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Resource nexus perspectives towards the United Nations Sustainable Development Goals

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Debate around increasing demand for natural resources is often framed in terms of a 'nexus', which is perhaps at risk of becoming a buzz word. A nexus between what? Over what scales? And what are the consequences of such a nexus? This article analyses why readers should care about the nexus concept in relation to the United Nations Sustainable Development Goals (SDGs). We discuss a five-nodes definition and propose perspectives that may lead to a reload of climate policy with buy-in from supply-chain managers and resource-rich developing countries. Our research perspectives address modelling approaches and scenarios at the interface of bio-physical inputs and the human dimensions of security and governance.

Demand for natural resources has been growing rapidly for decades, and is expected to continue growing, causing severe repercussions, risks, and threats for humans and ecosystems at different scales. Implementing the 17 SDGs may come with additional demands. Accordingly, resources must be managed in a more-sustainable manner and comprehensive approaches accounting for the interdependencies of resource use are needed[1]. The recent debate on a 'resource nexus' addresses such interlinkages.

The aims of this paper are to examine the nexus debate and to develop a research perspective on how a better understanding of resource interlinkages can be utilized to deliver the SDGs in an unprecedented integration. In doing so, we will discuss the ability of a nexus approach to assess critical interlinkages across five natural resource categories — water, energy, food, materials and land — along their value chains, and to enable sustainable resource use pathways, in particular with respect to the SDGs on food (SDG 2), water (SDG 6), energy (SDG 7), cities (SDG 11) production and consumption (SDG 12). The novel contribution is the clarification of nexus perspectives, in particular towards the SDGs, and the modelling of SDGs from a policy-relevant perspective.

The sections are organized as follows: in 'Examining the resource nexus debate' we provide a definition and conclude on a next generation of nexus research addressing scales and contexts. Then the section 'Perspectives towards delivering the SDGs' illustrates our perspective via three potential pathways and discusses new metrics for comparative research. It explores modelling the nexus towards the year 2030, by which point the SDGs ought to be delivered, and further into the future. In line with our transdisciplinary approach, the section discusses the need for new scenarios at the interface of bio-physical resource inputs and the human dimensions of security and governance. Finally, we outline our vision of useful directions for nexus research and SDG delivery.

From our viewpoint, the nexus concept should be applied in a flexible manner across multiple scales and does not offer a panacea. However, it will boost integration beyond what has been achieved so far, and can help in achieving national and regional sustainable development goals, and promoting wellbeing, health and equity across space. It is our opinion that nexus research can be aligned with a public purpose, helping to overcome silo-thinking and reducing the risks of trade-offs across the SDGs.

Examining the resource nexus debate

Acknowledging previous attempts at integrated resource management, we examine the recent nexus debate, provide a definition, and discuss relevant nexus dimensions.

The need for more integrated approaches. In the past, resource governance mostly focused on single resource categories such as water or energy along a supply chain that ran from primary natural resource, through processing and distribution to final consumption and disposal. The nexus concept[2–5] was formulated in response to such siloed thinking, and emphasizes the examination of critical interlinkages across resources, particularly synergies and trade-offs, in a more integrated manner.

The nexus debate has been quite vivid over recent years, especially in international organizations. Much research has been done on regional case studies. However, conceptual clarity often is lacking. Studies have assessed perceptions of business[6] and performed stakeholder analysis on the use of the term 'nexus'[7] — yet without moving forward on a perspective. So, has the nexus now become a buzzword, as a 2016 editorial in *Nature* suggested[8]?

