Nexus Approaches to Global Sustainable Development

Jianguo Liu[1], Vanessa Hull[2], H. Charles J. Godfray[3], David Tilman[4], Peter Gleick[5], Holger Hoff[6], Claudia Pahl-Wostl[7], Zhenci Xu[1], Min Gon Chung[1], Jing Sun[1,8], Shuxin Li[1]

[1]Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI, USA 48824, USA

[2]Department of Wildlife Ecology and Conservation, University of Florida, Gainesville, FL 32603, USA

[3]Oxford Martin School & Department of Zoology, University of Oxford, 34 Broad St, Oxford OX1 3BD, UK

[4]Department of Ecology, Evolution and Behavior, University of Minnesota, St Paul, MN, 55108, USA

[5]Pacific Institute, Oakland, CA, 94612, USA

[6]Potsdam Institute for Climate Impact Research, Potsdam, 14473, Germany and Stockholm Environment Institute, Stockholm 11523, Sweden

[7]Institute for Environmental Systems Research, University of Osnabrück, Osnabrück, 49069, Germany

[8]Key Laboratory of Agricultural Remote Sensing, Ministry of Agriculture/Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, 100081 Beijing, China

*Corresponding author email: liuji@msu.edu

Abstract

Many global challenges, though interconnected, have been addressed singly, at times reducing one problem while exacerbating others. Nexus approaches simultaneously examine interactions among multiple sectors. Recent quantitative studies have revealed that nexus approaches can uncover synergies and detect trade-offs among sectors. If well implemented, nexus approaches have the potential to reduce negative surprises and promote integrated planning, management and governance. However, application and implementation of nexus approaches are in their infancy. No studies have explicitly quantified the contributions of nexus approaches to progress toward meeting Sustainable Development Goals (SDGs). To further implement nexus approaches and realize their potential, we propose a systematic procedure and provide perspectives on future directions. These include expanding nexus frameworks that consider interactions among more sectors, across scales, between adjacent and distant places, and linkages with SDGs; incorporating overlooked drivers and regions; diversifying nexus toolboxes; and making these strategies central in policy-making and governance for integrated SDG implementation.

1. Introduction

With global population projected to exceed 9 billion and per capita buying power expected to more than double by 2050, global challenges such as reducing food insecurity, water scarcity and fossil energy use, as well as improving human health and protecting the environment, are increasingly pressing and deeply interconnected [1]. Major threats such as climate change and its likely social, political and economic consequences compound the challenges and add further interlinkages [2]. To address global challenges and threats, the United Nations has set 17 Sustainable Development Goals (SDGs) for 2030, including the provision of sufficient food, energy, and water for all [3]. But taking the SDG agenda seriously, and operationalizing it on the ground, is far from straightforward.

Achieving the SDGs requires all relevant stakeholders to work together and manage the synergies and trade-offs among different management or governance sectors (e.g. food, health, water, and energy) [4]. While focused expertise and management remain important, traditional "silo" approaches by specialized institutions and agencies alone cannot effectively address the linked challenges. Consider, for example, the Aral Sea. River water that had flowed into the Aral Sea was diverted to create irrigated desert croplands but also led to a substantial loss of a productive fishery as the lake dried and shrank to a tenth of its original size [5]. These major impacts were avoidable. Well-made canals and efficient irrigation could have allowed agriculture to flourish while protecting the lake's biodiversity so that it provided a sustainable fishery [6].

New integrated approaches and tools are needed to address the challenges posed by multiple and often conflicting human needs and demands, and to achieve the SDGs successfully. Numerous approaches have been developed to help address these issues, including the concepts of natural capital and ecosystem services [7,8], quantification of environmental footprints [9] and planetary boundaries [10], integrated water resource management and "soft path" approaches to improve water use efficiency [11], multifunctional landscapes [12], and integrated ecosystem management [13].

Each of these concepts has multiple dimensions and is valuable for addressing some of the SDGs, and they can be extended to address synergies and trade-offs among sectors [14].

The nexus concept builds on many of these approaches by emphasizing the importance of understanding connections, synergies and trade-offs. The word "nexus" (from the Latin *nectare*, to connect[15]) has long been used in philosophy, cell biology, and economics, to refer to approaches that address the linkages between multiple distinct entities [16]. Nexus terminology was first used in the natural resource realm in 1983 under the Food-Energy Nexus Programme, which sought integrated solutions to food and energy scarcity [16]. Since then, it has been applied most frequently to studying connections among food, water and energy, sometimes with the addition of issues like biodiversity protection and human health, or within specific framings such as responding to climate change. Although the term can be overused [17,18], we argue it is valuable to avoid the natural tendency to retreat into intellectual and institutional silos. Compared to previous integrated concepts, there has been a stronger demand for operationalization and solution-orientation by resource managers, policy makers, and other stakeholders. With broad interest and impetus, there is an opportunity for co-development of actionable knowledge from nexus assessments for problem solving such as simultaneously achieving multiple SDGs (Table 1). Cross-sectoral integration is a major issue for both nexus approaches and SDGs.

In this article, we address three key questions: What are the major advantages and costs of nexus approaches? What steps are essential for implementing nexus approaches? What are the main research gaps and directions? We also discuss how nexus thinking can help improve policy, management, and governance to ensure environmental sustainability while meeting human needs worldwide.

