



Towards a common understanding of water-energy-food nexus research: A view of the European nexus community and beyond

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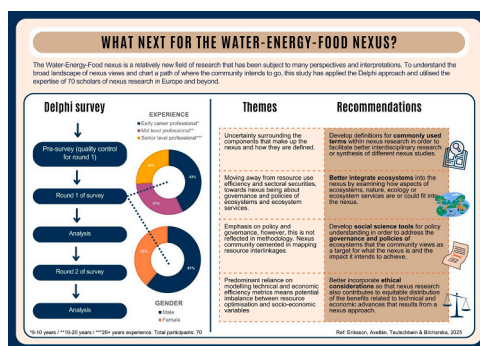
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HIGHLIGHTS

- Delphi study with 70 experts with research experience of the Water-Energy-Food nexus
- Aim of nexus research has shifted, however methodology has remained largely the same
- Policy and governance, especially of ecosystems, need to be integrated into the nexus

GRAPHICAL ABSTRACT



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ABSTRACT

The water-energy-food nexus is a relatively new field of research that has received much attention in research and policy. Applying a nexus lens can increase efficiency, reduce trade-offs, and build synergies that can help tackle future pressures caused by increasing demands and climate threats. However, the field is subject to many perspectives and interpretations. The nexus concept lacks a common definition or framework, and some scholars have made calls to include other components than water, energy, and food, such as ecosystems, land or climate. Advancing nexus research requires a clearer understanding of the definition, aims and approaches of the field. To better understand the broad landscape of nexus views and chart a path of where the community intends to go, we apply the Delphi approach, a tool through which consensus about concepts, views and perspectives can be gained through iterative questionnaires, and utilise the expertise of 70 international scholars specializing in nexus research. The survey reveals that the nexus approach seems to have moved away from being strictly about resources or sectoral securities, and towards governance and policy, especially in relation to ecosystems and ecosystem services. However, this is not reflected in methodology or in where to focus future research efforts. Though the aim of nexus research seems to have shifted, it is still somewhat cemented in mapping resource interlinkages, which could hinder addressing policy and governance concerns, and the ethical dimensions of the

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nexus. Based on the results of the Delphi survey, we provide recommendations for future research that could progress the field further.

1. Introduction

Human wellbeing relies unequivocally on access to water, energy, and food; yet the governance and availability of each of these resources are under intense pressures. Projections on global population growth indicate that the world could be home to 8.5 billion people in 2030, 9.7 billion in 2050 and 10.4 billion in 2100 (United Nations, 2022). With this will come a rise in urbanisation and consumption patterns that will significantly accelerate the demand for water, energy, and food (US National Intelligence Council, 2021). As the world increasingly approaches its physical capacity of safely sustaining human life (Rockström et al., 2009; Steffen et al., 2015; Richardson et al., 2023) a new paradigm of the water-energy-food (WEF) nexus has emerged that aims to tackle the threat of a threefold insecurity.

The World Economic Forum in 2008 and the Bonn 2011 Nexus Conference put the concept of the WEF nexus on the global research agenda by bringing attention to how applying a nexus lens to the WEF resources can increase efficiency, reduce trade-offs, and build synergies by integrating management and governance across sectors (World Economic Forum, 2011; Hoff, 2011). Research and policy interest in the WEF nexus have had a major uptake in the last decade (Newell et al., 2019). Shaped by integrated management approaches to natural resources, the WEF nexus owes much of its popularity to preceding holistic framings such as integrated natural resources management (INRM) and integrated water resources management (IWRM), as well as a bright spotlight on sustainable development in the last decade (Roidt and Avellán, 2019). A common argument for WEF nexus research is precisely related to such earlier approaches and the failures of integration from a sector-driven management perspective (Al-Saidi and Elagib, 2017).

There are similarities across both goals and features of nexus and integrated management approaches. They all aim for sustainability or sustainable development, apply systems thinking to allow for holism and complexity, and stress the need for stakeholder inclusion and participation that is inter- or trans-disciplinary (Roidt and Avellán, 2019). The innovation in the WEF nexus approach (past the main selling point of integration across sectors, rather than within them) is found in the goals that reflect governance and policy; the WEF nexus addresses aspects of decision-making and policy coherence, as well as synergies and trade-offs (Roidt and Avellán, 2019). However, while the WEF nexus is meant to differ itself from sector-driven management approaches that has their springboards in a specific sector or resource, the WEF nexus is often adopted by a researcher or team of researchers whose sectoral background influence what perspective is at the centre of the nexus (Leck et al., 2015), for example, while attempting to integrate the other two components of the WEF nexus into a water perspective.

The above example is a common one and water scientists have in many ways been a driving force in the development of and debate around the WEF nexus, meaning that water resources/availability is often placed at the centre of the nexus (Albrecht et al., 2018; Allouche et al., 2015; Sušnik et al., 2023). If that is a correct use of the nexus can be argued either way, as the WEF nexus lacks a commonly defined conceptual framework (Endo et al., 2017). Many authors build a definition of the WEF nexus around their unique experiences of resource interactions. However, there is also evidence of WEF nexus analysis being extended to include discussions on other components and factors, such as climate, soil, land, labour, livelihoods, population growth and many more (Dargin et al., 2019; Wichelns, 2017), as illustrated by a wide array of tools developed to assess the nexus (Dargin et al., 2019). Some components have been viewed equally essential so that their own nexus “framework” has been proposed, such as in the case of the water-energy-environment (WEE) nexus; the water-energy-food-ecosystem

(WEFE) nexus; and water-energy-land-climate (WELC) nexus (Endo et al., 2020). While some stress the value of narrowly focused research (Wichelns, 2017), others call for the development of a unifying framework of nexus research (Endo et al., 2017) and accompanying methods (Albrecht et al., 2018).

In fact, although numerous tools have been developed for assessing the nexus (Dargin et al., 2019), there is no established methodology or tools for practising and implementing a “nexus approach” (Endo et al., 2020). A systematic review by Albrecht et al. (2018) found that integrated models, economic tools, and environmental management approaches dictate the state of nexus methodology, but few studies offer distinguishing nexus methods or tools. Quantitative approaches are prevailing while the use of qualitative social science methods is relatively scarce. Some do not present explicit methods but rather employ the WEF nexus as a conceptual framework, where the underlying purpose of the nexus is to allow or promote an understanding of interlinkages for better governance, policy coherence or cross-sectoral collaboration (Albrecht et al., 2018; Keskinen et al., 2016). In relation to that, it is argued that the concept would benefit from developing nexus-specific tools that can enhance the understanding of WEF nexus interlinkages and address social and political issues (Albrecht et al., 2018). However, a counterpoint has been made that it was never an objective of WEF nexus researchers to develop a common nexus model and that the lack of a strict definition allows for application of the WEF nexus to various challenges (Sušnik and Staddon, 2022).

Furthermore, it has not been quantified if and how nexus approaches contribute towards achieving aims of sustainable and effective resource management. The advantages of a nexus approach are that it can help uncover synergies and co-benefits; detect harmful trade-offs; unveil unexpected consequences; and enhance integrated planning, decision-making, governance and management (Liu et al., 2018). But the cost of applying a nexus approach is also likely to be higher than that of a sector-specific approach. Not only is expertise of all relevant sectors needed, but a degree of coordination is also required to bring together this expertise, which means that nexus research takes longer and could cost more to carry out (Liu et al., 2018). It is also not clear how to integrate and implement the WEF nexus in terms of legal or governance aspects (Olawuyi, 2020). As it stands today, it is common practice for most countries to have a set of laws and regulations for each nexus domain, which is bound to have practical complexities for implementation of the nexus (Olawuyi, 2020). In relation to that, there is a need for both an understanding of the regulatory contexts across the nexus sectors and an institutional set-up that can effectively manage the coordination of decision-making and information sharing of all domains (Olawuyi, 2020).