We propose defining the resource nexus as a set of context-specific critical interlinkages between two or more natural resources

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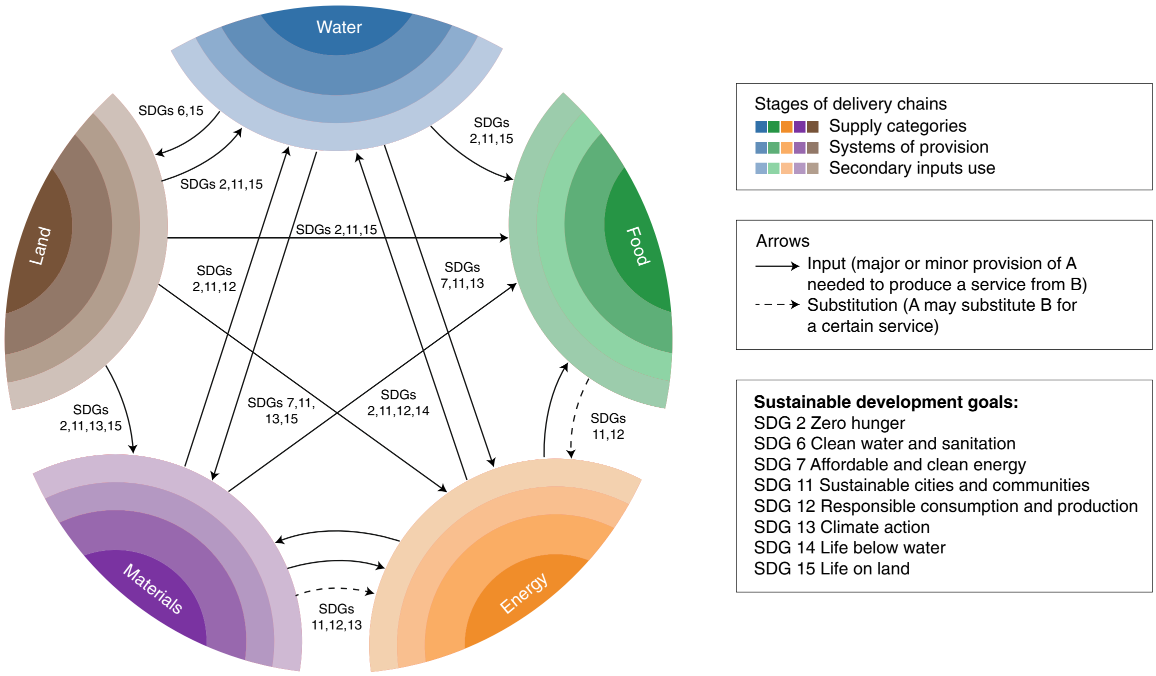

Fig. 1 | The nexus: interlinkages across resources and the SDGs. The main interlinkages across resource use, such as water being used to produce energy and vice versa. Main resource inputs into the chains of other resources are shown at three main delivery stages, illustrated through different shades of colour: primary production; systems of provision through production, distribution, and consumption; and potential secondary use. The figure describes a five-node approach, but fewer dimensions might be feasible following screening, in order to reduce complexities.

used in delivery chains towards systems of provision for water, energy, food, land and materials.

Figure 1 illustrates the main interlinkages in a generic manner. Some interlinkages may be more obvious than others, such as the connection between food and water. Others have become more critical through rapid recent changes, such as the materials needed for energy production. The figure also highlights that we should analyse the delivery chains from nature to consumers for each resource and its connection with the SDGs. Accordingly, the figure introduces layers addressing primary production, the socio-economic supply systems and their distribution, as well as recycling and re-use. The latter is well established for a number of materials and industrial water use, and broadening those activities is essential for a circular economy. Critical interlinkages may occur between corresponding or different layers, as illustrated by energy needs for pumping water through distribution systems to end-users.

As previously pointed out[9,10], such multifunctional approaches have a tradition, especially in forestry management and the Dublin principles on integrated water resource management (IWRM). Yet, integrated approaches are still the exception rather than the rule. In our fragmented world, attempts to integrate and actively seek for synergies are needed. Managing and governing such interlinkages is a key to achieve the SDGs — especially the cross-cutting SDG 12 on sustainable resource management. Such integrated approaches could also be applied when one resource (for example, a forest) is managed for multiple and often conflicting goals, such as biodiversity, water management, community livelihoods and timber production. Figure 2 illustrates the complexity of dealing with those SDGs and the manifold resource interlinkages; applying scores[11] appears useful.