Advantages and Costs of Nexus Approaches

By identifying positive synergies and negative trade-offs, nexus approaches can help enhance sustainability pathways through promoting higher resource-use efficiency [11], lower production of pollutants [19] and wastes [20], and more coherent policy [21]. This point has in the past been argued through chiefly qualitative analysis [18,22], and we see a need to extend this to more quantitative approaches. To demonstrate advantages, here we examine several recent quantitative studies on the food-energy-water nexus, which addresses fundamental human needs. Despite huge progress, 660 million people still lack access to safe drinking water, 2.4 billion do not have good sanitation services [23], 795 million people face chronic food shortage [24], and 1.2 billion have no electricity [25]. Food, energy and water interact and can affect all the SDGs (Figure 1), yet each is often treated in isolation.

Uncovering synergies and co-benefits. Nexus approaches can identify synergistic effects and co-benefits that might otherwise be missed in complex production systems and supply chains. This is particularly important in densely populated urban areas where the benefits of more efficient resource consumption are high. For example, multi-sectoral systems analysis reveals that in London implementing urine separation technology (UST) that requires less water than conventional methods could lead to a 10% reduction in water needs [26]. This reduction would lower the energy use in water supply by about 10% and wastewater treatment by nearly 25%.

The energy savings in wastewater treatment result from fewer toilet flushes (since the technology relies on urine diversion and composting as opposed to flushing with water) and reduced nutrient levels in sewage. Furthermore, nutrients captured by the UST would contain on average 2,300 tonnes of phosphorus and 24,000 tonnes of nitrogen annually that would be valuable as fertilizers [26]. These nitrogen fertilizers could satisfy the nitrogen needs for growing almost one million tons of wheat in the United Kingdom (~6% annual production) [27].

Detecting harmful trade-offs. Nexus approaches can help detect and minimize harmful trade-offs [28]. For example, trade-offs occur in drier regions where farmers choose between multiple types of crops that have different water and energy demands. In a recent integrated assessment of the Mediterranean region, researchers used geographic information systems and a gridded water balance model to examine water productivity and carbon footprints across eight crop types [29]. Among the crops examined, citrus had the highest water productivity (yield per unit water applied) at around 3,200 t of crop/Mm^3 water per year and the lowest carbon footprint at approximately 12 kg CO_2/t per year of emissions. Sunflower had the reverse, with the highest carbon footprint (73 kg CO_2/t per year) and among the lowest water productivity (~510 t/Mm^3 per year). Regional differences also occurred. For instance, water demand for irrigation per unit of product was 75% higher in Egypt than Spain, yet the local carbon footprint was three times lower. This difference is due to the predominance of gravity-fed (more water intensive) irrigation in Egypt compared to pressurized (more energy intensive) irrigation in Spain. Scenario analysis (a process of projecting future possibilities under different assumptions about the future) found that switching from surface (gravity-fed) to pressurized irrigation would reduce the water demand by 13% but increase the carbon footprint by 135% [29]. Switching from rain-fed to irrigated agriculture, which increases land productivity, would increase both the water demand and carbon footprint by 168% and 270%, respectively [29]. Possible net economic return from these crops also varies. For example, in Turkey, citrus crops yield roughly 1,790-3,400 USD/ha [30], but sunflower yields 570-1,690 USD/ha in Italy [31]. The relative benefits of different irrigation systems are variable across systems. Accordingly, a nexus approach helps to identify context-specific solutions adapted to the respective resource scarcities.

Unveiling unexpected consequences. Nexus approaches can assist in identifying unexpected consequences [32-34]. For example, biofuels were proposed as part of the solution to increased CO_2 emissions from burning fossil fuels, but unexpected side effects occurred [35]. World consumption of biofuels increased by 78% from 1950 to 2010 [36] and currently 64 countries have biofuel targets or mandates [35]. However, biofuels can have profound negative consequences for water scarcity as their production, processing and distribution can require up to 500 times more water per unit of energy than oil and gas. Biofuels may also have unintended consequences for food security and social stability: the large and rapidly-imposed US biofuel mandate was associated with a spike in global cereal prices [37], and in a tighter coupling of world market prices for energy and food, though the pattern of causation is debated. Roughly 25-50% of the net calories diverted from food to ethanol are never replaced in the agricultural sector (based on US and EU biofuel data) [38] and the consequent increase in food prices particularly impacts the world's poorest people with clear ethical implications. The food calories that were replaced came partly from increased productivity on existing farmland but also from conversion of land to agriculture. Both, and in particular the second, lead to GHG emissions that are frequently not considered [39]. There may be advantages of producing rain-fed biofuels on non-agricultural land, but it is important to consider possible trade-offs such as the loss of ecosystem integrity and biodiversity, and alternatives such as using the land for carbon storage [40].

Enhancing integrated planning, decision-making, governance, and management. By bringing together actors involved in different sectors, nexus approaches can promote cooperation, coordination [41] and policy coherence [21]. For example, there has been a global boom in hydropower dam construction with nearly 4,000 major dams, each with a capacity of more than 1 MW, either planned or under construction [42]. A nexus approach has been incorporated into a hydro-economic systems model and scenario analysis to investigate resource security and allocation in the Brahmaputra River Basin in South Asia which is home to 130 million people across four countries: Bhutan, China, India, and Bangladesh [43]. As in many large watersheds, there are conflicts of interest over water. The political economy of this watershed is complex as it contains two regional superpowers (China and India) as well as a much smaller country – Bhutan – that is dependent on hydropower generation for export income [43]. By tracking current and proposed water uses in the basin over space and time, the model elucidated the potential sustainability of alternative development pathways. Several insights emerged, including the need for thresholds of total allowable water diversion, which if exceeded would cause collapse of water security in the region [43]. Differences in the effects of human activities on different sectors were also revealed. For instance, China's planned water diversions [44] would affect India's water availability for rice production but not hydropower (which comes from other locations). Such information is useful for international water treaty negotiations that decide how water and associated benefits are divided among the multiple competing users. There are similar upstream-downstream relationships in other river basins such as the Ganges, Brahmaputra, Nile, and Meghna basins, where cooperative efforts are needed to address challenges such as floods, erosion, water storage facilities and demand, and spatial separation between hydropower potential and energy market [45]. Thus, it would be helpful to account for cross-sectoral and transboundary interlinkages in planning and governance to ensure system resilience and sustainability in the face of future uncertainties [46].

