Emerging themes and future directions of multi-sector nexus research and implementation (Supplementary Information)

Note: All the questions and responses presented in this Supplementary Information are raw, unedited responses to all surveys and so may contain spelling and grammatical errors.

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Supplementary Note 1. LIST OF ORIGINAL DEFINITION & SCOPE QUESTIONS

1. Do you believe there should be a clear widely adopted and operating definition of "nexus" which the scientific community should embrace to help advance scientific nexus theory or would this hinder the "discipline"? If so, why and how would you go about establishing this?
    a. Disciplines typically have guiding principles, concepts, and terminologies. Do you believe there should be a clear widely adopted and operating definition of "nexus" to which a scientific community should accept and embrace to help advance scientific nexus theory and application, or would this hinder the "discipline"?
    b. How to balance the selection of topics or focus of research by means of a strategy, if the research should consider the feasibility of the application of results or recommendations?

2. How do you currently define a nexus interaction? Which systems (physical, social, economic, ecological) do you think should be included and why? Do you consider interactions at each stage of the life-cycle (i.e. extraction, production, conversion, transfer, services, waste)? Do you think all interactions need to be considered for each problem or can some interactions be ignored depending on the context of the problem?
    a. Nexus research has often focused on the water/energy/ag "triangle". But as many studies acknowledge all parts of economies and systems are inter-connected. How do you decide which inter-sectoral linkages are more important than others?
    b. How can we define the boundary of resource management and boundary of social, economic and environmental impacts, respectively ?
    c. Do you think perhaps the nexus is too narrowly defined? For example, transpiration infrastructure can impact food security and has not been mentioned.
    d. How do you define when a nexus in fact exists? Do you ever see situations where the connections between F and E, between F and W, or between E and W, are tenuous?
    e. How the nexus is related to resources availability and how the nexus can address the issue of resources availability?
    f. Could incorporating material flows and their journey in the production-consumption system be a fruitful path for the development of nexus studies in the future? Would you agree this could be very helpful in improving our understanding of the implications of deeper forms of transformation of the underlying economic model -e.g. towards Circular Economy?
    g. To what extent are we being able to capture the health of the ecosystems in nexus models? E.g. impact on biodiversity or ecosystem resilience
    h. Is there really one Water-Energy-Food-Land-(-Climate-Economic) Nexus or is the Nexus specific to the studied problematic ?
    i. What are the main social / economical /physical relationship that need to be studied to better understand/model nexus interactions?
    j. What are the intersections of social-ecological-technical systems (SETS), nexus, and circular economy research? Do they operate at different scales?

k. Are there aspects of different nexi (water-energy, energy-waste, water-energy-land, water-energy-waste, etc.) that should be the focus in different contexts, or do we always need to integrate all elements of the nexus/nexi?
l. What is the meaning of "nexus" in the context of this paper - are we looking into interactions between resource systems and climate (energy, land, water) and/or the focusing on the provision of services and goods (e.g. electricity, water and sanitation, food), in addition to socio-economic factors and drivers?

3. Is "nexus" a new approach and is it different from integrated management? If so what are the differences and are there any benefits to a nexus approach as compared to integrated management?
    a. What is the difference between Nexus and integrated management and how easy is to apply the Nexus approach compared to integrated management?
    b. What is Nexus? is this a new approach and what are their benefits over integrated management?
    c. Isn't the Nexus just an entry point for integrated resource management. Perhaps we shouldn't be striving for a Nexus approach per se, rather we should be satisfied if Nexus studies lead to improved recognition of interconnections between resources. What would an effective Nexus approach look like anyway?

4. How do you make decisions in your nexus-oriented research about how to demarcate the spatial, temporal and sectoral boundaries of the systems you will consider, given that almost everything is connected in some way? How do you move between scales (e.g. from the globe to cities and from decades to seconds)?
    a. What are the primary variations concerning the food-energy-water (FEW) nexus at different resolutions? In particular, the global- and urban- scale FEW?
    b. What are the boundaries (sectors, space, time) of the nexus?
    c. How do you make decisions in your nexus-oriented research about how to demarcate the spatial and sectoral boundaries of the systems you will consider, given that almost everything is connected in some way?
    d. How can we couple the different spatial scales within the WEF-Nexus? From the global/continental scale we can derive future response scenarios for the different resources, but are those constraint useful at the local scale? Do we already have examples?

Supplementary Note 2. LIST OF ORIGINAL NEXUS METHODOLOGY QUESTIONS

1. To what extent do you think nexus data collection can or should be standardized across multiple sectors, spatial boundaries and temporal scales? How would we ensure data quality and reliability? Are there examples of other community databases we could follow? Who would host such an effort? Can/should AI or IoT play a role in data collection?
    a. How do you think to what extend the accounting is possible in the nexus and what are the role of IoT based technologies in the nexus study?

b. When working with global models how do you manage to adjust the national data of each country?
c. What kind of data do we need? What temporal and spatial resolution? How can AI algorithms help to implement the nexus?
d. What kinds of norms should the community establish, e.g., around data reporting, data sharing, methods?
e. What would we do with $10m in data collection/hosting efforts? What federal data would we like to see expanded or altered?
f. What importance would you attach to collecting and using reliable data for the NEXUS approach? How is this issue in your country or region? Is this status the same for every sector WATER-ENERGY-FOOD?
g. What data improvement could help to better understand/model nexus interactions ?
h. How to overcome the lack of quantitative data for many interdependencies between the sectors? For example, the impact of land use and land change on water basin or groundwater recharge.
i. On the global or regional scale, what are the barriers for Nexus research in terms of data availability and data collection? What are the basic data necessary for Nexus research? Do you think a shared Nexus database is necessary or possible? What kind of data should be included in the database?