A five-node resource nexus approach. Little agreement exists in the literature as to what natural resources are included in the resource nexus. The most widely acknowledged nexus approach covers water–energy–food[3,12], or water–energy[13]. We propose to broaden the scope slightly and add land and materials.

In line with other scholars[14–16], the inclusion of land in a resource nexus approach can be considered important because of its many critical environmental functions. Land provides a key supporting service for the formation of soil and other natural resources, for nutrient recycling and water production, regulation and purification, and it provides resources for livelihood and development. Figures 1 and 2 illustrate land as an input into all other categories, and its critical interlinkages with water. In scoping useful nexus approaches for implementation purposes, including land is essential to support SDGs 2, 7, 11, 13 and 15. Discussing land and food, the resilience of food systems is strongly dependent on functioning landscapes to provide water-based ecosystem services for agricultural production. The food system is essential for SDG 2, with inputs needed from all other resources and manifold critical interlinkages. Alternatively, having biomass as a dimension on its own is conceivable, in order to capture its relevance for food, for bioenergy and for bio-based materials from forestry. In Fig. 1, biomass is part of food, energy and land, illustrating the interlinkages and putting more emphasis on the systems of provision rather than on primary resources themselves.

In line with ref. [17], we also propose including materials for at least four reasons. First, materials are strongly linked to the other resource categories. Base metals, critical minerals and construction minerals have significant implications for energy production and distribution (SDG 7)[18], water provision (SDG 6) and urbanization (SDGs 9 and 11). Mineral fertilizers are also inputs for food production (SDG 2). Second, non-energy, non-renewable resources account for about 50% of natural resource use in most industrialized countries, measured in physical units according to the methodology of material flows analysis (see, for example, refs. [19,20]). Third, the costs associated with purchasing and processing materials in manufacturing industries have constituted about 40% of gross production costs throughout the 2000s[21,22]. Lastly, base metals and nutrients cause particularly significant environmental impacts, including land and water degradation and GHG emissions[23], and

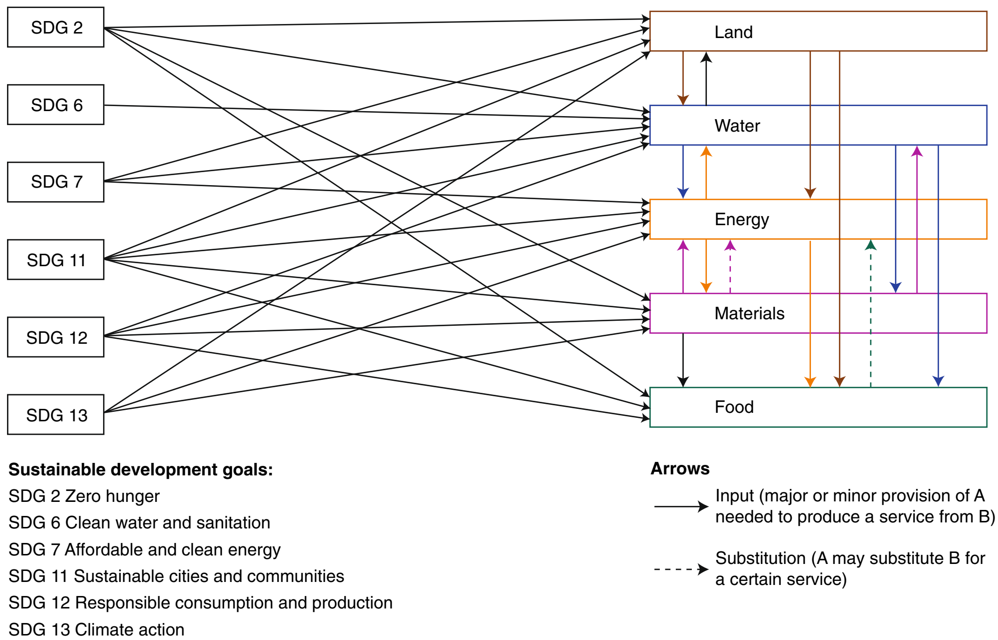

Fig. 2 | Main SDGs and the nexus. The main interlinkages between relevant SDGs and nexus categories. For instance, SDG 2 on zero hunger is relevant for land use, water use, materials (fertilizer) and food. It also reiterates main interlinkages across using resources in line with Fig. 1. Arrows indicate directions as input into other resources or mutual substitutions.

assessing optimal mineral inputs for agriculture can be investigated well through nexus research.

