption and production…sustainably managing its natural resources". This request extends national responsibility beyond a country's national borders. Sustainable consumption and production (SCP) is a principle that was already established in Agenda 21 back in 1992. SCP has been further spelled out recently in SDG 12, one of the most strongly interlinked and central SDGs (Le Blanc 2015; UNEP IRP 2015). SCP is about sustainable governance and management, including the efficient use of natural resources (SDG 12.2) and reducing waste generation through prevention, reduction, recycling, and reuse (SDG 12.5).

The universality principle of the SDGs in this case also requires accounting for external effects of domestic activities and, in particular, that domestic improvements must not be achieved at the cost of sustainable development in other countries or regions or globally. Their large per capita and external footprints (see for example Hoekstra and Mekonnen 2012 for water, Yu et al. 2013 for land or Oita et al. 2016 for nitrogen), provides a strong obligation for "developed countries taking the lead" in sustainable consumption and production (SDG 12.1), e.g., through improving their international supply chains. A possible means for reducing or internalizing negative externalities are taxes such as carbon taxes.

Downscaled Planetary Boundaries can support sustainable consumption and production and vertically coherent operationalisation of SDG 12, e.g., by defining vulnerable or stressed hotspot regions from an Earth system perspective (Steffen et al. 2015 supplementary material, Lenton et al. 2007). The Planetary Boundaries, in combination with supply chain analysis and consumption-based environmental accounting (and other information, e.g., the fact that water use efficiency of food production generally increases with per capita GDP, D'Odorico et al. 2014), can help to identify more sustainable patterns of consumption, trade, and production and eventually more sustainable sourcing. Environmental and socio-economic sustainability goals along supply chains and across regions have to be made coherent with economic goals which currently are key drivers of the externalisation of production and associated extension of supply chains, for vertically integrated SDG implementation and SCP.

Given the increasing length and complexity of supply chains, and the numerous environmental and socioeconomic impacts along the multiple processing and transport steps, analysing supply chains and tracing associated impacts has become an important task and major challenge to science. It requires appropriate tools such as Multi-Regional Input-Output (MRIO) models, Material Flow Analysis (MFA), Life Cycle Analysis (LCA) or Life Cycle Sustainability Analysis (LCSA, Guinee et al. 2011), and new combinations of these tools supported by horizontally and vertically coherent data sets such as currently developed under the UN System of Environmental Economic Accounting (SEAA). That can also help to develop and strengthen monitoring mechanisms for resource use at a global level (Bringezu 2018, Chapter "Key Strategies to Achieve the SDGs and Consequences for Monitoring Resource Use").

Box 2: Scientific tools in support of integrated SDG implementation and Sustainable Consumption and Production across regions

The EU15 has become the largest net importer of virtual land, mostly with agricultural products, by now importing four times more virtual land than, e.g., China, which has a population that is more than three times as large (Lugschitz et al. 2011). External agricultural land use for the EU27 imports amounts to about 45 million ha (O'Brien et al. 2015). Europe imports, for example, large amounts of soy from Brazil (which by now is the 2nd largest net food exporter, D'Odorico et al. 2014). Soy is one of the fastest growing export commodities, practically not grown in Europe itself. Conventional trade statistics do not tell the full story: on the one hand, they do not account for indirect soy imports, i.e. soy that has been used along supply chains in interim processing steps without physically entering the final consumer country; on the other hand, they do not allow to trace back supply chains to the locations of primary production (conventional trade statistics, for example, identify The Netherlands as the largest source country for Germany's soy imports although no soy is grown in the Netherlands, simply because the Netherlands is the first port of call for soy coming to Europe from overseas). These are critical obstacles to assessing consumption-based external footprints and hence external impacts on SDG implementation, when relying on conventional analysis methods.

With the help of a new environmentally extended Multi-Regional Input-Output (MRIO) model we could overcome these obstacles and calculated (i) that Germany's total consumption-based demand for soy, including virtual imports of soy used as input along the supply chain, is almost twice as large as the direct physical imports listed in conventional trade statistics, and (ii) that the total land area on which soy is grown for meeting all of Germany's consumptive demands (of products with supply chains that depend one way or other on soy) equals more than 20% of Germany's domestic cropland (Dawkins et al. 2016). The direct and indirect environmental (and socioeconomic) pressures associated with this land use and the underlying land conversion threaten the achievement of several SDGs in Brazil (and other producer countries). Soy, for example, has very low water use efficiency per kcal produced in comparison to other traded commodities and its export production hence puts additional pressure on scarce water resources. With the help of an innovative Material Flow Analysis (MFA) coupled with local-level data on production, transport and trade, we could show that some areas of soy production in Brazil for export to Germany are severely water scarce (different from Brazil's average situation at country level); this water scarcity is likely aggravated further by the additional soy water demand (Dawkins et al. 2016).