2. A large number of nexus frameworks and methodologies exist and continue to be developed in addition to several nexus review papers. Do you think there is a need and if so how can we coalesce and compare across frameworks? In your opinion what is the largest modeling gap left in nexus methodologies?
    a. How many models are existing and what are the shortcomings?
    b. Are we able to manage the nexus? Are there existing operational products? What would we need to have an operational product? And, who should manage it?
    c. Do we have established methods? (Many new papers introduce new frameworks/methods, but it seems like it might be time to try to coalesce for greater comparability.)
    d. What is the largest modeling gap left in the FEW-Nexus?
    e. How to streamline the implementation of nexus assessments? Is there evidence that different research teams and groups have used methods developed by other groups? Do collaborative efforts exist that aim at improving existing approaches or co-develop new and more effective ones?

3. What strategies/methods/metrics/visualizations exist or can be developed to explore the potential synergies & trade-offs of actions/policies across different sectors? Please share any examples or potential ideas from nexus or other disciplines?
    a. In the context of an inter-connected (Nexus) research, given the inherent trade-offs between different actions/policies, how is it possible to balance these side effects among all the analyzed disciplines?

b. Is there any well-accepted strategy/methodology to explore the potential synergies of actions/policies in different areas (e.g. climate and health) in an effective way? If not, do you consider this an important aspect of policy design?
c. What metrics have been, or should be, developed to assess the outcome of implementing the FEW nexus? What theory may be leveraged to develop the metrics?

4. The nexus approach is multi-centric by nature and definition. Have you been able to compare it against uni-centric (e.g. water-centric) and show the benefit of the nexus if any? If yes, benefit to whom? and how did you define benefit?
    a. The nexus approach is multi-centric by nature and definition. Have you been able compare it against uni-centric (e.g. water-centric) and show the benefit of nexus? If yes, benefit to whom? and how did you define benefit?
    b. What are the pros and cons of holistic (single model) versus linked-models modelling approaches to model nexus interactions ?
    c. Is it better to couple traditional silo approached models or to work on an integrated model capable to encompass the WEL nexus sectors together? What are the main challenges for each strategy?

Supplementary Note 3. LIST OF ORIGINAL NEXUS APPLICATIONS QUESTIONS

1. After almost a decade of nexus research, in your experience, has there been any significant shift towards integrated management in practice? Do you have any examples of applications of nexus concepts in the design, implementation or monitoring of any public policy? Do you have any examples of where ignoring the nexus interactions leads to (very) biased results/policies/infrastructure?
    a. After almost a decade of nexus research has there been any significant shift towards integrated management of sectors? Do you have any examples?
    b. How do you think managers of different individual sectors can coordinate when they operate on different regulatory spatial jurisdictions? (e.g. Water basins vs. grid regions vs. states/provinces making land decisions
    c. What emerging trends and technologies worldwide may push society and institutions to move against the tendency of siloed policies and approaches, and instead use nexus thinking in management of natural resources and economic sectors? Are there examples of such shifts?
    d. Are there models of top-down and bottom-up governance and decision making that have successfully been used (or have the potential to be effectively used) in communities for supporting nexus approaches?
    e. How can we now APPLY the beautiful conceptual frameworks that have been developed over the past decade? How can these frameworks lead to quantitative research at a local (city), state, or national level? Can we set up a framework of data management that will improve the process of accessing relevant data for nexus research? What are the implications of what aspects of the nexus we include/exclude from our studies (e.g.

the energy and water consumptions attached to inclusion/exclusion of food supplies that are imported vs exported vs consumed locally)?

f. Has your nexus-oriented research contributed to changing any decisions or planning/management approaches?
g. When working with a region that involves more than one country do you have representatives from each of them? do they collaborate?
h. Is a NEXO team in place in your country / region? If not, How is the approach institutionalized? If you had to say an approx. number, how many people are working with NEXUS in your coutry or region and with how many years of experience in this approach?
i. Has the NEXO methodology been applied in the design, implementation and monitoring of any public policy in your country / region? Do you know of any examples related to climate change?
j. What are examples where ignoring the nexus interactions leads to (very) biased results/policies/infrastructure ?

2. How significant do you think increased societal awareness of a nexus approach will be to the success of application of public policies? Do you think nexus approaches, monitoring and analysis should be regulated (e.g. through laws, decrees, mandates) in order to be effective? Should nexus methodologies become a consideration when evaluating future projects for sustainable incentives and financing?
    a. Do you think the NEXUS approach should be regulated, i.e. law, regulation, decree, etc.?
    b. Do you consider that the society appreciation to a NEXO approach is relevant to the success of the application of public policies?
    c. How can we help new climate and sustainable financing tools (such as subsidies, financial instruments and funds/finance facilities, policy instruments and related support mechanisms) to include WEF consideration? For example which criteria should be included to identify a sustainable economic activities sustainable and eligible to sustainable financing ?

3. In your experience have certain subsets of nexus inter-linkages been easier to implement in practice? Do you think the nexus approach becomes obscure/less useful at certain scales (e.g. at certain smaller scales other factors may take precedence for societal well-being)?
    a. Which sector (of the WATER-ENERGY-FOOD trio) did you find most vulnerable during the study?
    b. What are examples of inter-linkages of these systems that play an important role, where ?
    c. Have people observed that the benefits/importance of the F-E-W nexus approach become obscure at smaller (and isolated) geographical scales? I am talking about village and rural community scales. There are other factors (at smaller scales) that take precedence in community well being and, it seems, there are no particular advantages of the FEW approach in certain small scale scenarios. In other words, are there tipping points in terms of scale that make the nexus approach more germane?