Other debates have been raised about the level of innovation of the WEF nexus approach (Leck et al., 2015; Wichelns, 2017; Allouche et al., 2015). There are concerns that faith is blindly being put into the WEF nexus to solve long-term structural issues, when in fact, issues are as much linked to resource inequality and social instability (Allouche et al., 2015). By framing the WEF nexus in terms of resource availability or scarcity, nexus thinking sometimes falls short of addressing who benefits, and who is marginalised, when improvements are made to WEF resource efficiency, especially as nexus solutions are often technological in nature and may sometimes lack political, social and justice considerations (Allouche et al., 2015). Similarly, the idea of a WEF nexus approach that can optimise the use of important resources risks turning human needs for water, energy and food into a perfect equilibrium model that can “*encourage the commodification of resources, downplaying environmental externalities, such as biodiversity and climate change, as well as poverty alleviation needs, ignoring day-to-day realities, local priorities and*

needs" (Allouche et al., 2015, p.617).

As the current nexus approach is now more than a decade old, its implementation has happened in a multitude of geographical, socio-cultural, biophysical, disciplinary and governance settings, in a multitude of projects and with different research and development teams (Avellán and Roidt, 2022). Disparities in how to approach research from a WEF nexus standpoint inevitably led to a lack of clarity in what the concept aims to achieve as well as how to appropriately apply it. Often the implementation of nexus projects, and thus the nexus approach, is done in research settings, trying to answer research questions relevant to a specific project. Based on these many different experiences, categorisations of various research questions have emerged, such as the ones seen above on methods used within the nexus (How to assess the nexus and implement the nexus approach?), or the types of theoretical frameworks applied in the WEF or WEF nexus (What the nexus is?) (Lucca et al., accepted). However, it is increasingly difficult to fully grasp the impact that the nexus approach is making on the ground (Why to apply the nexus?), which in turn makes charting the future research pathway challenging. We ask ourselves, what **research** needs to happen to strengthen the nexus approach on the ground, in its diverse contexts? What new knowledge needs to be generated to improve the Why, the How and the What of the nexus?

To explore the diverse views within the nexus community and chart a direction for its future development, this paper aims at providing a clearer understanding of WEF nexus research, and how nexus scholars view its definition, aims and approaches. We address the gaps identified here by mapping out an understanding of WEF nexus research that the nexus scholarly community currently converges to. Our objective is to reveal how views align or differ on fundamental aspects of WEF nexus research (such as definitions, methods, stakeholder engagement, impacts and research gaps) amongst scholars in this field. To achieve that we chose to carry out a Delphi survey, which allowed scholars of the WEF nexus to express and develop their experiences and ideas of a relatively new research field that has benefited from much attention on the global scene in recent years, but is equally subject to many perspectives and interpretations.

2. Methods

2.1. Delphi approach

The Delphi approach is a reiterative survey process that revolves around structured group communication. It utilises experts who are asked to share their perspectives, estimates, opinions or similar, through a survey. The survey results are then compiled, organised, and fed back to the group of experts for continued discussion in further rounds (Beiderbeck et al., 2021). The approach usually includes two or more rounds and often the purpose is to generate consensus on a topic or challenge (Hanna and Noble, 2015). In this study, we aim at gathering the perspective of the nexus scholarly community on a number of areas relating to nexus research, and the Delphi approach allows for a larger set of participants to converge their response at their own convenience and irrespective of where they are located. Since the study had a tight timeframe of just over four months, and targeted an international group of scholars, this process is better-suited than, for example, holding nominal group processes or consensus development panels (Waggoner et al., 2016) where the participants need to be present face to face with each other. One of the key advantages of the Delphi approach is that the group is presented with a broad scope of views on a topic, while avoiding negative factors to group communication such as dominant individuals taking up majority of discussion or the group leaning into the views of individuals with influence and status, seeing as the process is anonymous (Belton et al., 2019).

What constitutes consensus is a somewhat loosely defined element of the Delphi approach. In some cases, the rounds are iterated until a minimum degree of stability is achieved in the responses, i.e., when

there is consistency in responses between rounds and thereby some level of consensus is reached (von der Gracht, 2012). However, due to the time constraints of the study, the process outlined in this paper (Fig. 1) consisted of one "pre-survey" with a small number of experts ("evaluators") and two main survey rounds with a larger number of experts ("participants"). Four different kinds of questions were asked, namely: questions on a five-point Likert scale indicating degrees of concurrence, single choice questions where only one option could be chosen, ranking questions that allowed for the ranked categorisation of answers, and open questions where participants could add free-text. As is often the case, factors such as time constraints tend to limit most Delphi studies to a specific number of rounds (von der Gracht, 2012). Therefore, consensus is usually measured by percentage of agreement with a statement or percentage of participants who score the statement highly (Diamond et al., 2014). Very high levels of consensus may be required when there is a critical decision to be made, however, in cases of determining trends, a lenient criterion might be better suited. 75 % is a frequently used consensus criterion (Belton et al., 2019). The purpose of the present study is to obtain a "common understanding" of the WEF nexus and to highlight similarities, and divergences, in research orientation relating to the nexus. As such, there is no overhanging resolution that needs to be met, but rather insights on an emerging research field to be mapped. The detailed consensus criteria for this project are presented in Table 1.

2.2. Logistics of a Delphi survey

The number of experts participating in a Delphi survey varies widely across studies, as there is no universally recommended or standard number. The definition of "experts" is similarly flexible, often relying on the researcher's judgement and common sense (Belton et al., 2019). While participants should possess significant expertise in the topic of interest, incorporating a diverse range of professional experience and demographic backgrounds can enhance the quality of insights by broadening the variety of skills and perspectives represented (Barrios et al., 2021).

For this study, six evaluators with knowledge and experience of the WEF nexus as a research field evaluated the initial pre-survey (Appendix A) of the Delphi survey. The pre-survey was drafted in December 2022, distributed to evaluators on 16 December 2022, and completed within three weeks. Following this pre-survey stage, invitations to participate in the Delphi survey were emailed to 293 individuals. All evaluators and experts were identified through purposive and convenience sampling based on the professional network of the authors. The list of potential participants comprised mainly scholars (as the aim of this study is concentrated on research) who have participated in work or research relating to the WEF nexus, either within the European COST Action NEXUSNET activities, or within relevant EU projects (e.g., SIM4NEXUS, NEXOGENESIS). Invitations to participate were sent in December 2022 and January 2023. 89 experts agreed to participate in the Delphi survey.

Two rounds of the survey were completed during a two-month period (Fig. 1). The surveys were conducted through an online survey tool. It was estimated that round 1 and 2 of the survey took around 15 and 10 min, respectively, to complete. Two reminders per round were sent out to participants before closing. Round 1 (Appendix B) was sent to participants on 2 February 2023 and was open for approximately two weeks. Out of 89 participants who agreed to take part in the survey, 70 responded to the first round of the survey (Table 2). Round 2 (Appendix C) was sent to participants on 29 March 2023 and was open for approximately two weeks. Out of 70 respondents who participated in the first round of the survey, 44 completed the second survey round, of which two had to be disqualified as they had not completed the first round (Table 2).