Such a five-node nexus comes with the advantages of consistency, comprehensiveness and policy relevance. It acknowledges the wider environmental functions of water, land and soil regulating and stabilizing the provision of inputs from other resources, such as biomass for food production. It retains the advantages of other nexus approaches in that it addresses SDGs 2, 6 and 7, and is potentially stronger in addressing SDGs 9, 11, 12 and 15 than other approaches. We acknowledge the potential disadvantages of growing the nexus model from two or three dimensions to a five-node one given that adding dimensions inevitably increases complexity in the model. However, utilizing a five-node nexus can be done in a flexible manner during a scoping process about the systems of interest, and may lead to research focusing on two or three dimensions rather than five. One may also note the straightforwardness of a nexus concept addressing and quantifying inputs, while additional complexity comes in through acknowledging boundaries of biosphere integrity and risk multipliers such as health and climate change[24]. Similarly to Liu et al. (ref. [25]), we propose that understanding the realities and complexities of human–environment systems and related environment-development goals as specified in the SDGs is the key objective of nexus research.

Multiple scales and securities. A significant number of regional nexus studies have been undertaken, for instance on Brazil (Ch. 16 of ref. [2]), South and Southeast Asia[26,27], Asia and the Pacific[28], the Middle East and North Africa (MENA) region[29], southern Africa[30] and others. Chatham House[31] and the Transatlantic Academy[4,5] stress the security dimension — in terms of both traditional national and inter-state security and a much broader human-security agenda[3,5,31,32].

While previous research has focused on risks of a resource curse and resource conflicts, interest is now turning toward assessing linkages to the security-related aspects of climate change, public health[33] and a host of vexing justice and equity-related concerns. Traditional and human security concerns are thus central to SDG implementation. Polycentric governance, as explored by Elinor Ostrom[34] and her many followers, brings advantages of adaptability, more effective social learning and increased legitimacy towards a new generation of global governance approaches. We conclude on the usefulness of such research in a comparative perspective.

For future nexus research we propose more research across scales[35] and securities; doing so will require assessing various institutional contexts and a number of critical interlinkages for both ecosystems and human actors. In some cases, criticalities might be particularly strong for human actors (for example, risks of extended electricity outages), in others for ecosystems.

Perspectives towards delivering the SDGs

Anticipating ambitious nexus research in the future, perspectives for new pathways may emerge in climate action, supply chain management, and for resource-rich countries.

Three new pathways. A nexus approach seems well-suited to the development of new pathways, by encouraging assessment tradeoffs and identifying synergies across scales. Such trans-disciplinary efforts, encompassing and integrating various disciplines and involving a wide range of stakeholders[36], hold promise for new knowledge creation on how scales and contexts can be integrated in nexus research. The three areas of climate change, supply-chain management, and resource-rich countries may serve as illustrations.

Following the 2015 Paris Agreement on climate change, nexus research could potentially improve implementation of Nationally Determined Contributions (NDCs) by building synergies among climate mitigation and adaptation and more sustainable economic development. Afforestation for climate mitigation should become more integrated with sustainable water regulation, so that subsequent water yields[37] do not counteract climate adaptation efforts and compromise communities' water security. Similarly, risk assessment for bioenergy plantations, unconventional hydrocarbons, hydropower and CCS technologies should include water criteria — as practiced in a number of strategic environmental impact assessments. Enhancing soil carbon in agriculture may synergistically serve climate mitigation and adaptation, by sequestering carbon from the atmosphere and simultaneously reducing fertilizer and irrigation demand and enhancing drought resilience. Multi-functional systems such as agro-forestry adapted to local contexts can increase local co-benefits across climate adaptation and mitigation and other natural resources[38], and must be assessed against potential productivity losses. Also, adapting to increased water scarcity through desalination of seawater can advance mitigation goals, if driven by renewable energy. Regarding our proposed scope of the nexus, more sustainable pathways for cement and steel[39] and other base materials are relevant. Altogether, this is a perspective which relates SDG 13 on climate change with peoples' concerns, as represented through SDGs 2, 6, 7, 9, 11, 12 and 15, and others. As the next section proposes, developing suitable integrated dynamic models can support such a perspective.