    d. Given different local contexts, how can nexus research and practice be tailored to fit specific conditions, while remaining within a framework that allows comparability across cases?
4. To what degree do you think the Nexus is an academic initiative rather than a way of operating public policy? Will modelling/studying the Nexus really have an impact if countries do not implement this Nexus view at a government level? Do we need to train scholars and professionals differently, in order to successfully design and implement nexus approaches?
    a. What types of digital technologies (data, models, information and communication technologies) are practitioners and/or researchers using (or developing) to enable a nexus approach to decision making in communities?
    b. How to connect our findings with real policy? How to create the nexus also at the policy level?
    c. Given the complexity, uncertainty and gap with policy, should we aim for very complex models, which will be unable to cope with the former, or rather develop simple relationships, understandable by policy makers, and robust enough?
    d. Several models optimize the nexus (interrelationships between different sectors), but how can we actually implement those mathematical models in the real implementations?
    e. To what degree do you think NEXUS is an academic initiative rather than a way of operating public policy? How linked do you thinkg are this sectors in your country or region?
    f. To what extent do you think the success of the NEXUS approach depends on the interest of the government?
    g. Do you think we need 'nexus in practice' and 'nexus practitioners' like we now have integrated water resources management in practice? Could this solve the apparent nexus research to policy/practice gap?
    h. Do you consider that the training of professionals with a NEXO perspective is important for the success of the future implementation? How could a NEXO perspective, that is transversal to different careers, be incorporated into the degree's study plans into the Universities?
    i. How to communicate the results from Nexus modelling for policymakers in a way it can promote integration between the different systems' policies, regulations, acts?
    j. Do we need to train scholars and professionals differently, in order to successfully design and implement nexus approaches?
    k. Will modelling/studying the NEXUS really have an impact if countries do not implement this NEXUS view at a government level? Meaning, modifying the fact that water, food and energy matters are usually divided in different ministries.
    l. How to design the right incentives to do multicentric Nexus research and policy? This includes academic incentives, publishing venues, and administrative connections.

Supplementary Note 4. LIST OF ORIGINAL CHALLENGES & FUTURE DIRECTIONS QUESTIONS

1. What do you think are the main challenges in applying a nexus approach in practice?
    a. What barriers remain in the way of developing interdisciplinary research that allows to understand the multi-faceted dimensions of WEF challenges? How do these barriers differ in the context of cross-sectoral cooperation?
    b. What do you think is the main challenge of applying NEXUS in your country/region?
    c. What are the criticisms of the nexus? Can we address them?

2. What do you think are the most important questions in nexus research in the next decade and the next five decades, respectively?
    a. What are the most important questions in food-energy-water nexus in the next decade and the next five decades, respectively? How should we design our research plans to achieve short-term and long-term synergies while avoiding potential tradeoffs?

3. Do you believe that the amorphous scope and breadth of nexus research creates challenges for students in building core disciplinary strengths (i.e. expertise) within a focus area, or does it provide more opportunities? In other words, are we just branding a group of generalist scientists without deep expertise in a subject, or does the nexus, itself, present a separate discipline, where expertise can be developed?
    a. Is the potential for innovative solutions sufficiently represented in nexus studies? Are nexus models ready to represent not only incremental innovation but disruptive/systemic change?
    b. Given the complex and dynamic nature of Nexus, there are no clear future scenarios nor existing past experience for evaluating possible consequences and probabilities of adverse events, how do we analyze risks and building resilience the Nexus systems?
    c. What are the roles for migration, human behaviour and evolving norms in better modeling nexus problems at global scale?
    d. Local to global issues cannot be solved by investigating a single field of action. Within a nexus-approach scientists and practitioners try to interlink their knowledge to contribute to a more sustainable future. This, however, implies looking at the right connections: (1) Which mechanisms and methods can be used to ensure that all relevant interlinkages are covered? (2) How will these interlinkages change in the future with rising population or climate change processes? (3) What can be done today to guarantee that the research undertaken now will still contribute to sustainable development in the future?
    e. Is the covid19-pandemic interfering in the nexus, if yes how ? are there examples of studies ?

4. Is the potential for innovative solutions sufficiently represented in nexus studies? Are nexus models ready to represent not only incremental innovation but disruptive/systemic change as well as extreme events, shocks, migration?
    a. Is the potential for innovative solutions sufficiently represented in nexus studies? Are nexus models ready to represent not only incremental innovation but disruptive/systemic change?

b. Given the complex and dynamic nature of Nexus, there are no clear future scenarios nor existing past experience for evaluating possible consequences and probabilities of adverse events, how do we analyze risks and building resilience the Nexus systems?
c. What are the roles for migration, human behaviour and evolving norms in better modeling nexus problems at global scale?
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e. Is the covid19-pandemic interfering in the nexus, if yes how ? are there examples of studies ?

Supplementary Note 5. LIST OF ORIGINAL ANSWERS TO DEFINITION & SCOPE QUESTIONS

1. Do you believe there should be a clear widely adopted and operating definition of "nexus" which the scientific community should embrace to help advance scientific nexus theory or would this hinder the "discipline"? If so, why and how would you go about establishing this?
    a. Nexus so far has been used interchangeably with definitions such as 'interactions', 'linkages'. Personally I think this can convey the idea.
    b. I think there is not one type of nexus, and it would be interesting to add those defnitions in the text. I'm mainly interested from the resource perspective, so you even can ask yourself if the defnitions of the water-energy-food nexus is good enough. Better to replace food by land
    c. I like the flexibility in NOT having a widely-adopted definition. The "nexus" embraces a wide spectrum of research. However, I think there should be some clear variants and I think these are emerging... for example, most of the literature I see which is relevant to my research says "Water-energy-food nexus" or sometimes just "water-energy nexus" and it's clear to me what the topic of the research will be. On the other hand, I don't immediately understand what "water-energy-land nexus" or when "ecology" or "agriculture" in the mix mean and how they are different from the usual titles. I'm not sure that makes those terms bad, just less clear within the larger body of research I've seen.
    d. My opinion is that there is already a well-defined enough definition of the nexus, in that we understand what we are talking about, and that it is flexible enough to advance research. I would not try to make it more specific.
    e. I think that the term ""nexus"" should imply that the analysis has been developed by explicitly considering all the possible interactions between x and y, to the extent is possible. In my opinion, the term could be applicable for either quantitative (modelling) or qualitative studies. I don't think that there exist significant differences with the

integrated assessment, which treats different dimensions/modules as a whole. Therefore, I believe the strength of the nexus literature (relative to IA), should be the details of all the possible connections between the analyzed elements. If these connections/interdependencies are weak or not ppropiately explained, I don't see how this studies would be attractive to the audience, given the potential level of detail of LCAs, CGEs or IAM models.