The first round had a total of 70 participants and spread across 19 countries. These were mostly European, with a handful of exceptions (Australia: 1; India: 2; Iraq: 1; USA: 1), because participants were sought

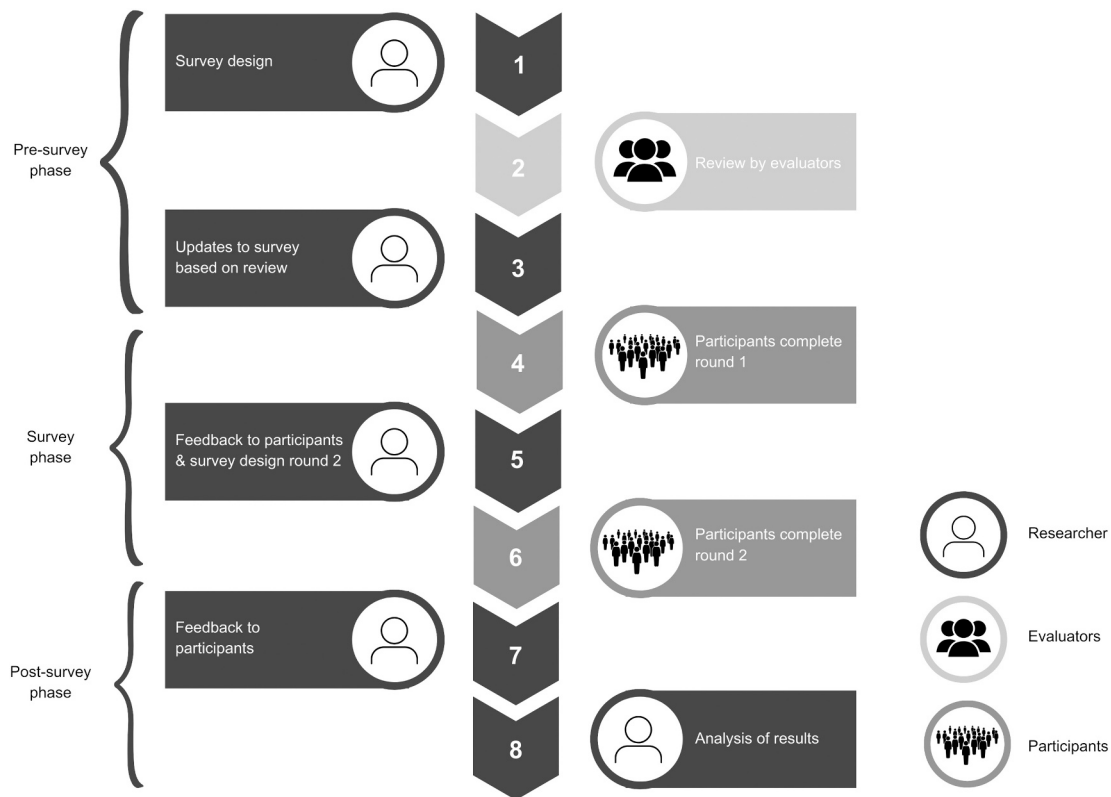


Fig. 1. Steps (1–8) performed in the study, categorised according to pre-survey, survey, and post-survey phase.

Table 1
Consensus criteria.

Type of question	Consensus criteria
Five-point Likert scale	At least 75 % of participants score 4 or 5
Single-choice Ranking	At least 75 % of participants choose a single alternative N/A. Individual selections are collected, weighted according to position, and presented according to overall ranking, i.e., the group's ranking.
Open	N/A – Only used in round 1, i.e., answers coded, categorised, and presented as scoring questions in round 2

Table 2
Response rates.

Round 1			
Agreed to participate	Responded to survey	Response rate (%)	
89	70	79 %	
Round 2			
Participated in round 1	Responded to survey	Response rate (%)	Additional responses in round 2 that were disqualified due to not participating in round 1
70	44	60 %	2

out from their involvement in EU-funded projects such as NEXUSNET, SIM4NEXUS and NEXOGENESIS. Roughly half of the participants had 10+ or 20+ years professional experience, whereas the other half were early career professionals (less than 10 years professional experience). A strong majority, around 80 %, were from academia. Nearly 40 % of participants were women (Appendix D).

2.3. Questionnaire design and survey stages

The first step in the survey design was a non-systematic literature review to map out the relevant content of the questionnaire to be used in the first round. Four searches were made in the Scopus database with keywords relevant for the study area (*water energy and food AND research; water energy and food AND (methods OR theory); (integrated management OR integration) AND nexus; nexus AND sustainable development*). It focused on articles published in the last 10 years that were peer-reviewed and in the English language. At the results level, the titles and abstracts of (a) the top 10 articles according to relevance and (b) the top 10 articles according to highest number of citations were examined to determine the focus of the article. In total, 11 scientific articles were chosen (Appendix E) and the five main sections of the survey were developed based on insights gained from these papers: (1) nexus thinking and components; (2) methods for nexus research; (3) stakeholders; (4) impact and ideal circumstances; (5) research gaps and future research. Also included in the review was the background paper for the Bonn 2011 Nexus Conference by Stockholm Environment Institute (Hoff, 2011). Although categorised as grey literature, this paper was included due to its significant influence on nexus literature and its role as widely cited catalyst for the increased attention the WEF nexus concept has gained over the past decade.

The second step – the pre-survey stage – included expert feedback on the survey design from six evaluators that reviewed the contents and structure of the draft questionnaire. The evaluators were asked to score each question on a five-point Likert scale, according to relevance, clarity, and sufficiency; with the option to comment on the score. All but the open questions had further pre-survey questions relating to the presented alternatives, e.g., if there were alternatives that were missing. Recommendations from the evaluators included adding “unsure/I don’t know” to the scoring scale; shortening questions and alternatives; categorising alternatives and ensuring consistency in the terminology (Appendix F). The first round of the Delphi survey comprised five

Table 3
Sections in each survey round.

Round 1	Round 2
<p>1. Nexus thinking and components</p> <p><i>Aim:</i> To define what a nexus approach or nexus thinking means in a research context. To map out what components (energy, water, food, ecosystems, and so on) the nexus community considers important to include in ‘the nexus’.</p> <p>In the first round the components were placed into four categories to conjure a discussion around if any area holds more weight, e.g., if nexus research is more about, say, sectors than ecosystems. In the second round, we asked participants to themselves categorise the alternatives; in order to test how easy or difficult it is to define components and terms that are commonly used in nexus research.</p> <ul style="list-style-type: none"> - Please offer a short explanation of what nexus thinking/a nexus approach in research means to you. [open] - Most commonly one talks about the WEF nexus. What components are important to be included in the work with the WEF nexus? These could be specific sectors, policy areas, resources or ecosystems. Please score the particular components below. [Likert scale] 	<ul style="list-style-type: none"> - Nexus thinking is about... [Likert scale] - In your opinion, which category is the best fit for each of the below additions made by participants in the first round? [single choice] - What components are important to be included in the work with the WEF nexus? [single choice]
<p>2. Methods for nexus research</p> <p><i>Aim:</i> To understand if certain methods are more relevant than others in nexus research and how this differs for different types of knowledge, i.e. system knowledge, target knowledge and transformation knowledge. The methods to be scored in the second round were additions (to the list of methods) made by participants in the first round.</p> <ul style="list-style-type: none"> - How relevant are particular methods for understanding the system? (System knowledge) / How relevant are particular methods for understanding the target state? (Target knowledge) / How relevant are particular methods for understanding the pathways from the current system to the target state? (Transformation knowledge) [Likert scale] 	<ul style="list-style-type: none"> - How relevant are particular methods for understanding the system? (System knowledge) / How relevant are particular methods for understanding the target state? (Target knowledge) / How relevant are particular methods for understanding the pathways from the current system to the target state? (Transformation knowledge) [Likert scale]
<p>3. Stakeholders</p> <p><i>Aim:</i> To map the role of stakeholder engagement and what stakeholder groups should be included in nexus research.</p> <ul style="list-style-type: none"> - Please score the following statements. The role of stakeholder engagement in Nexus research is to: [Likert scale] - In your opinion, which stakeholder groups are necessary to include in a nexus research process? [Likert scale] 	<ul style="list-style-type: none"> - Please score the following statements. The role of stakeholder engagement in Nexus research is to: [Likert scale] - Which stakeholder groups are necessary to include in a nexus research process? [Likert scale]
<p>4. Impact and ideal circumstances</p> <p><i>Aim:</i> To map the potential impacts of applying a nexus approach in research, and what needs to be in place for a nexus approach to happen. In the second round, participants were first asked to score and then rank the enabling conditions that had come out of the open question in the first round. The aim of this was to make the participants prioritise and avoid the trap of “everything is important”.</p> <ul style="list-style-type: none"> - What are the potential impacts of applying a nexus approach in research, compared to sectoral approaches? [Likert scale] - In your opinion, which are the most important enabling conditions for applying a nexus approach in research? [open] 	<ul style="list-style-type: none"> - What are the potential impacts of applying a nexus approach in research, compared to sectoral approaches? [Likert scale] - The most important enabling condition is... [Likert scale] - If you had to prioritise, how would you rank these enabling conditions? Please order them from most important (top) to least important (bottom) [ranking]
<p>5. Research gaps</p> <p><i>Aim:</i> To list the most important gaps that the nexus community thinks should be tackled in order to advance nexus research.</p> <ul style="list-style-type: none"> - What research gaps do you see that require further research in relation to the nexus? [open] 	<ul style="list-style-type: none"> - In the first round you were asked to write what research gaps you see that require further research in relation to the nexus. Answers from participants were categorised, which formed the basis for the below research gaps. Please read through them below and consider their importance. [Likert scale]
<p>6. A context-specific nexus (round 2 only)</p> <p><i>Aim:</i> To address comments by participants in the first round saying that it was difficult to score which components should be included in nexus research as a nexus approach depends on the research objective or case at hand.</p>	<ul style="list-style-type: none"> - Please choose one of the following statements regarding nexus components that you agree the most with: [single choice] - With your answer for the above question in mind (for example, if you chose alternative 1, the nexus components are water, energy and food), please choose one of the following statements regarding component categories that you agree the most with [single choice]