Scientific evidence for guiding vertically coherent sustainable consumption and production and integrated SDG implementation across regions, scales, and levels is increasingly becoming available (Bringezu et al. 2016). As in the case of the Planetary

Boundaries, the available information already provides a good indication of status and critical trends, here related to the externalisation of environmental pressures with trade. This information can already be communicated to policymakers for initiating action and for co-developing further more targetted knowledge through science-policy dialogues (see section below). The available information also points to the need for more integrated analyses of different environmental and also socioeconomic pressures and context-specific impacts at every step of the supply chains, in order to better guide sustainable consumption and production (SCP) across regions.

Further scientific development in support of SCP and SDG implementation will also be required in terms of integrating the results from top-down and bottom-up analyses, e.g., Planetary Boundaries, environmental footprints, and local environmental sustainability issues, such as natural resource scarcities or vulnerabilities of land or ecosystems. Another dimension of integration that science needs to address is that of integrating environmental and socioeconomic sustainability criteria across scales, e.g., by overlaying context-specific social metabolism and human security needs (as listed for example by Raworth 2012) with environmental sustainability criteria across scales. With that it will be possible to better align global (environmental) ambitions and national and international fairness and equity criteria (see next section) and compensation mechanisms (for countries disadvantaged by international schemes) with national SDG implementation.

5 Science-Policy(-Society) Dialogue for Vertically Integrated and Fair SDG Implementation

Setting of Planetary Boundaries and the allocation of the associated global safe operating space to individual countries or groups and protecting global commons is not a strictly scientific exercise, but it has strong normative components. The different justice and equity dimensions involved need to be spelled out, discussed, and negotiated, in order to eventually achieve a vertically integrated SDG implementation that meets the required global level of ambition while simultaneously also being perceived as fair and legitimised at national and local level.

Some of the possible (downscaling and) allocation mechanisms that have already been discussed in the literature for the global climate goal and related national allowances or contributions (Raupach et al. 2014) include:

- equal-per-capita allocation (either production- or consumption-based)
- grandfathering (meaning an allocation of the global emission allowance proportional to countries' present emissions)
- right to development, meeting development needs, ín terms of human securities and living standards
- capacity and ability
- leaving no one behind (according to the 2030 Agenda)
- corrective justice, historical responsibility, e.g., historic GHG emissions

- accounting for resource endowments and quality of resources
- cost efficiency, least cost solutions
- meritocracy principle
- no envy principle
- voluntarism.

The consequences of these very different principles and their operationalisation, e.g., in terms of required changes in consumption, production and trade patterns, need to be spelled out further and discussed and eventually agreed upon nationally and internationally. The climate negotiations and the Paris Climate Agreement hold several lessons learned. A continuous and iterative science-policy dialogue not only provides relevant results and legitimacy for SDG implementation, but it also feeds back to the scientific process and can eventually sharpen scientific concepts and analyses such as the Planetary Boundaries.

6 Conclusions

The Sustainable Development Goals are universal; there is a call for integrated implementation. While the need for horizontal or cross sectoral integration (the "horizontal nexus") has been recognised for quite some time, vertical integration across levels, scales, and across regions remains to be addressed and operationalized. In a globalising world in which humanity is changing its environment up the global scale, national SDG implementation needs to be aligned with global environmental sustainability criteria such as the Planetary Boundaries, but also with universal socio-economic sustainability criteria, such as the human rights to food or water. Accounting for the "global level of ambitions" that the 2030 Agenda mentions, requires an integration of top-down and bottom-up perspectives and approaches. Sustainable Consumption and Production (SDG 12) must not stop at a country's border but instead needs to take a cross-regional approach, accounting for external footprints along international supply chains and internalizing these externalities, for doing more and better with less. Scientific methods, tools, and data are increasingly becoming available for supporting these vertical Nexus Approaches. This paper presents initial analyses and interpretations of vertically integrated SDG implementation (e.g. how Germany complies with the downscaled Planetary Boundary for nitrogen) and for vertically integrated Sustainable Consumption and Production (e.g. how much of its environmental footprints Germany externalises through international supply chains). Further refinement of these methods in support of integrated SDG implementation requires close and continuous dialogue between science, policymaking, and society at large, in order to realise synergies, reduce negative externalities, and negotiate trade-offs in an evidence-based manner.

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