In another pathway, a nexus approach could support relating SDG 12 on responsible production and consumption with business understanding of risks[6] and international supply-chain management efforts. A nexus concept can enable a wider understanding of resource efficiency towards a circular economy at a variety of scales[40]. In line with UNEP's International Resource Panel we view resource efficiency as a general concept of using less resource inputs to achieve the same or improved output as value added to business and society; the circular economy offers a vision in which materials and products are reused and recycled at highest utility and value within the production and consumption system, and may ultimately nourish the Earth. This increased understanding would offer benefits for manufacturing industries, firstly through reducing the costs of purchasing and processing natural resources and materials[21,41,42] and secondly by innovating along entire supply chains, introducing novel products and systems. The nexus concept adds at least two useful features:

- A life-cycle wide and international approach addressing different resource-intensities and efficiencies of each processing step along and across supply chains, to reduce total water, land, carbon and other footprints[43].
- A more comprehensive approach to critical resource use thresholds, supported by quantitative and spatially explicit nexus assessment tools.

Future nexus research could facilitate the SDG resource efficiency targets (8.4, 9.4, 11.b and 12.2) and support implementation of SDGs 2, 6 and 14.

From a third perspective, resource-rich developing countries could benefit. Up until now they have tended to have a low resource efficiency performance compared to the world average[19], even declining over time in areas such as the MENA region[44]. A nexus approach could offer opportunities for example, for Australia[45]:

- Assessing the wider resource input requirements for mining and processing.
- Supporting integrated assessments for future planning across sectors and (potentially scarce) resources.
- Establishing 'soft extraction' pathways that increase revenues for countries, yet minimize cross-resource input requirements, and develop suitable, context-specific integrated policy options.

In our view, a nexus approach would complement on-going natural resource governance efforts and help countries and communities to establish inclusive and green growth pathways (SDG 9). Nexus research could draw lessons from livelihood research[46], participatory approaches and regional cases. In the long run, possible guidelines for planetary mineral consumption[47] could also be supported.

Resource input coefficients for key interlinkages

Such nexus research across scales and addressing contexts will have a data dimension in developing resource input coefficients. While

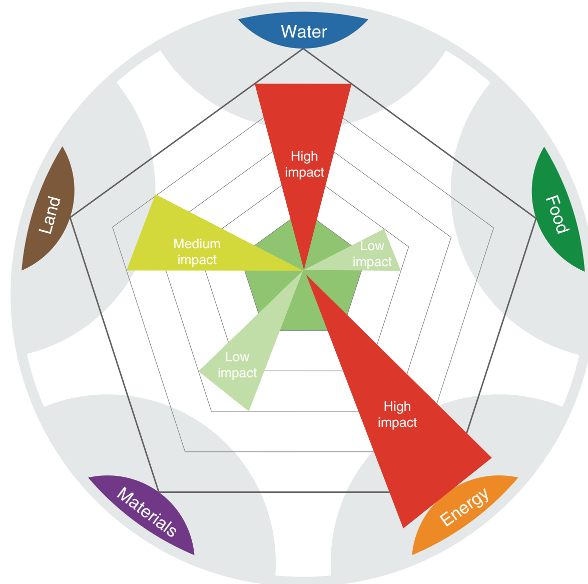

Fig. 3 | Interlinkages and impacts of using resources. The generic criticalities across resource use are shown, as are significant impacts that potentially transgress dangerous limits such as blackouts (in the case of energy use) or are close to such limits (causing water stress). Food and materials are less critical. The figure underlines the relevance of doing research on such critical impacts and interlinkages compared with analysing simple trends along one silo, and the option of focusing on relevant interlinkages after a screening process.