sections and a total of eight questions. The second round comprised six sections and a total of 13 questions (Table 3).

The data from the first round of the Delphi survey were analysed both qualitatively and quantitatively, summarised and fed back to the participants in the second round. There are no set guidelines on how the data from the previous round should be presented, i.e., how the feedback should be provided. However, common ways include qualitative feedback, e.g., a summary of participants’ comments; and quantitative feedback, e.g., a statistical summary such as the median response (Boulkedid et al., 2011). Belton et al. (2019) recommends “providing the median and inter-quartile range for responses made to individual ordinaly-measured question items” and complementing text with visual summaries such as bar charts (Belton et al., 2019). The two types of questions in the first round were open questions and Likert scale questions (questions with alternatives that participants were asked to score). Using qualitative content analysis (Bryman, 2012), the open question responses were coded into categories of similar thematic content. Coding was done in the open-source qualitative research tool *Taguette*. The codes were then summarised into statements that participants were asked to score or rank in the second round. The statements reflected the main themes of the open responses, i.e. topics that had been mentioned

in some shape by several participants. This meant that if only one participant had raised a certain topic it was not brought forward to the second round, with the exception of responses that were very comprehensive and detailed. The Likert scale questions from the first round were organised into a summary of statistics, with indicators showing whether alternatives fell above or below the consensus criteria. In effect, some final results were produced already from the first round, i.e., whether at least 75 % of participants had scored the alternatives highly (four or five on the five-point scale) or not. In terms of what was brought forward to the second round from the Likert scale questions, it was the suggestions produced in the first round. For each Likert scale question in round 1, participants had the option to add alternatives they felt were missing. The questions themselves were consistent across rounds, and in the second round, all alternatives were the suggestions made by participants earlier.

Following the second round, most of the questions in the Delphi survey were analysed in the same manner and with the same consensus criteria as above, as they mirrored the questions in the first round. An exception is one question that was unique to the second round. In section 1, participants were presented with list of components suggested during the first round as potentially important for inclusion in nexus research.

Along with scoring these components, participants were also asked to assign them to one of the categories defined by the researchers for this project: resources, policy areas, sectors, and ecosystems. For the analysis, a category was considered established if at least 50 % of participants assigned a given component to that category. If no category reached the 50 % threshold for a component, it was considered undecided, and labelled as “unspecified”.

3. Results

3.1. Nexus thinking and nexus components

Nexus thinking can hold different meanings for different researchers. In the first round of the Delphi survey, participants were invited to describe, through an open-ended question, what nexus thinking or a nexus approach in research means to them. Based on a content analysis of their responses, 14 statements were developed for the second round, where participants were asked to rate their level of agreement with each.

Two statements reflecting the core principles of how nexus thinking is usually described – *identifying and understanding synergies between nexus components* and *identifying and understanding trade-offs between nexus components* – received the highest level of agreement amongst participants (98 % and 95 %, respectively). Related statements focused on the practical application of these concepts – *exploiting or creating synergies between nexus components* and *avoiding or minimising trade-offs between nexus components* – received slightly lower agreement levels but still ranked highly, with 88 % and 86 %, respectively. Participants also strongly agreed that nexus thinking involves *analysing interrelations between nexus components* and *resource management and efficiency* (all statements listed in appendix G, fig. G1). However, the group refrained from centering nexus thinking on any single component (e.g., on water, food or energy).

Notably, two of the four statements that fell below the consensus threshold (75 %) each emphasised a specific component: either water (*sustainable and integrated water use. It aims to integrate water management across nexus domains that depend on water, 52 %*) or soil (*the complex understanding of landscape surface and functions of soil, 31 %*). The other

two statements that did not reach consensus suggested that nexus involves *debunking complexity* (45 %), or that *all components of the nexus are of equal importance* (52 %).

Closely tied to the concept of nexus thinking is the challenge of defining the nexus itself. While the WEF nexus is commonly referenced, there remains ambiguity about how its components should be conceptualized and integrated. Participants in the survey rated a number of components (not limited to water, energy, and food) on whether they should be included in the work with the nexus. The first round of the survey generated significant input, with participants suggesting 46 additional components for consideration in the second round. This diversity indicates the wide range of perspectives on what the nexus encompasses. Participants were also asked to categorise each component into one of four predefined categories – resource, sector, policy area or ecosystem – or leave it as unspecified if no clear categorisation was possible.

Fig. 2 presents the large number of components that participants considered relevant to nexus research. While many components were categorised as policy areas and ecosystems, the largest group consisted of components that participants were unable to specify (all components, including those below consensus level, listed in appendix G, figs. G2-G6).

In addition, several participants expressed in the first round that it was difficult to score which components should be included in nexus research, emphasising that as a nexus approach depends on the research objective or case at hand. For example, some comments participants argued that the core components are water, energy, and food, while other listed items either represent “subsystems” of these existing core components, or cannot be classed as resource systems. Others highlighted that some certain categories, such as policy areas, should be integrated into nexus analyses, but should not be thought of as nexus components themselves.