f. I believe that there should be at least some sort of delineation of the area with broad definitions. Anyway, in my opinion, a key aspect of nexus studies should be the ability to analyze/assess/quantify societal implications and consequences of the nexus. It is not enough to pick some sub-sectors (e.g. agriculture, energy) and show the trade-offs and call it a nexus. Let me give an example; a reservoir operation exercise that shows diverting more water for irrigation will reduce hydropower production is not a “nexus” study. One needs to analyze what happens to energy production (perhaps some additional wind energy helps mitigating the effect of hydropower reduction) and food sector (perhaps the increase in irrigation has minimal effect on agriculture because majority of production and labor are coming from rainfed agriculture) (Wu et al., 2020; RCR, in press). The scope needs to be wide enough to allow for assessment of the societal impact; i.e. how the overall sectors of water, food, and energy are being affected and managed.
g. There is already a widely adopted definition of WEF/WEL/CLEWS nexus, which probably still needs to be strengthen and needs to penetrate into the research agenda of the so called traditional 'disciplines'. Nexus research is multi-disciplinary, therefore comparison to a single discipline results hard, it includes aspects of the disciplines and adds the complexity of the interaction. I think Nexus research will be dynamically include other sectors than just WEL and therefore this community, which mostly belongs to water, energy and food/land research, should not use the word 'Nexus' alone as a brand. It should rather acknowledge the possibility of linking to other disciplines (i.e. materials, services). To guarantee an effective dissemination of Nexus concept into the scientific and policy spheres, it is needed continuous direct information to the involved departments in universities, research organization and ministries, and inclusion in project proposals."
h. We could also look at it from interdisciplinary sciences, rather than just a nexus perspective. This paper has people from many different disciplines too. Going from there to look at a "nexus" might help explain it from a scholarly perspective
i. I think there should be a clear definition of the nexus within the scientific community. Some scholars have critiqued the nexus because of the ambiguity of term definition (Smajgl et al. 2016; Cairns & Krzywoszynaska 2016), as the lack of clarity can prevent application of the nexus in policy and practice. Thus, creating a unified definition and framework could provide support for practical implementation (Endo et al. 2017). This consensus would advance nexus theory by providing a common foundation for future nexus research by synthesizing previous literature and conceptualizations. This could be established by doing a meta-analysis literature review of definitions of the nexus to find the common elements, components, and goals of different conceptualizations and then create a definition of consensus. This definition should, however, provide the flexibility

for the nexus to be evaluated by a diversity of different methods across various disciplines.

j. I think the word "nexus" when used in scientific contexts deserves an adopted definition. The "Food-Energy-Water" nexus also deserves a definition we can rally around. It's difficult to position our research without it. It's difficult to come up with a definition, the words "system" and "design" have the same problem, but the research communities have good definitions for those without being self-referential.
k. NEXUS is a captivating word but its exact definition is still evolving. Increased questions on how does it differ form other approaches (e.g. integrated management) are increasing with the risk of weakening its momentum. Time to give a definition, but keeping in mind that definitions are not forever. Makes me think about the definition of "Ecosystem" that has evolved greatly in the past 150 years or so.
l. I believe that the nexus should investigate, identify and study the interrelationships between different key sectors important to reach the SDGs or other goals, such as to avoid to exceed the planetary boundaries [Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E., ... & Nykvist, B. (2009). Planetary boundaries: exploring the safe operating space for humanity. Ecology and society, 14(2).]. Most of the time we refer to water-food-energy nexus but I think this concept might be limiting and we should avoid to do this while framing the concept. It is ok to define some boundaries for our own research since it is very difficult to cover everything, but at least the concept should not be limited. For instance, the WFE nexus can be easily expanded to the soil, emissions, nutrients, rare materials, climate change, etc. I will thus establish the nexus as a living theory/concept that has the water-food-energy interrelationships as starting point, as a core since they are fundamental for our survival. This is to avoid to put boundaries to a concept that should not have intrinsic boundaries.
m. I think yes. It is necessary to create a solid framework. Maybe the first step could be discussing in small groups about what the definition should include and make a draft. And a second step could be a workshop with different stakeholders to discuss the draft and include other points of view. Finally, summarize the conclutions and define a definition.
n. A few dictionary definitions: An important connection between the parts of a system or a group of things (cambridge dictionary); A nexus is a connection or series of connections within a particular situation or system (collins dictionary);
o. I believe there should be a broad set of definitions that guide what "nexus" is at different scales. However, I believe a strict one definition cannot be inclusive of different levels of nexus integration and scales of studies. Perhaps Urban nexus versus regional nexus studies etc could be used to delineate a single broader definition.
p. A clear widely adopted and operating definition of "nexus" should include the main interconnected areas of knowledge or disciplines on which the scientific advance is focused on, since currently, different interlinkages or “nexus” are being approached, as water-energy-land-food (our focus), forestry, health, climate, Source-to-Sea, among others.
q. A more explicit definition could support future research. First, a broader audience could be reached if a basic understanding of the topic investigated exists between all

participants. Second, proposals for third-party funding could better be defined target-oriented once a precise reference to the general framework exists.

r. Most of the previous nexus definitions have been typically linked to the specific resources under consideration. This has typically produced many different types of sector oriented Nexus approaches: NEXUS-WEF (Water-Energy-Food), WEFE (Water-Energy-Food-Environment), and others where other sectors or components have been subsequentely added (Climate, Land Use, health, social, etc.). It might be far more inclusive to declare a flexible NEXUS approach which could be more “discipline” independent, but rather more focusing on interlinkages between resources supplies and uses across disciplines and sectors linking conflicts/sustainability/SDGs. This may add some value in the implementation of nexus over newer disciplines.

s. I believe a clearly static and narrowed nexus definition is not mandatory to the scientific community advances in this field. In the last 10 years the nexus studies have been developing a more robust core in order to become an important aspect to be considered. All this is happening with a broad definition that is capable to encompass many different perspectives associated to the nexus. I think that it is much more important that each study makes clear which nexus branch is being analyzed instead of define a strict nexus concept.