Costs of nexus approaches: The costs of nexus approaches are generally higher than those of silo approaches, but no quantitative information is available about the additional expertise, time, coordination, and financial resources required. Nexus approaches need expertise in all relevant sectors instead of just one sector. Furthermore, it is necessary to coordinate experts in different sectors. For example, research on food-energy-water nexus requires expertise on food, energy, and water as well as coordination of experts in these sectors. To accomplish the common overall goal, experts need to understand each other's work. As a result, it takes more time and financial resources to conduct nexus research.

Implementation of Nexus Approaches

Nexus approaches are increasingly being used in quantitative research [47] and in policy implementation [26,28]. To help their operationalization, we propose five major steps (Figure 2), though noting different steps may be returned to more than once.

Formulating nexus research goals. Research goals may be motivated by practical problems that require understanding specific interrelationships among sectors or analyzing nexus dynamics in defined regions. More foundational work includes developing new nexus methods and exploring mechanisms underlying nexus dynamics. So far, nexus studies often have aimed to detect nexus co-benefits [48], trade-offs, [49] and synergies [34] in order to optimize resource use and production and to achieve water security [50], food security [15,51], human health [52], and energy security [53]. Most studies have focused on specific nexus questions [54] (e.g., How can we benefit across sectors from the association of the water sector with new technologies? [26]). Others have concentrated on solving specific problems [56] such as the sustainability of the food-energy-water nexus in BRICS (Brazil, the Russian Federation, India, China, and South Africa) [57], while a few have tested specific hypotheses such as energy efficiency techniques can be extended to improve efficiency of other sectors, especially water [58]. However, no quantitative nexus studies have linked with specific SDGs.

Defining nexus systems of interest. Systems(s) of interest can be socially or spatially defined or bounded. Their boundaries may be geographical, political, or administrative. Examples include studies on watersheds such as the nine river basins in Sri Lanka [59], cities such as London, UK [26] and Bologna, Italy [58], and countries like Brazil, the Russian Federation, India, China, and South Africa [57]. Defining systems using administrative and political rather than geographical boundaries has immediate policy relevance because policies are usually developed and implemented within those boundaries [56]. However, other criteria (e.g., geographical boundaries such as river basins) are also needed to define boundaries for managing transboundary resource stocks and flows that pose special judiciary difficulties and require unique political agreements.

Developing nexus conceptual frameworks. Developing nexus conceptual frameworks is essential to clarify complex relationships across sectors and provide a foundation for further analysis. Many conceptual frameworks have been developed for nexus research. For food-energy-water nexus, food systems may include fisheries, aquaculture, and land-based agricultural production; energy systems may consist of geothermal, fossil fuels, hydro, shale gas, and renewables; and water resources may range from ground water, surface water, recycled and desalinated water to precipitation [55]. Another nexus framework put forward by the World Economic Forum [50] focuses on assessing risks across the sectors. Some other frameworks highlight key points of interest such as ecosystem services [34] or the role of stakeholders in achieving policy objectives [60]. However, few frameworks have integrated sectors across regions or made specific linkages to SDG goals, targets and indicators [61]. Furthermore, more efforts should be placed on integrating sociopolitical and biophysical processes to make the frameworks more applicable to the real world. An example is an actor-ecosystem services approach that integrated multi-level governance concepts in a livestock-biogas-drinking water system in Europe [62].

Quantitatively analyzing nexus relationships. Many methods can be used for quantitative nexus analysis. For example, nexus relationships can be represented by a suite of indices, in particular cross-resource or cross-sectoral input intensities such as the amount of energy used for food production (e.g., production of fertilizer) and water production (for pumping and extraction of water) [22], amount of water for food production (especially irrigation) and energy production [63], and associated food security, energy security, and water security in food-energy-water studies [64]. Some studies have developed nexus indices that collapse the main nexus variables into a single number that is convenient for assessing different strategies and scenarios [65]. Some indices in nexus studies overlap with SDG indicators [66], such as CO_2 emissions and environmental footprints [26,29], facilitating direct connections between nexus research and SDGs.

Nexus relationships can be analyzed using a variety of tools such as life cycle assessment, material flow analysis, input-output analysis [67], Multi-sectoral System Analysis [26], Integrated Assessment Models [68] and general linear model statistical analyses (Table 2). There are different types of data available, such as resource production, productivity, use, attitudes, intentions, and perceptions [69], biophysical measurements [69], and remote sensing data [70]. Data may come from different sources, including experiments, the literature, governmental agencies, and international organizations [67]. Different tools serve different purposes. For example, network analysis quantifies embodied energy and GHG emissions from irrigation through virtual water transfers in food trade [71]. Sankey diagrams [72] are useful to visualize the relationships and flows among different components. While multi-objective optimization has been used in other fields, the method has just begun to be used in food-energy-water nexus research and decision-making [73], such as optimizing cropping pattern for maximum economic water and energy productivity and minimum use [65].