To address these perspectives, two sets of statements were developed for the second round of the survey to explore whether such “context-specificity” is widely recognised as a key aspect of nexus research. Firstly, participants chose between statements that addressed the components that make up the nexus (Fig. 3). There was a relatively equal

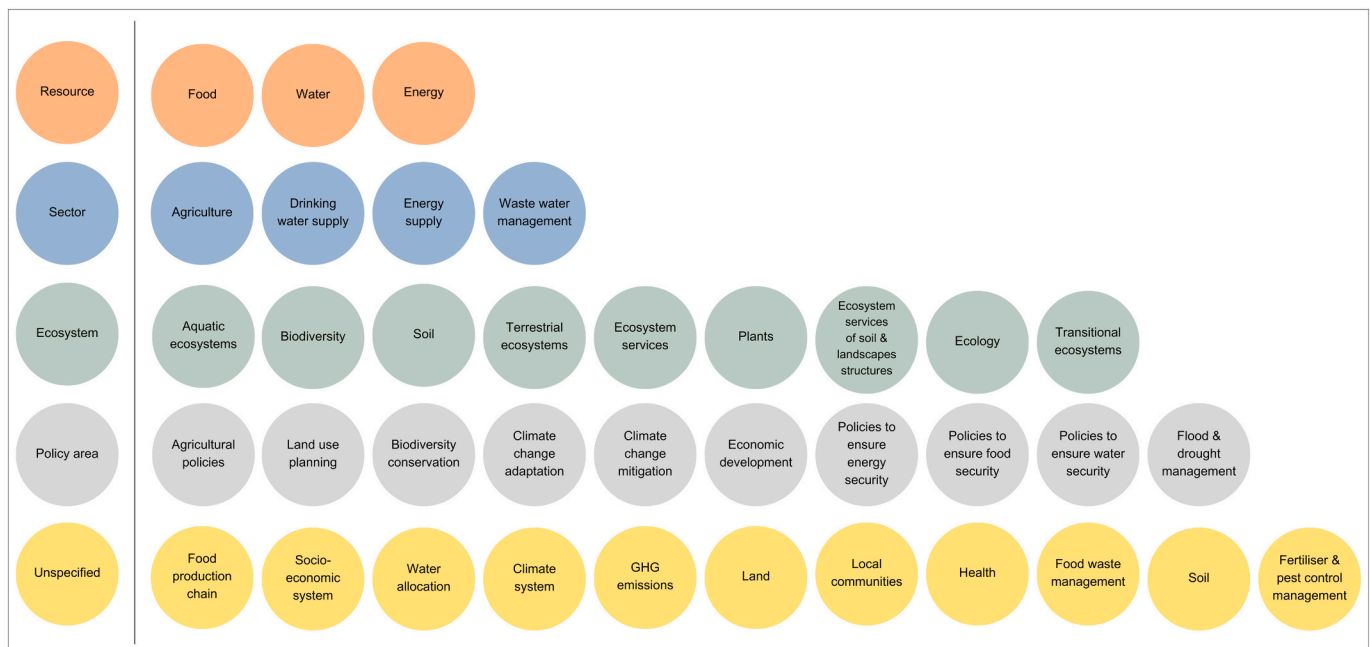


Fig. 2. Components that participants deemed important to include in nexus research, including which category participants placed each component in. The components are listed in order of importance, with the highest scoring components to the left. Those that derived from participant suggestions have kept their original wording from the survey responses.

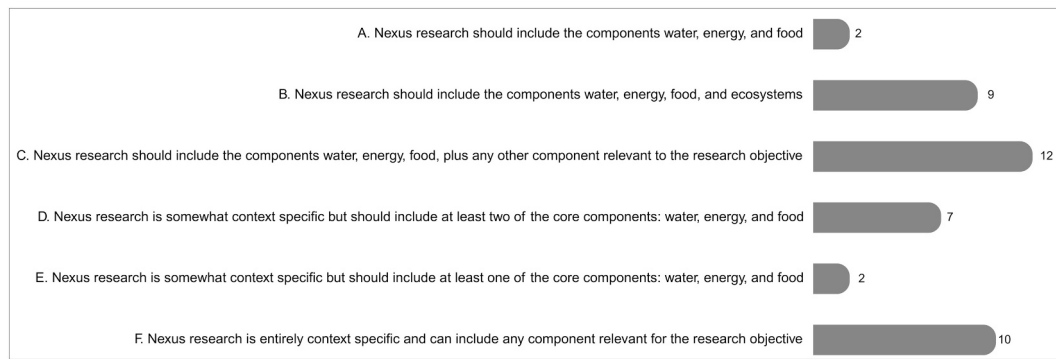


Fig. 3. Number of participants that agreed with each statement on nexus components. Participants were asked to choose the one that they agree the most with.

spread between four of the alternatives (B, C, D and F) meaning that it is difficult to determine a clear consensus. Alternatives A and E can be discarded as they were each chosen by less than 5 % of participants. It is worth noting that this includes the statement *nexus research should include the components water, energy and food*, which highlights the core components of the WEF nexus: water, energy, and food. Though participants were mostly spread between four statements, both D and F highlight the context-specificity of the nexus – either that nexus research is somewhat, or entirely, context-specific – and though statement C refers to a certain fixed base (water, energy, food) it also implies adapting the nexus according to context by adding any other component that is necessary to the research objective. With this in mind, 29 participants referred to some context dependency; while 9 participants were in favour of the WEFE nexus.

Secondly, participants chose between statements that addressed what *types* of components, or categories, make up the nexus. More than half of participants agreed that the nexus is a *mix of the component categories: resources, policy areas, sectors, and ecosystems*; and more than a quarter viewed the nexus as a *mix of individual components* (e.g., water or biodiversity, etc.) *of any of the component categories* (i.e., resources, policy areas, sectors, and ecosystems). While research often refers to the resource nexus or speaks of the nexus in terms of cross-sectoral integration, very few participants chose statements that claimed the nexus to be *solely about resources or sectors* (all statements listed in appendix G, fig. G12).

In terms of research gaps that relate to nexus thinking or nexus components (Table 5), the participants viewed understanding the role of ecosystems in the nexus as an important topic for the community to tackle in future research. They did however not consider defining the principles of the nexus, or extending the nexus to include other components, as important research gaps (all research gaps listed in appendix G, fig. G11).

3.2. Nexus methods

The process of generating and sharing knowledge can be categorised into three types: system knowledge, e.g., defining the current and future state of the system and its characteristics; target knowledge, which identifies the desired future state of the system; and transformation knowledge, which outlines the pathways that allow for transformation of the system, from the current to the new state (e.g., ProClim, 1997; Avellán et al., 2022; Brandt et al., 2013). With this in mind, the participants scored a set of methods on their relevance for use in nexus research for each of the types of knowledge (Table 4).

Out of the 22 methods, 15 were deemed relevant for generating system knowledge. At least 90 % of participants viewed systems analysis, participatory workshops and integrated modelling relevant for system knowledge. The number of methods that were considered relevant lessened for each knowledge type, resulting in 12 relevant methods for generating target knowledge and 11 for transformation knowledge.

Table 4

Methods that participants deemed relevant for different types of knowledge creation, listed in order of highest level of consensus.

Methods that are deemed relevant for <u>system knowledge</u>	Methods that are deemed relevant for <u>target knowledge</u>	Methods that are deemed relevant for <u>transformation knowledge</u>
1. Systems analysis	1. Scenario analysis	1. Land use change modelling
2. Participatory workshops	2. Land use change modelling	2. Scenario analysis
3. Integrated modelling, e.g., System Dynamics Modelling	3. Participatory workshops	3. Integrated modelling, e.g., System Dynamics Modelling
4. Trade-off analysis	4. Integrated modelling, e.g., System Dynamics Modelling	4. Processes of co-creation of information and knowledge
5. Hydrological modelling	5. Climate modelling	5. Cross-impact analysis
6. Land use change modelling	6. Cross-impact analysis	6. Participatory workshops
7. Cross-impact analysis	7. Hydrological modelling	7. Qualitative approaches to governance
8. Multi-criteria analysis using indicators, metrics or indices	8. Multi-criteria analysis using indicators, metrics, or indices	8. Climate modelling
9. Scenario analysis	9. Interviews	9. Hydrological modelling
10. Interviews	10. Processes of co-creation of information and knowledge	10. Systems analysis
11. Climate modelling	11. Systems analysis	11. Trade-off analysis
12. Processes of co-creation of information and knowledge	12. Trade-off analysis	
13. Geospatial analysis		
14. Sectoral modelling, e.g., hydrologic modelling		
15. Life cycle assessment		

Various methods were also *not* deemed as relevant for use in nexus research for any of the types of knowledge: these were economic modelling; footprinting; input-output analysis; the use of Artificial Intelligence methodologies/tools; questionnaires/surveys; and network theory. Though some of these were just under the consensus criteria for being considered relevant, for example economic modelling for system knowledge (71 %) and questionnaires/surveys for target knowledge (73 %) (all methods listed in appendix G, fig. G7).