such coefficients are often studied separately, consistent coefficients across a five-node nexus are a research frontier. A sensible next step would be to undertake a few studies on a limited number of critical interlinkages among resources[23,48–50] for key sectors and materials. Existing databases from FAOSTAT (from the Food and Agriculture Organization of the United Nations) as well as from research (such as the Multi-regional Environmentally Extended Supply and Use/Input Output database EXIOBASE, the Eora global supply chain database or the Material Flows Analysis Portal at 'materialflows.net') should allow for a robust approximation. Particular attention must be paid to context-specific deviations from global average cross-resource input intensities and interlinkages. The Group on Earth Observation (GEO) has proposed a Global Earth Observation System of Systems (GEOSS) that might be useful for the future.

Sankey diagrams in a circle might be a good way to visualize interlinkages[51]. Several indicators can be combined into a single index and visualized in a radar graph. Figure 3 is a radar graph visualizing the impact of proposed changes on systems of provision, against the background of the already existing pressure compared to reference countries. Changes can lead to higher, similar or lower sustainability than existing trends; some impacts might be positive while others are negative. The area of the polygon indicates the impact of the intervention: the larger the area, the bigger the impact. The usefulness of our life-cycle nexus approach with layers along supply chains can be illustrated via hydro-dams, which require assessing the evaporation of dams and the risks of electricity blackouts downstream. One will note the relevance of scales here as water areas tend to differ in scale from electricity systems. Another case illustrating our five-node nexus is sand: a 'looming tragedy' is being observed that connects demand from construction activities and international trade (partly illicit) with losses in land use and ecosystem services[52].

Over time, such resource input coefficients might become part of international hubs — an aim of UNEP's International Resource

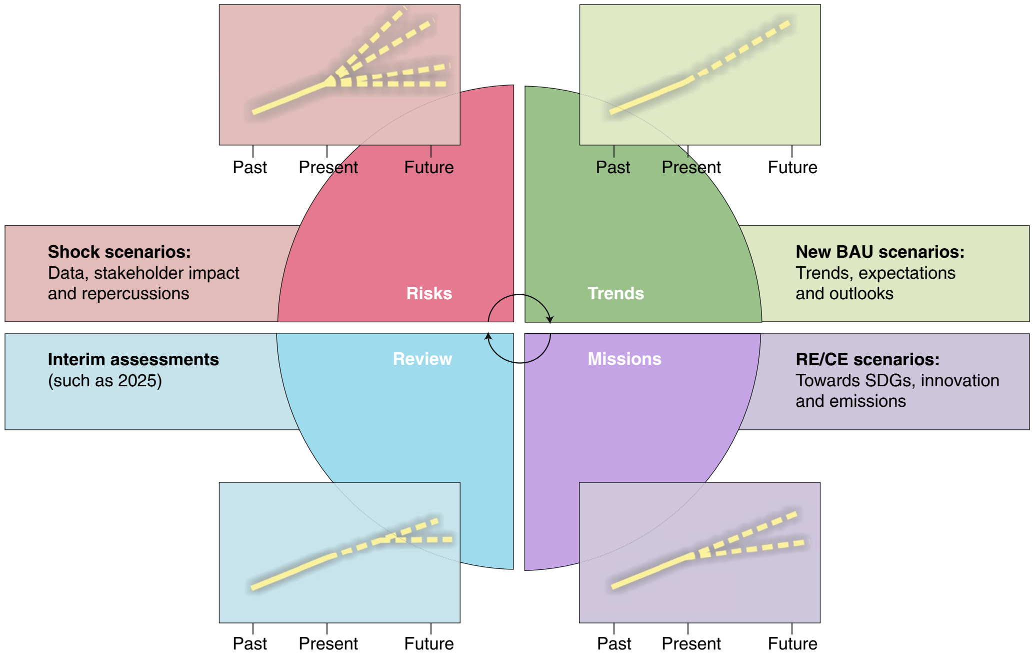

Fig. 4 | A set of scenarios supporting decision-making processes. The figure describes four novel types of scenarios that are relevant for nexus research. 'Risks' may include shocks, for example, if critical limits are being transgressed. 'New BaU' (business as usual) scenarios may include on-going environmental changes and expected saturation trends. 'Review' refers to measures taken and their assessment towards goals and gaps. 'Missions' refers to new and ambitious scenarios on resource efficiency (RE) and a circular economy (CE) more likely to meet goals and attract multiple actors.