Simulating nexus dynamics. Nexus studies can benefit from computer simulations, which can evaluate temporal nexus dynamics (e.g., intergenerational trade-offs, time lags, and legacy effects) in the absence of long-term empirical data and project when SDGs may be achieved. Nexus models can elucidate the consequences of various scenarios such as different technology adoptions [26] and different levels of savings and cost effectiveness [74]. Scenarios can also identify complex and dynamic interactions such as temporal trade-offs [75], co-benefits [76] and synergies [70] among different nexus sectors or components [26,75]. Model simulation results may include values of various environmental and socio-economic nexus indicators and indices.

It is challenging to examine the performance of nexus models because outputs of all sectors and their interactions need to be evaluated. For model validation, empirical data are needed for assessing all nexus sectors and their interactions instead of just one focal sector as in "silo" models. More efforts are needed to evaluate how sensitive each sector and its interactions are to changes in other model components or how uncertainty associated with errors or lack of knowledge affects all sectors and their interactions [74].

Engaging with stakeholders. Working with relevant stakeholders to co-design, co-produce and co-implement the research [77] throughout all the steps illustrated above can enhance the relevance of research by incorporating experiences and needs from the stakeholders [55]. Stakeholder involvement is challenging [78] as it requires more time and money as well as more organizing and coordinating efforts, but it is essential to identify conflicts and solutions such as how the real-world conflicts might be overcome by nexus approaches. Although co-production of knowledge between scientists and stakeholders is not a new concept, it has gained more traction recently [54]. However, so far only a small proportion of studies have engaged stakeholders [79]. For example, stakeholders participated in collecting data for the simulation model of water allocation for food production and hydropower generation in Sri Lanka , reviewing and implementing the water allocation plan, and reviewing the implementation outcomes [59]. Another example is a study where researchers engaged in scenario building with local stakeholders in Ethiopia and Rwanda to hone the design of a nexus toolkit for addressing interrelated issues such as biomass use, hydropower, and irrigation [80].

Future Directions

Application and implementation of nexus approaches are still in their infancy. Below we identify major research gaps and offer suggestions for enhancing their applications to research, policy, governance, and management.

Expanding nexus frameworks. Nexus frameworks need to be expanded in several different ways. First, more and different sectors need to be included, such as the health impacts of alternative diets, of alternative energy sources, and of alternative crops and agronomic practices. Indeed, the numerous linkages among agriculture, diet, health, GHG emissions, biodiversity, water and energy are sufficiently strong that effective policies may need to consider all of these sectors simultaneously. So far, most nexus studies focus on two sectors, such as energy and water, water and food, food and energy, and food and biodiversity (Table 1). New efforts are underway to evaluate nexuses with three sectors (Table 1), such as the food-energy-water nexus. Few studies have included four or more sectors [67,81] (Table 1). As new sectors are added, the number of interactions among sectors increases greatly and it is important to evaluate the benefits and costs of adding more sectors.

Second, it is important to bridge nexuses across small and large scales or levels (integrating both top-down and bottom-up approaches). For instance, food-energy-water nexus at the state level may affect various sectors at the county as well as national and international levels. California is a major food producer and exporter, which requires substantial energy and water, yet it also experiences growing conflicts over water resources and shortages [82,83]. Food-energy-water connections at the level of California have important impacts on health, food, energy, and water policies at the national and international levels.

Third, more widely applicable nexus frameworks are needed to simultaneously address nexuses in multiple places and the increasing spatial separation between resource production and consumption, which may reallocate costs and benefits across different places. In other words, achieving SDGs in one place may enhance or compromise achieving SDGs in other places. However, the current nexus conceptual frameworks often focus on a specific place or context [84]. The new integrated framework of metacoupling (socioeconomic and environmental interactions across space) can account for nexuses within a specific place (intracoupling), between adjacent places (pericoupling), and between distant places (telecoupling) [85] (Figure 3). Each place can be viewed as a coupled human and natural system [86]. Sustainability is a coupled human and natural systems issue, not just a technical issue, although techniques such as quantitative methods and computer models can help address drivers and dynamics of sustainability challenges such as growth in population size and number of households, economic growth, power relations, and policies [87] (Figure 3). The metacoupling framework takes an interdisciplinary perspective to examine socioeconomic and environmental causes (drivers) and effects of flows (e.g., movement of matter, energy, information, people, organisms, and capital) between systems like countries facilitated by various agents such as investors, traders and policy makers. It can help identify and explicate nexuses within as well as between adjacent and distant systems. For example, food trade can affect the food-water-energy nexus i) in food exporting countries by increasing water and energy use for the food produced, ii) in food importing countries by reducing water and energy use for the food consumed, and iii) globally by increasing or decreasing overall global resource use efficiency and associated environmental impacts.

Fourth, it would be useful to apply nexus approaches to SDG implementation. Nexus approaches can help achieve SDGs because SDG goals are interconnected [88] and linked with the sectors of a particular nexus. For example, the food-energy-water nexus is directly linked with SDGs 2 (zero hunger), 6 (clean water and sanitation), and 7 (affordable and clean energy) [3,89]. This nexus also directly or indirectly affects all other SDGs (Figure 1), such as improving human health and well-being (SDG 3) by enhancing water quality and quantity, bolstering food safety and nutrition, and energy security; advancing economic development (SDG 8) through using food system residues to generate bioenergy, treating polluted water using the bioenergy, and using treated water to grow food; and mitigating climate change (SDG 13) through increasing resource efficiency and reducing CO_2 emissions. As nexus frameworks can make the direct or indirect relationships with and between SDGs clear (Table 1 and Figures 1 and 3), they can enable integrated SDG implementation as requested in the Agenda 2030. Accordingly, nexus approaches can also monitor progress towards integrated SDG implementation.