On the topic of methodology, quite a large part of the gaps that should be addressed in future research (Table 5) related to tools and methods and scored highly amongst participants. For example, connecting data and methods from different disciplines, mapping interrelations between nexus components, developing integrated models to model the nexus, and developing nexus methodological frameworks were all considered important research gaps.

Table 5

Key messages from the Delphi survey results. In the survey, ‘research gaps’ was a separate section, here, they are presented under the relevant topic and include the % of participants that deemed it important. Red indicates that the respective statement fell below the consensus level.

Nexus thinking and nexus components	
Key messages	<p>Nexus thinking is about identifying and understanding synergies and tradeoffs, resource management and efficiency, and analysing interrelations between nexus components.</p> <p>Ecosystems and policy areas dominate as components to include in nexus research; still, the largest group of components is unspecified. Only a few components are assigned as sectors and resources.</p> <p>What components are included depends on context and objectives, therefore the nexus is not limited to energy, water, and food – but all or some of these core components should be included.</p>
What research gaps are important to tackle in future research?	<p>83% <i>Understanding the role of ecosystems in the (WEF) nexus</i></p> <p>67% <i>Defining the principles of the (WEF) nexus, such as components or input/output flows</i></p> <p>62% <i>Extending the (WEF) nexus to include other components (systems, sectors etc.)</i></p>
Methods for nexus research	
Key messages	<p>Most methods available are there to generate system knowledge in nexus research, while not as many methods are applicable to target knowledge and transformation knowledge. Natural science tools dominate nexus research.</p>
What research gaps are important to tackle in future research?	<p>95% <i>Mapping interrelations between (WEF) nexus components and scales.</i></p> <p>86% <i>Understanding transitions and achieving transformative change in a (WEF) nexus context.</i></p> <p>83% <i>Development of integrated models (to model the nexus).</i></p> <p>76% <i>Developing (WEF) nexus methodologies, or a methodological framework.</i></p> <p>76% <i>Surrogate modelling to enable fast simulation and impact assessment of complex systems.</i></p> <p>60% <i>The integration, or interpretation, of artificial intelligence or other complex modelling.</i></p> <p>52% <i>The use of artificial intelligence to support more efficient decision making.</i></p>
Stakeholders	
Key messages	<p>Stakeholder engagement is central to nexus research. The role of stakeholder engagement relates to benefiting stakeholders themselves, improving the researcher’s position, or broader objectives of democracy and inclusivity.</p>
What research gaps are important to tackle in future research?	<p>95% <i>The implementation and practical application of the (WEF) nexus.</i></p> <p>90% <i>Stakeholder engagement and making the (WEF) nexus accessible to stakeholders.</i></p>
Impact and ideal circumstances	
Key messages	<p>There is high emphasis on the positive impacts (in particular, improved cooperation and policy coherence) of applying a nexus approach in research compared to sectoral approaches.</p> <p>Interdisciplinary is key in facilitating a nexus approach.</p>
What research gaps are important to tackle in future research?	<p>93% <i>Connecting data, methods, and/or language from different disciplines to facilitate application of (WEF) nexus thinking.</i></p> <p>88% <i>The socio-economic dimension of the (WEF) nexus: examining impact on livelihoods, quality of life etc., or power relations within a nexus context.</i></p> <p>86% <i>Data collection; developing open source datasets; developing coherence in data across sectors.</i></p> <p>79% <i>Empirical evidence of the (WEF) nexus approach.</i></p> <p>76% <i>Governance and policy from a (WEF) nexus perspective; examining the role of governance and policy frameworks in fostering cooperation between sectors and their effectiveness in supporting a nexus approach.</i></p> <p>74% <i>Examining impacts on human health from a (WEF) nexus perspective.</i></p> <p>64% <i>Evaluating the impact of a (WEF) nexus approach compared to IWRM, or similar approaches.</i></p> <p>40% <i>Discussion on the ethical implications of the (WEF) nexus.</i></p>

3.3. Stakeholders in nexus research

Due to the complexity and cross-sectoral nature of the nexus, a variety of stakeholders interact with nexus issues. Who are the key groups and what is their role? A broad set of statements on the role of stakeholder engagement elicited overall high levels of agreement to this (all statements received the participants' agreement) which resulted in a variety of reasons for why stakeholders are or should be involved in nexus research. The role of stakeholder engagement relates both to improving the researchers own position, for example gaining feedback on analysis, gaining better understanding of the nexus, and utilising stakeholders as a source of data; but also to benefit the stakeholders themselves, for example developing solutions that reflect stakeholders' concerns and objectives, improving stakeholders' understanding of dilemmas and alternatives by providing fair information, educating and empowering stakeholders by enabling them to make decisions for the nexus. There is also a third aspect to stakeholder engagement, which relates to broader objectives of democracy and inclusivity, for instance invoking the democratic right of stakeholders to participate in processes that affect them, and ensuring that marginalised stakeholders, for example indigenous communities, are heard (all statements listed in appendix G, fig. G8).

In terms of what stakeholder groups should be included in nexus research, again, most stakeholder groups are scored highly. Only two stakeholder groups fall under the consensus criteria and are not deemed necessary to include in nexus research by participants: these are *media; organisations dedicated to science communication; and "ordinary" people who, while not actively engaged in any nexus component, are the end-users of*

water, energy, and food; or affected by proposed measures. Both authorities at national and local level are regarded as necessary by nearly all participants; as are landowner organisations and individual land owners; businesses that supply nexus-related goods or services; and academia or universities. (All groups listed in appendix G, fig. G9). The importance of including stakeholders was also acknowledged in the research gaps (Table 5), as 90 % of participants agreed that stakeholder engagement and making the nexus accessible to stakeholders requires further research.

3.4. Impact of and conditions enabling a nexus approach

If a (WEF) nexus approach is developing into a research discipline in its own right, it is important to gain clarity of what the consequences of an increased utilisation of such an approach in the future might be. Nearly all participants considered *improved cooperation and policy coherence through integration of planning, management and decision-making* to be a potential impact of applying a nexus approach in research, compared to sectoral approaches. Other potential impacts included *increased resilience-building, more context-specific solutions* and a *paradigm shift towards holistic thinking*. The results indicate that there was greater agreement with statements that framed the positive impacts of nexus research. Those statements that highlighted potentially lengthy processes and the need for more time and financial resources were not considered potential impacts of a nexus approach by the participants (all statements listed in appendix G, fig. G10).