Panel and Future Earth — and facilitate integrated planning as well as modelling and new scenarios. From such a perspective, more critical assessments across scales and assessing both environmental and human security could be incorporated.

Modelling perspectives

Modelling is relevant in analysing and assessing complexities in delivering SDGs via a nexus approach. Yet, in an inter- and transdisciplinary effort one should be aware of simplifications, assumptions and limitations. Dialogue is also necessary to train researchers and practitioners from the non-modelling world, and to communicate across realms. Systems thinking and complexity theory offer useful approaches.

Vertically consistent regional, national and local policy planning can be obtained through hierarchical nesting of models or consistent soft-linkage methodologies. Downscaling routines may be used for quick-scan visual interpretation of much coarser modelling results. Downscaling is useful for linking with integrated assessment models. However, downscaled results typically cannot be used for decision processes or choices of policy instruments operating at higher scales. Therefore accompanying research on multi-level, polycentric resource governance (including trade) seems useful, ideally in a dialogue with modelling efforts to inform choices and planning evidence.

In addition, modelling can also be deployed across temporal scales. This is relevant for the SDG time perspective of 2030 and beyond, modelling anthropogenic stocks and access to secondary resources. Clearly, in a nexus context, treatment of time preferences across all resources and environmental goods and services is a relevant research area. For example, a climate mitigation strategy expressed by an endogenously determined carbon price might lead to large-scale deployment of bioenergy, thereby creating pressure on land, water and food systems in the second half of the twenty-first century, as well as implications for biosphere integrity. Approaching this from a nexus perspective is relevant to more integrated risk assessment processes and developing response strategies.

Bio-physical models already describe several natural resources included in the five-node nexus discussed above, particularly water, energy, biomass and land. They exist at various scales, including global Integrated Assessment Models. Minerals and materials are not yet well represented in such models, and there is a lack of socio-economic variables. However, they can be extended and are useful for trend analysis, impact assessments and reviews (see Fig. 4).

System dynamics approaches allow the testing of a novel hypothesis and determination of trade-offs and other impacts. It facilitates understanding of the dynamics of coordination between different factors and relationships between environmental resources. Through such an approach, research may address regional and sub-regional non-linear dynamics such as UCL IDA3/IDA5 (the University College London Integrated Dynamic Assessment three/five node nexus models) (Ch. 16 of ref. [2]), and add interactions between such factors as climate change impacts and government policies in order to identify suitable strategies.

Industrial ecology models assess societal metabolism in physical terms (that is, flows and stocks of materials and energy); they are technology-specific and relevant for industrial sectors and supply chains. Among recent developments is the emergence of Life Cycle Sustainability Analysis, a framework with the goal of being more policy relevant by including economic and social aspects, forward-looking research, and upscaling[53].

Recent socio-economic work uses environmentally extended Input Output Analysis to incorporate water, food, land and particularly energy[54]. Computable General Equilibrium (CGE) models such as ENV-Linkages (Organisation for Economic Co-operation and Development, Environmental Linkages) coupled with integrated assessment models such as the IMAGE model (Netherlands Environmental Assessment Agency, Integrated Model to Assess the Global Environment) or University College London's ENGAGE (Environmental Global Applied General Equilibrium), and other hybrid approaches, may prove suitable for analysing economy-wide implications of resource-use interlinkages and trends (see Fig. 4), despite so far lacking some of the technological details.