t. 1) Terms and concepts should be clearly defined in each context within which they are used. 2) It is important to distinguish between concepts, however, I do not think that one should only accept a single definition, as that would limit the development of the field (especially at the intersection of multiple disciplines). When a new concept is introduced, it should be made clear how it is distinct from concepts used earlier in the field from which it emerged, so that we do not ""sell old wine in new bottles"". The definition of the nexus in the context of the water-energy-food nexus was established at the Bonn Nexus Conference in 2011 as a development from the concept of ""Integrated Water Resources Management"", which attempted to integrate other sectors, but was too much focused on the water sector. In an effort to allow for integrated management that coordinates different sectors at eye-level, the concept of the nexus emerged (Ringler et al. 2013, Leck et al. 2015). An agreed-upon definition of the water-energy-food nexus currently does not exist (Simpson et al. 2019). Leck H, Conway D, Bradshaw M, Rees J (2015) Tracing the Water – Energy – Food Nexus : Description, Theory and Practice. Geogr Compass 9(8):445–460; Ringler C, Bhaduri A, Lawford R (2013) ScienceDirect The nexus across water , energy , land and food (WELF): potential for improved resource use efficiency ? Curr Opin Environ Sustain 5(6):617–624; Simpson GB, Jewitt GPW (2019) The development of the water-energy-food nexus as a framework for achieving resource security: A review. Front Environ Sci 7:8:1–9.

u. Yes, that would really help. However, there are some conventions and common used approaches. The idea of having an unique definition would force different communities to get intouch. For example, through specific events, conferences, etc.

v. Yes. Major paradigms need a big group of experts to lay the foundation upon which research is built. The paradigm may change in the future, but that is part of learning. A large workshop, stakeholder engagement and researcher dedicated group, and final

defining report and subsequent publications would be how I would go about establishing this.

w. Yes, I think there should be a clear operating definition of "nexus." Given that the Earth and systems of certain scales (regional, urban, community...) are circulating as a whole, the nexus should have a clear definition or framework for better integration of trans-disciplinary research efforts and data collection from different regions or timelines.
x. Clarity on "nexus" would be helpful and enable the identification of a new "discipline". Dialogs such as this can help to identify how to define nexus.
y. I think it would be useful for the community to think more about the methodological framework that could support nexus definitions (e.g., node definitions, resolving issues of scale, etc.). But some publications go as far to suggest the systems that should be included in nexus definitions, and I think that reinforces the same siloed thinking that the concept of the nexus tries to avoid.

2. How do you currently define a nexus interaction? Which systems (physical, social, economic, ecological) do you think should be included and why? Do you consider interactions at each stage of the life-cycle (i.e. extraction, production, conversion, transfer, services, waste)? Do you think all interactions need to be considered for each problem or can some interactions be ignored depending on the context of the problem?
    a. Nexus definition should be problem-speicific. It's not necessary to always include all components.
    b. I see the nexus starting with the 3 resources (land, water, energy) and how they are coupled in different stages of the transfer. With Sankey Diagrams you can make this very clearly visbile. The challenge is that you need to transfer from Joules to liters of water or kcal.
    c. I think you have to ignore (but acknowledge) many interactions/parts of the life-cycle when actually trying to put numbers to any of the nexus frameworks. We have only been considering end products in our analysis, actually; water directly used to produce energy, energy directly used to produce water... then there's the food aspect, and we've been struggling to constrain it to just end products and wondering whether that really limits the analysis (even though the other parts of the life-cycle are acknowledged).
    d. Related to my previous answer: A nexus interaction is any (physical, social, economic, political) interaction between two sectors that are traditionally considered separate from a practical (political or economic) perspective. Of course, all interactions along the life-cycle should be considered, although some of them can be prioritized or ignored depending on their relative relevance for the case studied.
    e. I think that the systems inlcuded should be defined for each study. There is too much complexity to address all the interconnections between the mentioned systems (physical, social, economic, ecological) with a high level of detail. Similarly, it is difficult to efficiently cover all the stages of a single system. I believe the problem has to be contextualized with literature or, if possible, discussed with the stakeholder/client in order to identify which interactions/connections are the most interesting. There would always be an indirect connection or effect that could not be covered with the applied methodology, so the problem definiton would be essential for this literature."

f. Currently, I consider physical, social, and partially economic and ecological. In the future, I would like to emphasize more and consider more environmental aspects. However, I call for caution when considering economics. Nexus studies should not be trapped in the idea of monetarizing things and should not be tempted to represent every stakeholder as an economist who tries to minimize cost. In several aspects, the society go for more expensive options for various reasons. Here comes the role of the "social" as the driver of the nexus are the societal demands. Even economics, I recommend them to be under the bigger "social" umbrella. I think we can live with the expression of "socioeconomics" as long as we really mean it that the two are intertwined. As for the interactions at stages of the life cycle, this is one of the major challenges in nexus modeling! Ideally (I have not done this yet!) we should benefit from the concepts of socio-environmental/sociohydrological systems to simulate how society (various stakeholders, including policy makers) would react to the biophysical and socioeconomic outcome of natural and built systems at different times through the life cycle, which triggers actions, change in course of actions, and change in outcomes,…etc. I think the context should dictate a scope. It is unrealistic to consider the Universe as our scope every time we are addressing the nexus.
g. I think interactions at any stage of the life-cycle should fall into the category of Nexus interactions. But not all should be always included, it depends on the problem and the questions. Similarly the systems should be interconnected as soon as there is awareness of important cross-sectoral feedback in the real World. Currently, physical, economic and ecological systems are often connected in single-discipline as well as Nexus analyses. Social aspects are often missing, but this detachment happens also in sigle-discipline studies and models. This gap needs to be fulfilled.
h. Nexus according to me is one which also includes interactions between different sectors. So not just the systems, and life cycle, but also the interaction between one sector and another. For example, water is used for food, energy, drinking, mining, etc. This interaction causes the systems interaction too (limited resources, i.e. physical and ecological affecting social, economic dynamics). We should look at the relevant interactions for each problem.
i. I define a nexus interaction as one where two or more of the physical resources or governance sectors (within the food-energy-water nexus) interact such that there are trade-offs, co-benefits, and/or direct relationships between them. Taking a sustainability science approach, this includes the physical resources; the societal, political, and governance sectors of the resources; the economics of them; and the environmental and ecological context in which the resources are imbedded. However, all these systems do not need to be considered equally in all contexts. Some contexts may allow for one specific nexus resource or system type to be prioritized over another. This allows for the context-specificity to be considered within nexus research, allowing for greater implementation in practice and for greater examination of specific aspects of the bigger system or interaction.
j. A nexus interaction is a connection between three or more critical infrastructures and/or systems that causes feedbacks to the system as a result of the interaction. I think