Furthermore, to advance the use of nexus thinking in research, the Delphi survey explored enabling conditions for applying a nexus

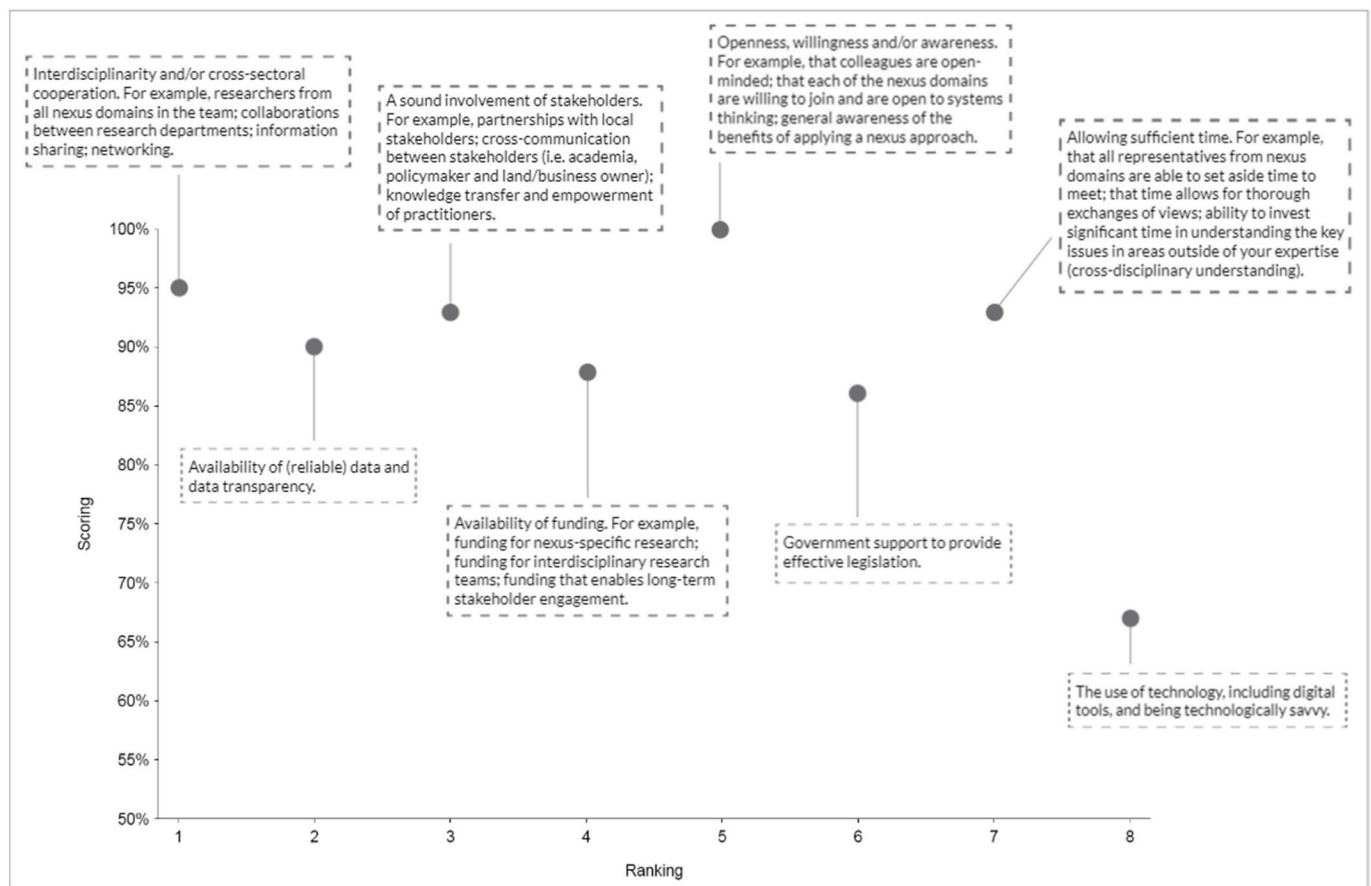


Fig. 4. Enabling conditions for nexus research. Participants were asked to score each statement (Y axis: percentage of participants who view statement as an important enabling condition). Following that they were asked to rank the same statements according to importance (X axis: statements ranked from 1 to 8, where 1 is the most important enabling condition).

approach. The open responses to the first-round question formed the basis for eight statements that the participants then scored according to importance in the second round. Following this, the participants were also asked to prioritise and thereby rank the eight statements. This led to a variation in results for the same eight statements (Fig. 4). While all participants viewed *openness, willingness and/or awareness. For example, that colleagues are open-minded; that each of the nexus domains are willing to join and are open to systems thinking; general awareness of the benefits of applying a nexus approach* as an important enabling condition for applying a nexus approach in research, this statement is only placed at number five out of eight in the overall ranking. It is worth noting that most statements received high scores. The only statement to fall under the consensus criteria is *the use of technology, including digital tools, and being technologically savvy*, which is also positioned last in the ranking.

The emphasis on interdisciplinary was also reflected in the perceived research gaps (Table 5), as nearly all participants (93 %) agreed that *connecting data, methods, and/or language from different disciplines to facilitate application of (WEF) nexus thinking* is an area that should be addressed in research. The same goes for ensuring that data is available and coherent across sectors (*data collection; developing open source datasets; developing coherence in data across sectors*, 86 %). The favourability of the positive impacts of a nexus approach could be somewhat mirrored in the research gaps, as the participants do not view it important to focus future research efforts on *discussion on the ethical implications of the (WEF) nexus* (40 %) or *examining impacts on human health from a (WEF) nexus perspective* (74 %).

4. Discussion

The Delphi survey revealed that putting a particular component of the nexus at the centre of analysis is not necessarily unfavourable. While it has been suggested that nexus thinking is about not prioritising any component and that all components are of equal importance, participants in the Delphi survey do *not* agree with this statement. This implies that it is fine to proceed from one specific component with the intention of integrating the others. The results of the Delphi survey also display that nexus scholars might not (anymore) be overly water-centric, as the group does *not* agree with the statement focusing solely on sustainable and integrated water use. Disagreeing with the view that nexus thinking is about integrating water management across nexus domains that depend on water implies that nexus research needs to be open for all relevant components so that they can be fitted into nexus analysis as needed. Here, a systematic approach to choosing or developing a fitting framework is of importance; Anandhi et al. (2023) classify nexus conceptualisations based on their simplicity or complexity and advocate for tailored frameworks depending on the scope of application. Such proposed spectrums of narrow to broad definitions and simple to complex conceptual frameworks of the nexus could help address the challenges of having to adapt nexus research to suit specific contexts. However, whether a narrow or broad definition of the nexus is applied, it is apparent that there are many words that are in frequent use within the nexus community without having any proper definition. When researchers employ a nexus approach they talk of, for example, sectors and resources with the assumption that the meaning of these terms are obvious. It becomes particularly clear in the final round of the Delphi survey when participants are asked to categorise the components, that this is not an easy task. This is shown both in the large number of components that cannot be categorised, and in comments from participants which highlight that the exercise was difficult; that some suggested components could rather be subsectors; that the exercise itself was difficult to understand; or that it is not clear what the categories mean. This conceptual confusion can slow down the advancement of the (WEF) nexus as its own field of research, and while there has always been an overarching idea of what the (WEF) nexus entails, the lack of a clear definition of the language being used has perhaps concealed that nexus research has been evolving and is no longer merely focused on

resources or sectors.

Other recent research into WEF nexus trends identifies governance, ecosystems, policy and decision-making as key themes in the most recent (past five years) literature, but points to difficulties evolving the nexus past a theoretical system (Rhouma et al., 2024). The results of this Delphi study support that nexus research is particularly attentive to governance and policy, especially in relation to ecosystems and ecosystem services. Therefore, it may need to move away from (being viewed as) dealing inherently with resource use efficiency or sectoral securities. While very valid conflicts of aims and institutional barriers to translating WEF research into policy were raised by Rhouma et al. (2024), this Delphi study also shows an imbalance in how particular aspects of nexus research are prioritised methodologically. Stakeholders clearly have a very important role to play in nexus research and most stakeholder groups are considered necessary to include, despite that few methodological tools reflect this. It also seems that nexus scholars are cemented in mapping resource interlinkages, whereas methods that can address governance and policy (which, as can be seen from the results on the principles of the nexus, is highly important to the nexus community) are somewhat lacking. Social science tools do well at enhancing transformation processes (Fisher et al., 2022), and methods to better address nexus policy needs to include engaging stakeholders and policymakers in participatory activities, and processes of knowledge co-creation (Jacobi et al., 2022), but it is highly uncertain whether that is enough to create comprehensive pathways that can allow for transformation of nexus systems. Stakeholders from the media may in fact play a vital role in spreading the word and explaining the need and pathways for transformative change (Avellán et al. (forthcoming)). However, media stakeholders are seldom considered as groups to engage within nexus research, and were not identified as a priority by the research experts surveyed in this study. It appears that social science tools still need to be further incorporated into nexus research.