A number of tools have been developed to support planning and management[55]. The Water Evaluation and Planning (WEAP) and the Long-range Energy Alternatives Planning (LEAP) have led to a new tool, the WEAP-LEAP framework, which is beginning to become integrated with land use[16]. A step forward towards more integrated planning is the climate, land-use, energy and water (CLEW) modelling framework[56].

Towards future scenarios

Soft interlinkages across these models and planning tools is pertinent[57,58] — alongside and in interaction with stakeholders[59]. In our view, nexus research has a responsibility and a capability to engage with stakeholders through consultations, transformative workshops and tailored discussion papers. Such co-production of knowledge is a key ingredient in accomplishing SDGs. It is also important to keep in mind that contemporary modelling often suggests conclusions based on optimal and efficient scenarios, while in reality second-best options prevail, unexpected shocks occur, and management is often more of a muddle and more sequence-driven than might exist in 'perfect' scenarios. Models thus are important to simplify understanding of interlinkages and assess the complexity of new directions, together with communication, interaction and learning. This way research can generate future missions that can be ambitious, activate innovation across sectors, across actors and across disciplines, and enable bottom-up solutions and experimentation.

A structured comparative approach to case studies will be useful in gaining additional understanding of the variety of critical intersections and will help to develop 'shock scenarios' (Fig. 4), for instance about water and food crises contributing to social unrest, political instability or violence. Given the variety of possible resource futures around the globe, based on real-world imperfect choices, we also suggest the development of new business as usual scenarios incorporating different lessons from history and long-term time series, and likely climate change impacts and other transgressions of planetary boundaries in the future. Indeed, evaluations of strategies via modelling impact assessments need to be part of such a set, and all need to be done in an iterative manner.

Figure 4 illustrates that those different types of scenario processes can be aligned with stages of decision-making processes. It also suggests that a variety of scenario analysis approaches are yet to be developed in future nexus research.

Outlook

This paper addresses concerns over future resource demand and the delivery of the SDGs in an integrated manner. It develops a definition for nexus research, centred on critical interlinkages between using two or more natural resources as inputs into socio-economic delivery chains. Referring to a five-node nexus of water, energy, food, land and materials, we also underline the relevance of scales and contexts, and the need for flexible applications[60]. Our perspective suggests new conceptual underpinnings at the interface of environmental research and human security and suggests strategic choices to enable a new generation of pathways, planning tools, scenarios and modelling to contribute to delivering the SDGs.

In the short run, nexus research could help SDG planners overcome silo mentality and enable more synergistic approaches. Being aware of doing so is easier said than done. Research should provide key coefficients and help develop new missions, pathways and roadmaps. Such perspectives seek more impactful research with actors from business, other stakeholders and involvement of developing countries, moving from necessary conditions for risk assessment toward more likely conditions for success in large and more complex systems.

Over time, integrated planning can be developed, addressing provisioning systems of water, energy and food; in rural areas and for supply chain management, land use and extractive activities ought to be included. We pledge for new foresight capabilities and scenarios that look into potential shocks and opportunities resulting from a nexus perspective. Planning and foresight would need to be supported by modelling and an enhanced understanding of how those approaches interact with governance in the real world. As a result, we imagine a reload of climate policy and more emphasis on water, food and land, all with more enthusiasm from supply-chain managers and resource-rich developing countries.

Through adding resource inputs, interlinkages and governance, knowledge on the nexus thus complements and strengthens existing sustainability research on the Anthropocene, on planetary boundaries, and on earth systems governance that typically follows a more top-down approach, and it also complements environmental research on natural capital. It also connects well to research on anthropogenic stocks[61], and on-going debates about a circular economy that yet need to reach out to development concerns.

Finally, this paper stresses the role of research in challenging times. It endorses a view on SDGs and broader sustainability ambitions that stresses inclusive development for those facing economic hardship and towards improved international relations. As much as we consider a nexus approach indispensable to deliver the SDGs, those employing it should seek to apply academic rigour to data, evidence and modelling, and they should disseminate, upscale and generalize findings via missions and pathways across fora and scales. Nexus research could become salient for the integrated, effective and efficient implementation of SDGs.

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Competing interests

The authors declare no competing interests.

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