we should include all the systems, a good diagram is in this paper: https://onlinelibrary.wiley.com/doi/full/10.1002/sres.2215

k. I will start from answering the last question which is to me the most relevant: useless and detrimental to consider all interactions overtime; the interactions to consider or ignore depend on the context. E.g. water use efficiency in agriculture is not relevant in climates that can completely satisfy crop water requirements with rainfall. How do I currently define a nexus interaction? Any variation in one sector (or sub-sector) that determines a relevant change in another sector. e.g. increasing irrigated agriculture (food sector) determines a change in water demand: This is an interaction. Changes in the energy mix do not determine a change in the energy needed for water pumping, so this is not an interaction. Which systems (physical, social, economic, ecological) do you think should be included and why? I think that the beauty of NEXUS, but also perhaps the most challenging aspect, comes when the analysis includes both the bio-physical components and the socio-economic components. I say this because major feedbacks on the bio-physical components go through socio-economical changes and, the other way around, most often Socio-economic models fail to capture the local limiting resources. e.g. the CAPRI model, an economic model for the agricultural sector, uses crop production coming from a crop model (DSSAT) but this model assumes that all the water need for a crop is available whereas at local level water supply may well be below demand. Do you consider interactions at each stage of the life-cycle (i.e. extraction, production, conversion, transfer, services, waste)? Only the stages needed to analyse the interaction with other sectors. Could be all or only a part of them."

l. Currently, I am involved in operationalizing the water-food-energy nexus in the irrigation sector on large scale. We try to identify whatever is affecting the interrelationships among water, energy and food in the irrigations sector. We also included the soil and the nutrients link in the water-food-energy nexus interrelationships. As I have explained above, as a researchers we put boundaries to the concept to make it more applicable due to our limits, in particular time and research focus. Nevertheless, as concept, we should not put boundaries in terms of links or areas that could be included in the nexus. More are the links and the areas involved and better is the understanding of single or multiple processes. The water-food-energy nexus is closely linked to the physical, social, economic and ecological spheres and those should be also included. One example can be the social aspect related to diets. A more plants-based diets can significantly affect the water-food-energy nexus and the economy (economic input to farms, health costs, etc.). Currently, I do not consider all the stages of the lifecycle, but it is for sure something that will be embedded in the model we are working in the near future. In particular, I am interested in what is related to the monetization of the indirect positive and negative effects, or how other economic sectors affect each other in terms of natural resources allocation. I think that if more interactions are included/considered, then we have a better picture of how the object of our study interact with other sectors. For instance, I can model the WFE nexus in the agricultural sector as much detailed as possible but if I do not include other key economic sectors that compete with the agricultural sector I will miss something extremely important that affects and/or can be affected.

m. The interaction between energy, water and food sector, taking into account the social, economic and ecological system. I think all the dimensions of the issues should be considered in a firts step. But, depend on the problem, maybe some interactions are not representatives.
n. The Nexus is all the existing inter-relations between the water, energy and land(/agriculture/food) systems (considering, the physical, social, economic and ecosystem dimension). When considering a specific problem, a nexus interaction between two elements needs to be considered when there is a dynamic feedback effect that could lead to co-benefits or if neglected would lead to a biased assessment of the problem.
o. Currently a working definition for me includes interaction of physical resources (water, energy, land) and related sectors at minimum. This also implicitly or explicitly has to have a social dimension (eg. the optimisation of resource allocation and use has to consider the different stakeholders that use or are impacted by the decisions). In nexus studies or optimisation, economics of WEF is common essential denominator. Ecological concerns come in as constraints in some of my nexus work and are absent in others.
p. Significant nexus interactions to solve a problem, although usually identified, are complex to prioritize and approach. Besides, most of the systems (physical, social, economic, ecological) should be included, since at least in the case of water-energy-land-food, it will not be practical to exclude completely any of the systems, due to the risk of leaving out any important condition involved. The integrated or holistic approach that is the basis of nexus, must consider interactions at each stage of the life cycle. An effort should be made in the early phases of work, in order to identify and prioritize the stages of the life cycle which should be treated more deeply. The interactions for each problem should be analyzed, and some interactions should be given a higher or a lower level of scientific consideration depending of the main structure and context of the problem identified and to be treated.
q. Focusing on SDGs a nexus interaction exists once more than one SDG is affected by a certain action or activity. While some SDGs are more closely linked to physical systems (like SDG 6 to water), and others are more connected to e.g. economic systems, the question of which system should be included in an analysis should not be constrained from the beginning. Rather, all stakeholders and affected systems should always be defined and recorded at the beginning of each analysis.
r. From a modelling stand point I see usually interactions where they can be physically represented. I see also this mostly as a scale-dependent problem: the larger the scale, the more aggregated and generalized the processes to be represented. At each scale certain processes may be more relevant or easy to be reproduced, rather than others. This last aspect is also linked to the nature of data availability, which has a different scale dependent representation (County/regional/national). Therefore, we must verify the opportunities in terms of data processes available, and highlight relevant and opportune interactions based on stakeholder involvement (and sensitivity analyses).
s. The interactions considered in each study depends their focus. Studies that are analyzing the power sector will of course zoom in this sector, considering the interactions that are important in this system. LCA studies also have a historical debate

regarding what to encompass in each analysis. It is not possible to include all interactions in all studies, it would make impossible specific evaluation for different aspect of the same object. Likewise in entropy studies, it is mandatory to define the system that will be considered as closed system, otherwise the universe is the limit. Once you have defined your system it is possible to make assumptions about outside interactions, as well as emphasize which aspects are not being considered.