In terms of the research gaps that are identified by the nexus scholars, where to focus research efforts appears to follow a similar theme of emphasising the importance of interdisciplinarity and stakeholder engagement. Developing coherent sets of data and connecting language from different disciplines seem like logical next steps, and are considered important gaps to tackle by nearly all scholars. But while it has been shown that governance and policy can be seen as the thing that sets a (WEF) nexus approach apart from earlier integrated management approaches (Roidt and Avellán, 2019), and the Delphi survey confirms the nexus community has a strong focus on policy in relation to nexus components and potential impacts of the approach, this aspect is not placed highly on the list of research gaps. Interestingly, around the time of the Delphi survey and subsequently, research has started to emerge that addresses how systems connect to policy and vice versa; for example, addressing the lack of nexus policy coherence assessments (Suda et al., 2024; Blicharska et al., 2024), quantifying WEF system resilience under different policies (Ioannou and Laspidou, 2022), and nexus governance in transboundary settings (Mooren et al., 2024). Very last in the list of identified research gaps is *Discussion on the ethical implications of the (WEF) nexus*, which the community does not consider important. This could support concerns that a nexus approach at times fails to address resource inequalities and how efficiency improvements to the nexus are distributed (Allouche et al., 2015). When contemplating the collated statements of what the nexus scholars consider nexus thinking to be, one participant opposed the statements describing nexus thinking as being about resource management (ensuring holistic/integrated management of resources) or resource efficiency (supporting the efficient utilisation of resources). They expressed that these statements... “...could suggest, in my eyes, a rather uncritical view of what ‘management’ and ‘efficiency’ are. What does it mean to manage resources in an integrated manner? For what purpose? Even more so, what does it mean to be ‘efficient’? Does that mean the highest economic benefit? If so, who stands to profit from that? Power dynamics are important, but often omitted from conceptualisations of the nexus.” While the socio-economic

dimensions of the nexus are acknowledged as important within the research community – and these discussions are not entirely absent – the prioritisation of research efforts suggests that concerns about the nexus approach being overly focused on optimising resource use are valid. This narrow focus may overlook critical considerations of equity, power dynamics, and the broader societal implications of resource management.

Lastly, it is necessary to note the limitations of using the Delphi approach. A Delphi survey offers a possibility to accommodate a large number of expert views while eliminating risk of certain individuals taking over discussion or steering the group towards their own opinion, however, it also takes away the ability to discuss how they view the question and to agree upon common parameters of their answers. As we offered the ability to comment on each section of the survey we can see that many participants expressed difficulties answering some of the questions without specific context or examples. Weighing detail vs. simplicity was an important part of the survey design and the initial review of the six expert evaluators, but it is likely that the survey answers referenced each participant's experience with past projects (projects that presumably differ in scope and objectives). Furthermore, the diversity of the scholars has an impact on the outcomes of the survey. There was a relatively even spread between experience levels and gender, however, most of the scholars were Europe-based as a result of the networks that the authors of this paper drew upon; mainly EU-funded projects such as NEXOGENESIS, NEXUSNET and SIM4NEXUS. Other Delphi studies have shown differing opinions between participants from the global North and South (Dahal et al., 2023), and therefore it is important that the findings of this paper are placed in a European research context. Notwithstanding the potential bias inherent in our study, we believe it still offers valuable insights regarding the different aspects of the nexus research that can help advance future nexus research agenda.

5. Conclusion and recommendations

In light of the findings from the Delphi survey, we offer four recommendations for future research:

(1) *Developing definitions for commonly used terms within nexus research:* While there are many terms that are commonly used in a nexus context, few of them are properly defined. From the Delphi survey it is apparent that there is uncertainty in how nexus components are thought of. There has been a presumption that the nexus deals with resources and their securities, however, the findings here suggest that the bulk of the components that are seen as important to include can be categorised as ecosystems and policy areas. That the nexus community has been so hesitant to define the principles of the nexus – and still is, according to the lack of importance placed on this in future research needs in the Delphi survey – could have contributed to concealing this fact. Because of the highly interdisciplinary nature of nexus research, it is particularly important to be clear about the definition of terms and concepts being used since they might be interpreted differently by researchers from different disciplines, which may, for example, prevent future comparisons or synthesis of different nexus studies. Adding glossaries or definitions of terms and concepts from trust-worthy resources should thus become a standard practice in nexus publications.

(2) *Integrating ecosystems:* Most scholars consider the nexus to be a mix of resources, sectors, policy areas and ecosystems, and specifically what components to include depends on the context of the research. However, overall, the nexus approach seems to have moved away from resource use efficiency and sectoral securities, and towards governance and policies of ecosystems and ecosystem services. Therefore, it may be ill-advised to talk strictly about a resource nexus or cross-sectoral solutions. Instead it is important to examine how aspects of ecosystems, nature, ecology or ecosystem services are incorporated into the nexus.

The nexus community should thus prioritise the approaches to integrating ecosystems into nexus research. As such a theoretical paper is in process towards publication on the various paradigms of the WEFE Nexus approach found in the literature and recommendations on how to strengthen it going forward (Lucca et al., accepted).

(3) *Developing social science tools for policy understanding:* The nexus scholars put particularly high emphasis on the importance of policy and governance, both in terms of principles of the nexus and the potential impacts that a nexus approach has compared to siloed approaches. But this is not reflected in the methodology and future research needs. Here, the nexus community is still cemented in mapping resource interlinkages, which begs the question of how the nexus research community can address the most important components of the nexus if these are not prioritised also methodologically? The Delphi survey reveals that nexus scholars have a large number of mainly natural sciences tools at their disposal for investigating status quo, i.e., system knowledge. However, there are less relevant tools available for transformation knowledge within nexus research. Considering that understanding transitions is an important identified research gap, as well as the emphasis on policy and governance, which are most likely influential functions in a transition, there needs to be both stronger consideration for the tools that can enhance transformation knowledge, as well as stronger recognition for prioritising governance and policy mapping. It appears that social science tools need to be further incorporated in nexus research in order to complete its transition away from “just” mapping resource interlinkages and sectoral securities, towards also addressing the governance and policies of ecosystems that the community views as a target for what the nexus is and the impact it intends to achieve. Example of how this integration can occur is being demonstrated in nexus research projects, for instance in the Horizon 2020 funded project NEXOGENESIS, where policies are translated directly into parameters of context specific System Dynamics Models and their impact is thus assessed on the WEFE resources now and in the future.

(4) *Incorporating ethical considerations:* Though the aim of nexus research seems to have shifted towards governance and policy, it still relies in great part on modelling technical and economic efficiency metrics. Perhaps this is also why there are crucial gaps in addressing the ethical dimensions of such advances. Nexus models need to evolve beyond resource optimisation to include socio-economic variables in order to ensure that nexus research is not solely a theoretical exercise but also translates into socially responsible and just policies. Future research should contribute to understanding and mitigating the impacts of resource optimisation on various communities, particularly the marginalised, and ensure that the benefits of improved resource management are equitably distributed and aligned with broader societal values.

CRedit authorship contribution statement

Nairomi Eriksson: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tamara Avellán:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Claudia Teutschbein:** Conceptualization, Investigation, Methodology, Validation, Writing – review & editing. **Malgorzata Blicharska:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2025.178775>.

Data availability

The data that has been used is confidential.

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