Incorporating overlooked drivers and regions. Some important drivers of (un)sustainability and geographic regions have been overlooked in nexus research. Below we highlight household dynamics and marine and coastal regions.

Households are the basic units of consumption (and production in many regions) and need to be linked with nexus approaches to improve understanding of synergies and trade-offs. Human population size has been widely recognized as a major driver of nexus dynamics, e.g., as a key determinant of GHG emissions [90] and demand for resources [37] with their consequent effects on the environment. During the 20th century, global population increased by 270% but inflation-adjusted global per capita buying power increased by 360% [91]. Household size influences per capita buying power. As recent advances show [92,93], household perspectives can offer new insights that differ from population perspectives because globally the number of households increases faster than population size. The faster increase in household numbers and in household incomes leads to dramatically higher environmental impacts and demands for resources [94,95]. Building on the many studies that have evaluated household consumption of different resources separately [96-98], more work is needed to assess the synergistic effects of consuming resources (e.g., changing food consumption may alter energy and water consumption as energy and water are needed to prepare food). Evaluating household consumption of resources simultaneously may lead to more accurate estimates of global demand for resources, with implications for more effective policies.

Nexus research should also be expanded to marine and coastal systems. Nexus efforts to date have focused mainly on terrestrial and freshwater systems, although marine systems make up around 70% of the earth's surface and have great potential for providing food, energy, and other ecosystem services [99]. Some studies have linked marine and terrestrial processes, for example, work on desalination of sea water to mitigate freshwater scarcity [100], seafood as a partial solution to food security [101], and offshore oil drilling as an important energy source [102]. However, little is known about nexus synergies and trade-offs, or the full potential of marine and coastal systems, including nearshore or open ocean cages for aquaculture, to help meet global resource needs and environmental sustainability. Marine aquaculture increasingly depends on crop-based feeds that indirectly impact the terrestrial food-energy-water nexus. For instance, one study estimates that for one tonne of salmon production, standard feed with high levels of fish meal and oil used 30.0 m^3 of water and 32,159 MJ of energy [103]. Estimates are similar in low-fishery feed which replaces fish meal and oil with plant-based sources (34.1 m^3 of water and 31,688 MJ of energy) [103]. Thus, intensifications of aquaculture may cause an increase of nutrient pollution and degrade coastal and marine ecosystems, e.g. through higher hypoxia rates [104]. On the other hand, sourcing fish meal from open oceans damages marine ecosystems, and genetically modified (GM) crops with healthy lipid precursors may serve as a potential promising alternative [105]. Nexus approaches such as those applied in the Sahara Forest Project in the coastal zones of Qatar and Jordan could change conventional thinking and practices by contributing a new and transdisciplinary lens to the emerging field of "blue growth" [106] that promotes sustainable development across marine, coastal and terrestrial systems.

Enlarging and diversifying toolboxes. There have recently been several advances in qualitative methods to understand nexus issues, including institutional network analysis and environmental justice frameworks [107,108]. However, the development of comprehensive quantitative or mixed quantitative/qualitative toolboxes for nexus research has lagged behind. Although a number of quantitative methods have been "borrowed" from different disciplines [109] (Table 2), their applications to nexus research could be improved. Traditional methods used within the individual sectors such as life cycle assessment [110] or footprint analysis [9] often cannot fully capture cross-sector interactions. Future methods should be more diverse and have the power to implement comprehensive nexus frameworks (e.g., Figure 3), quantify complex systems, collect and integrate data on relevant factors from multiple sources, transfer results from case studies to other contexts, and scale up findings from local to global levels as well as scale down large-scale sustainability criteria to local policy- and decision-making [111]. Tools are needed to work across all spatial scales at which nexus problems should be governed and managed, and to identify which positive and negative outcomes of the nexus are local, regional, and global [112]. Common standards are also needed to allow comparisons among studies using compatible boundaries, scales, units, and methods to avoid mismatches and minimize differences in estimates.

In the age of "Big Data", greater efforts should be made to integrate data across sectors of the nexus, including remotely sensed data such as those from the Global Earth Observation System of Systems (GEOSS [113]). Predicting future resource demand and availability can benefit from the integration of environment and development scenario projections such as those from Shared

Socioeconomic Pathways [114]. There is great potential to integrate existing "Big Data" frameworks together to create an interdisciplinary repository of "Big Nexus Data". However, harmonizing data and indicators globally is quite a challenge, as the current indicator effort related to the SDGs demonstrates.

New integrative metrics and methods are needed to measure interrelationships across sectors [115]. Some metrics relate to efficiency and productivity, such as water and food per unit energy, water and energy per unit crop yield, and energy and food per unit water [116]. These simple metrics can serve as a foundation for building more comprehensive cross-sector metrics and models. Besides considering social values, there are also technical and political difficulties in terms of how to weight the importance of different resource productivities in both models and management planning. Addressing these issues can help develop comprehensive and effective guidance for nexus planning and governance.

Toolboxes need to integrate both the advances in qualitative analysis and quantitative modeling for adaptive nexus governance and management processes. These processes should address uncertainties systematically and support robust decision-making for achieving SDGs. As addressing SDGs will be associated with considerable uncertainties, improved methods are needed to assess, communicate and manage interlinked risks in the face of global change.