t. My definition of the nexus is the systemic exploitation of synergies and consideration of tradeoffs across sectors. An example of a synergetic nexus interaction is the production of energy (heat, electricity from methane gas) and extraction of nutrients from sewage sludge, where the nutrients are used for the fertilization of food crops, and the energy is used for the treatment of wastewater (which can be reused for water supply/irrigation). An example of a tradeoff is the production of electricity from hydro-power (ecological tradeoff, potentially social tradeoffs, such as resettlement of populations in the Three-Gorges Dam project), or in nuclear power plants (increased water demand in potentially water-scarce regions), the production of water in desalination plants that are run with fossil fuels (ecological tradeoff from discharged brines and due to climate impacts from fossil fuel emissions). Nexus approaches are distinct from life-cycle analyses (focused on individual products or materials), urban metabolisms (focused on urban scale resource demand and emissions), or the circular economy (another concept without a single, agreed-upon definition (Calisto Friant et al. 2020, Bauwens et al. 2020)). Ideally, and where feasible, nexus interactions should be considered at each step of the life-cycle. But caution should be taken in over-technicizing and rationalizing processes, which is why it is important to consider synergies and tradeoffs across social, economic, ecological, and technological systems from local to global scales. Bauwens T, Hekkert M, Kirchherr J (2020) Circular futures: What Will They Look Like? Ecol Econ 175(November 2019):106703; Calisto Friant M, Vermeulen WJV, Salomone R (2020) A typology of circular economy discourses: Navigating the diverse visions of a contested paradigm. Resour Conserv Recycl 161(104917). doi:10.1016/j.resconrec.2020.104917

u. In our system, physical, social, economic, ecological sysmtems are included. It includes climate, water resources (human water use, management), crop growth (crop management, technological improvement), land use (human decision for the land conversions or transitions), and natural ecosystem (GHG exchange by vegetaion and soil). This model is used to understand the impacts of climate change on water, food, energy (bioenergy), land use, and ecosystems. Interaction to socio-economic changes are not completely interacted. The model description paper is published recently (https://gmd.copernicus.org/articles/13/4713/2020/gmd-13-4713-2020.html)

v. A nexus interaction is the linkages between two or more sectors. The systems could be economic-social-ecological; because public policies should seek economic development, understanding the pressure on the resources (social) and ensuring environment quality.

w. The more systems, the more we become aware and appreciate the complexities. This does not mean that our work becomes more realistic with the inclusion of more systems. A nexus interaction should include at least 2 disciplines. In multi-sector dynamics, the "nexus" is typically grounded in the reality of primary or secondary sectors of the economy acting within human-environmental systems; therefore,

"physical" systems will always be one of the necessary components of nexus research in my opinion. Socio-economic systems seem another potentially necessary component for completing the human-environmental interactions. Although ecological components add more reality, these systems seem to always require at least 2 other systems in consideration for nexus research. Not all interactions need be considered - it depends on the question and the desired level of complexity.

x. Physically, a nexus interaction occurs when units of one resource (e.g., water, m3) are related to units of another (e.g., energy, kWh) to produce a metric (e.g., kWh/m3). This can apply across all systems, because they can all be related to a physical unit (e.g., $/kWh, jobs/water supply). Interactions within and across each stage of the lifecycle are necessary. Some interactions can be ignored for particular analyses, in part because it would be too difficult to capture everything all the time.
y. I think a nexus interaction should involve a tradeoff where compromises must be made to reach a decision. For example, in regions when there is plenty of water, hydro power, irrigation for agriculture, and leaving sufficient water to support salmon spawning are not in competition. However, in California, water is scarce, so these three demands compete for the limited water. A nexus only exists when decisions must be made.
z. This question gets at the tradeoffs I see in defining a “nexus”. I think the concept is to define how systems interact and affect one another. However, in reality, there is no way to truly map all of the interactions between physical, ecological, biological, economic, social [… and on and on…] systems. Thus, I think it would be defying the very concept of nexus thinking to constrain it to a set of systems. There is no way that a set of researchers could map all of the interactions, and I think there is merit in different sets of researchers defining and mapping the nexus systems that they know best, rather than trying to define all interactions in a very diluted way. Like any mode of science, there are tradeoffs between depth and breadth; I see both as very critical to really understanding nexuses. As an example, perhaps there is a set of 10 researchers that publishes a study that maps out the social, economic, physical, and ecological connections across their topical interest. There is usefulness in painting this broad picture for other more specialized researchers to really pick apart the interactions between various subsets of these disciplines. If we over-constrain our definition of what “should” be included when we think about water management, for example, we might completely miss some connection that has been under-examined.

3. Is "nexus" a new approach and is it different from integrated management? If so what are the differences and are there any benefits to a nexus approach as compared to integrated management?
    a. From my understanding, if integrated assessment includes feedbacks between different components, then it is the same as nexus study.
    b. The new part is that the neuxs appraoch is balanced. I mean that with integrated water resource management you focus from the water perspective and take the other sectors as boundaries, while solutions and innovations should be part on all parts.
    c. I am not sufficiently knowledgable in the definition of integrated management to properly answer this.