Transforming policy-making, governance, and management. Researchers and stakeholders need to have closer dialogues to co-generate knowledge relevant for policy- and decision-makers and other stakeholders [117], and for complementing sector-focused approaches with nexus-based approaches in support of more integrated policies. Such an enhancement can facilitate coherence, complementarities, and coordination among sectors [64], detect major constraints and potential leverage points for triggering change, and map feasible and effective pathways for addressing multiple SDGs.

Nexus approaches can help to reconcile the human health-, environment- and development-oriented goals and targets within and across the SDGs [52,115]. For example, circular economy concepts that reframe wastes as valued resources instead of negative production externalities can help reduce environmental footprints and enhance economic efficiencies [118] and improve livelihoods. New uses for byproducts such as biogas from waste and bioenergy from plants with crassulacean acid metabolism also hold promise [118]. Rethinking trade-offs between bioenergy and food security can promote further synergies. For instance, well-designed biofuel programs might have positive effects on food security through diversifying income sources, increasing energy for food supply chain and domestic use, and generating beneficial spin-off effects on water and other sectors [119].

Nexus approaches that consider inter-sectoral and inter-regional interactions help to avoid "leakage" or "spillovers", i.e., transferring problems from one sector or region to another instead of solving them [120]. Reflexive governance offers potential to implement such approaches because it encompasses networks of relevant actors such as policy-makers, entrepreneurs, and civil society from multiple sectors that reshape governance structures as situations change [120]. Under a reflexive governance framework, actors engage in self-reflection that considers social relationships and broader institutional structure and functioning that can be modified over time. Nexus research can also help design systemic and flexible governance instruments that support integration both horizontally (across organizations at the same level) and vertically (across organizations at lower and higher levels) [121] and also across regions. One example is an integrative social network approach that identified complex synergies across different levels of institutional structure for food-energy-water nexus management in the Blue Nile river in Ethiopia [14]. Stakeholders engaged in participatory network mapping, which revealed the complexity of conflicts and communication bottlenecks over in-demand resources such as land for food, water, and energy development. Such instruments need to integrate market-based and network-based approaches that support innovative co-production of knowledge and learning [121]. They should better account for the political economy and social science aspects of decision-making in the nexus to guide and influence consumers' choices. By doing so, nexus approaches could also improve political stability among countries competing for common resources (e.g., water in the Middle East) by enhancing human securities while reducing environmental pressures and resource demand.

There are many cross-sectoral coordination challenges [122]. Barriers to coordination arise from rigid sectoral regulatory frameworks as well as planning and implementation procedures, entrenched domain interests and power structures, and established sectoral communication structures. Currently, most educational and management systems do not embrace cross-cutting expertise and instead conform to traditional "silo" approaches [122]. Few policy frameworks exist that explicitly address nexus coordination. To address this gap, the nexus concept is entering the center stage of debates among private, public, academic, and other stakeholders [123]. Changes need to be implemented among institutions to harmonize cross-sectoral policies, align strategies across sectors and incentives, encourage cross-sectoral investment, and encourage the development of an interdisciplinary knowledge base [122].

Nexus governance should be closely connected with the integrated SDG implementation because nexuses are directly or indirectly related to all SDGs (Figure 1). Although some studies have recognized synergies and trade-offs among SDGs within a place [124], little is known about the SDG interrelationships among different places [85]. There are explicit and implicit statements that the goals should be achieved everywhere. For instance, SDG 1 aims "to end poverty in all its forms everywhere" [3]. However, the gaps between the current conditions and SDGs are vastly different among countries [125]. Applying the metacoupling framework would help enhance contributions of nexus approaches to achieving SDGs within as well as across adjacent and distant places [126]. Other advances such as integrating Advanced Sustainability Analysis and network analysis to quantify synergies among SDG indicators across different places [127] shows promise and should be combined with the nexus approaches explored in this article.

Conclusions

The nexus approaches highlight the need for and potential benefits of taking a broad, multi-sector, multi-scale and multi-regional perspective to solve global challenges, such as those related to the SDGs. Although giving a name to this perspective may be viewed as the needless creation of a buzzword [17,18], the reason for bestowing this terminology is to remind researchers and policy makers of the strong linkages among sectors, scales and regions and the potential need to be aware of trade-offs and to seek synergies when solving major problems. Nexus approaches can help uncover synergies and detect harmful trade-offs among different sectors, scales and regions, reveal unexpected consequences, and promote integrated planning, decision-making, governance, and management. As a result, they can help enhance cooperation and reduce conflicts among sectors, scales and regions, increase resource-use efficiency, and reduce wastes and pollutants. Management of cross-sectoral, cross-scale and cross-regional integration is a major issue in both nexus approaches and SDGs.

There are reasons for optimism but the challenges are also great: providing an anticipated global population of 10 to 11 billion in 2100 with sustainable resources will require new perspectives and strong partnerships among science, government, industry and citizens. More efforts are needed to develop, implement, and apply comprehensive nexus frameworks; incorporate overlooked drivers and regions; expand and diversify nexus toolboxes; and mainstream nexus approaches into policy-making, governance, and management. Because nexus approaches require a broader range of expertise, more data, more coordination among sectors and more resources, they are challenging to implement. The examples so far demonstrate that nexus approaches can be feasible. However, it will be important to determine those problems for which nexus approaches would provide sufficient added value to justify the added effort. By continuing to expand the implementation efforts, novel interventions will emerge to meet the resource demands of a richer and more populous world while maintaining human well-being and building a sustainable and resilient planet.

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Competing interests

The authors declare no competing interests.

Corresponding author

Correspondence to Jianguo Liu (liuji@msu.edu)

Table 1. Nexus examples and direct relationships to Sustainable Development Goals (SDGs). Each example also has indirect linkages with many other SDGs as illustrated by food-energy-water nexus' linkages with all SDGs in Figure 1.

Nexus example	SDGs

Food-energy-water nexus [32]	2 ZERO HUNGER; 6 CLEAN WATER AND SANITATION; 7 AFFORDABLE AND CLEAN ENERGY
Water-food-energy-climate nexus [128]	7 AFFORDABLE AND CLEAN ENERGY; 2 ZERO HUNGER; 6 CLEAN WATER AND SANITATION; 13 CLIMATE ACTION
Food-energy nexus [129]	2 ZERO HUNGER; 7 AFFORDABLE AND CLEAN ENERGY
Food-water nexus [130]	2 ZERO HUNGER; 6 CLEAN WATER AND SANITATION
Energy-water nexus [131]	7 AFFORDABLE AND CLEAN ENERGY; 6 CLEAN WATER AND SANITATION
Energy-economic growth-CO2 nexus [132]	7 AFFORDABLE AND CLEAN ENERGY; 8 DECENT WORK AND ECONOMIC GROWTH; 13 CLIMATE ACTION
Water-land-energy nexus	6 CLEAN WATER AND SANITATION; 2 ZERO HUNGER; 7 AFFORDABLE AND CLEAN ENERGY
Energy-water-food-education nexus [133]	7 AFFORDABLE AND CLEAN ENERGY; 6 CLEAN WATER AND SANITATION; 2 ZERO HUNGER; 4 QUALITY EDUCATION
Water–energy–people nexus [134]	6 CLEAN WATER AND SANITATION; 7 AFFORDABLE AND CLEAN ENERGY; 10 REDUCED INEQUALITIES
Women-water nexus [135]	5 GENDER EQUALITY; 6 CLEAN WATER AND SANITATION
Energy-poverty-climate nexus [136]	7 AFFORDABLE AND CLEAN ENERGY; 1 NO POVERTY; 13 CLIMATE ACTION
Food, energy, water, and health nexus [137]	2 ZERO HUNGER; 6 CLEAN WATER AND SANITATION; 7 AFFORDABLE AND CLEAN ENERGY; 3 GOOD HEALTH AND WELL-BEING
Tourism growth-water security nexus [138]	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE; 6 CLEAN WATER AND SANITATION
Food-biodiversity nexus [139]	2 ZERO HUNGER; 14 LIFE BELOW WATER; 15 LIFE ON LAND
Mining-water nexus [140]	12 RESPONSIBLE CONSUMPTION AND PRODUCTION; 6 CLEAN WATER AND SANITATION
Nexus between financial autonomy, service provision, stakeholder participation and the resultant allocation of water [141]	17 PARTNERSHIPS FOR THE GOALS; 6 CLEAN WATER AND SANITATION
Nexus of climate change, water and food security, energy and social justice [142]	13 CLIMATE ACTION; 6 CLEAN WATER AND SANITATION; 2 ZERO HUNGER; 7 AFFORDABLE AND CLEAN ENERGY; 16 PEACE, JUSTICE AND STRONG INSTITUTIONS
Nexus between water service provision and property development [143]	6 CLEAN WATER AND SANITATION; 12 RESPONSIBLE CONSUMPTION AND PRODUCTION
Renewable energy consumption-economic growth nexus [144]	7 AFFORDABLE AND CLEAN ENERGY; 12 RESPONSIBLE CONSUMPTION AND PRODUCTION; 8 DECENT WORK AND ECONOMIC GROWTH
Urban-water-energy-climate nexus [145]	11 SUSTAINABLE CITIES AND COMMUNITIES; 6 CLEAN WATER AND SANITATION; 7 AFFORDABLE AND CLEAN ENERGY; 13 CLIMATE ACTION

Table 2. Example methods used in food, energy, and water (FEW) nexus quantifications. Note that many studies integrate multiple different methods (e.g., physical models and economic models were integrated to create multi-sector systems models).

Method	Functioning	Examples
Biogeophysical model	Investigates biogeophysical processes related to FEW	• Linking hydrological (VMod), meteorological, floodplain (EIA 3D model), and climatological models (GCMs) to investigate consequences of changes in a watershed for local economies (with respect to FEW resources) [146] • Hydrological models (HYMOD_DS) are used to simulate changes and implications for FEW in the Brahmaputra River Basin, South Asia under different scenarios [43]
Production model	Represents the amount of a FEW resource produced in different scenarios	• Tradeoff frontier models- Investigation of rice paddy and hydroelectric production in Sri Lanka under different management regimes [75]
Life cycle assessment (LCA)	Evaluates "the inputs, outputs and potential environmental impacts of a product, process or system throughout its entire life" [110]	• Investigation of the impact of agricultural production and evolving renewable energy programs on the FEW nexus in Qatar [110] • Assessment of the impact of Kellogg Europe cereal production on FEW (GaBi Software) [33]
Ecological footprint (or water/energy footprint) analysis	Evaluates the total environmental impact of a product or activity on FEW systems (normally in terms of area or natural capital)	• Calculations of water and energy footprints for different agricultural products grown in Nepal [147] • Estimates of the water footprint of energy use in California [83]
Material or resource flow analysis (MFA/RFA)	Quantifies flows and stocks or materials/resources in a FEW system	• Analysis of water fluxes, deforestation, and energy flows for cooking and heating in Uganda using Sankey diagrams- implications for food security [51]
Econometric model	Probabilistic modeling used to predict economic variables affecting FEW; often used for forecasting	• Analysis of the impact of energy demand and water availability on food security in BRICS countries (Brazil, Russia, India, China, South Africa) using panel econometric models [57]

Cost-benefit analysis (CBA)	Evaluates strengths and weaknesses of alternatives of a measure or action for FEW using a business framework	• Evaluation of costs and benefits of alternative irrigation technologies for FEW in Nepal [147]
Supply chain analysis	Investigates inputs and outputs across all stages of a product's production as it moves from primary production through supplier to customer in FEW systems	• Investigation of sources of waste in all three sectors of global FEW and targeting points in the supply chain to improve efficiency [148]
Input-output model	Quantifies the economic relationship (monetary flows) between two entities (or sectors) as related to FEW	• Quantification of two-way interdependencies among food, energy, and water and their implications for resilience of FEW systems; application to evaluating new policies such as organic farming [149]
Computable General Equilibrium (CGE) Model	Estimate how an economy responds to changes in FEW policy or other factors by following a general equilibrium paradigm	• Prediction of potential future scenarios of Australia's environment and economy under different FEW and climate conditions [32]
Agent-based model	Models actions and interactions among individual actors and their impacts on FEW systems	• Analysis of diverse FEW-related factors affecting individual farmer decision-making in the Midwestern USA with particular focus on biofuel crops [150]
Systems model	Examines relationships among multi-sectoral FEW systems, often incorporates scenario analysis and decision support tools	• Multi-sectoral analysis (MSA) of urban FEW use, flows, and resource metabolism in London- towards strategies for better resource efficiency [26] • Integrated assessment models such as PRIMA models [47] or CLEWs models [68] that integrate across multiple systems (e.g. climate, hydrology, agriculture, land use, socioeconomics, and energy systems) to make policy assessments • Other systems models include BRAHEMO [43], WEF Nexus Tool 2.0 [28], Foreseer Tool [51], and WEF SI [115]

Figures

Figure 1. Impacts of nexus approaches on Sustainable Development Goals. The figure illustrates that the food-energy-water nexus approach can influence the achievement of all SDGs directly or indirectly through helping strengthen synergies and reduce trade-offs and creating cascading effects beyond food, energy and water sectors.

Figure 2. Five major steps involved in implementing nexus approaches. Stakeholders may be engaged throughout all the steps.

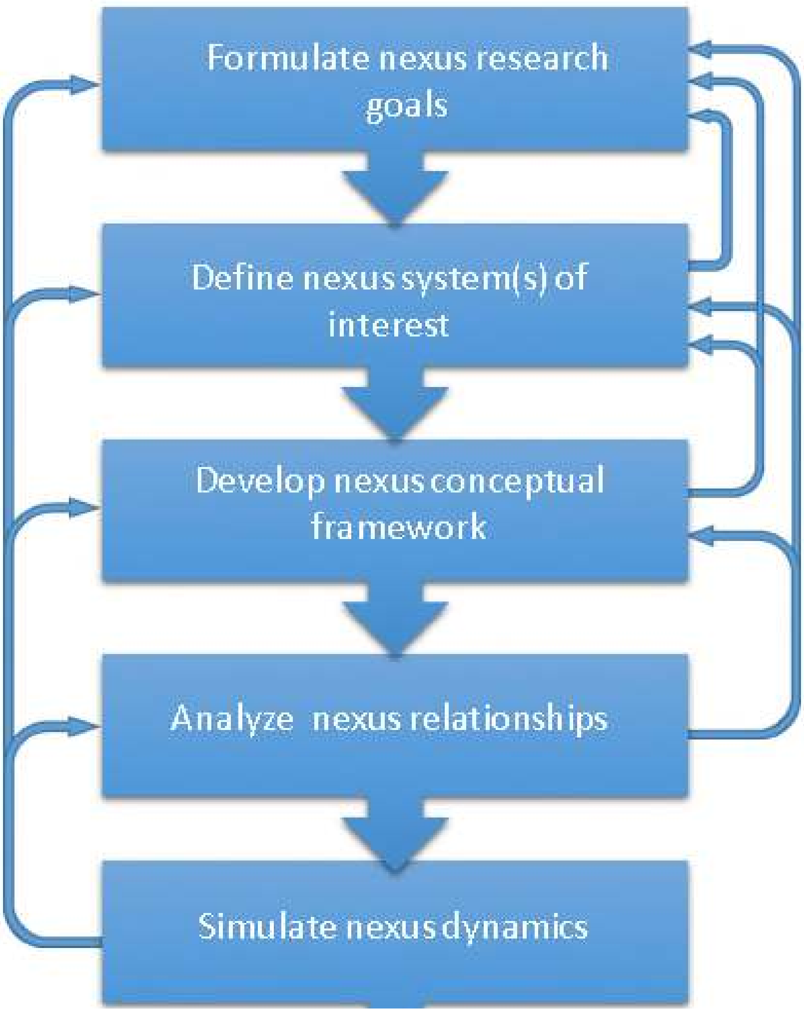

Figure 3. Conceptual framework of nexus approaches (using food-energy-water nexus asan example) across metacoupled human and natural systems. It includes intracoupling – human-

nature interactions within a coupled human and natural system, pericoupling – human-nature interactions between adjacent coupled systems, and telecoupling – human-nature interactions between distant coupled systems. Each coupled system consists of two major subsystems (humans and nature) and includes a wide range of drivers such as population, economic growth, urbanization, power relations, and conflicting goals The nexus is directly or indirectly connected with all Sustainable Development Goals. For the sake of simplicity, dynamics over time and differences at organizational levels are not shown.