d. Integrated management can be similar to "nexus", if defined broadly enough. Of course an integrated management should address all the interactions between systems, and also include long-term planning, joint scenarios, etc. If we define integrated management too narrowly (looking only at operational levels, or not addressing feedbacks) then of course it may be more limited than the nexus.
e. I think that the line between integrated management/assessment and ""nexus"" is very difficult to identify. There are well-accepted IAMs and CGEs that are continously increasing their capacities, what means that they can represent an increasing number of interconnections. Therefore, following my previous responses, I think the nexus literature should focus on a limited number of dimensions but adding a high level of detail on all the possible interactions. For this purpose, the stakeholder engagement would be an appropiate way for any problem definition, and it's normally ignored by global/regional models.
f. In my “philosophical” opinion, the difference between the nexus and integrated management is very little. The theoretical definitions of the “integrated management” are almost perfect “nexus approach”, but applications always fell short, which led to the emergence of the nexus approach as a way of scientists to reiterate concepts with new names when they see that the old package did not function as anticipated. However, integrated management seems to be sector-centric; for example integrated water resources management is water-centric, taking into consideration consequences on all other sectors. But the nexus is supposed to be multi-centric in a way that all sectors are treated equally and competing to achieve realistic societal welfare. I see the ultimate decision-maker in a nexus system to be the highest level in a jurisdiction, e.g. Governor of an American State, a Premier of a Canadian Province, a Prime Minister of a country.
g. The Nexus approach is not only about integrated management, but also integrated assessment and awareness of the natural-economic-social dynamics that characterize the world we live. Integrated management is just the final step of this approach, which links assessment to management or policy implications.
h. Not too sure about this, but integrated management seems like it is more about the bottom line (or profits) at the end of it, rather than the end goal being societal or environmental benefit
i. While I don't think a nexus approach is completely new, I do believe it offers new perspectives from integrated management. Integrated management generally focuses on prioritizing one resource and managing it by considering trade-offs with related resources or sectors, making it mostly crossdisciplinary (viewing one discipline from the perspective of others). While the nexus approach can, and often does, use a similar approach, it offers opportunity for more equal integration where all three food, energy, and water sectors are considered equally. This provides opportunity to move towards multidisciplinarity (multiple disciplines working together) or full interdisciplinarity (integrating methods and knowledge from across disciplines to create a true synthesis).
j. Integrated management studies the combined systems as a whole, and often without feedbacks. Nexus approaches concern with the actual connections between systems and focuses on specific points of feedback. In nexus approaches, the connections between systems are often more important than the individual systems themselves.

While in integrated management, the individual systems are more important and take center stage.

k. Yes, I think that the main differences is that focus is put on the strength of interactions between sectors and less on the quantitative calculation of meeting supply with demand. Another difference with integrated management is the number of feedback loops that can be of first order (sector a affects sector b and b affects a) or second order (a affects b that affect c that affects a). This complex feedbacks are often not considered in integrated management.

l. This is one of the main criticism of the nexus approach (new wine in an old bottle?) [FAO, 2014. The Water-Energy-Food Nexus A new approach in support of food security and sustainable agriculture.] [Altamirano, M. A., van Bodegom, A. J., van der Linden, N. H., Rijke, H. D., Verhagen, J., Bucx, T., ... & van der Zwaan, B. C. C. (2018). Operationalizing the WEF nexus: quantifying the trade-offs and synergies between the water, energy and food sectors.]. I think one the novelty of the nexus approach is to promote the overcoming of institutional barriers and power imbalances between different sectors. Another novelty of the nexus approach is to involve all the stakeholders through engagement and collaboration to have a holistic solution of the problem. This kind of approach allows to find new opportunities, interlinkages and synergies among different sectors and stakeholders.

m. Yes, it is different. I guess that the main difference is that the nexo view is focused in the interactions between all the sectors. This is a benefit because is part of the analysis take into account all the linkages and their eventual issues.

n. In the water sector, Integrated Water Resource Management (IWRM), was acknowledging that there are different sectors/stakeholder (e.g. cities, agriculture, hydropower, ecosystems) sharing the resource and that assessing them jointly can produce co-benefits, while not doing so could lead to biased assessments https://doi.org/10.1061/(ASCE)0733-9496(2007)133:5(427). Interestingly, the definition of IWRM as established by the Global Water Partnership (GWP) in the year 2000, could also correspond to the Nexus definition: “a process that promotes the co-ordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/04-integrated-water-resources-management-2000-english.pdf). However, in practice IWRM focused on the water system and the direct interactions with other sectors, as pointed by https://doi.org/10.1016/j.jhydrol.2015.12.033 it contradicts itself by the name, as it promotes a holistic approach while having water as its central focus. In contrast, the Nexus approach is not necessarily centered around a specific resource. However, in practice, nexus studies are also centered on specific system (e.g.: http://dx.doi.org/10.1016/j.gloenvcha.2014.01.005 investigates cooling water constraints within the water-energy nexus, https://doi.org/10.5194/hess-23-4129-2019 focuses on water investments within the water-energy-food nexus, https://doi.org/10.3390/su12156274 reviews the nexus around irrigated agriculture). As observed by http://www.ecologyandsociety.org/vol13/iss2/art29/ assessing IWRM, to

be of value a framework should ""(1) be based on a correct causal understanding of the phenomenon concerned …, and (2) have translated this understanding correctly into processes for producing and applying knowledge about management intervention into that phenomenon."" Hence it might be sound that studies are centered around the system where the decisions can be implemented (considering stakeholders, institutions). In practice the evolution that was observed between IWRM and (water centered) Water-Energy-Food Nexus studies is that more interrelations with and between the energy and agricultural systems have been considered.

o. It is different from Integrated water management because of its scope of integration and because "nexus" approaches do not necessarily have to be centric. However, as is in this collaboration, and much of nexus research, water is central, and often as the limiting resource. In IWRM, energy and other resources are often dealt with as external demands/supplies. A nexus approach allows a completely integrated approach that can explicitly link all the WEF resources and optimise their provision. As such, the interventions considered can also be broader than water related interventions.
p. “Nexus” is actually a new approach to study and propose science-based solutions for related problems. I think the “nexus” approach is rather focused on studies and research, providing information required for integrated management, which is an implementation process of actions, activities or measures, most of which should have been defined after information and research results in the framework of the “nexus” approach.
q. Focusing on each SDG independently is necessary to understand the impact of each goal but is not sufficient to achieve sustainable development. The full potential can only be reached when the goals are treated as interdependent and indivisible. The nexus approach explores the interlinkages between the goals and reveals potential synergies or trade-offs between them. Integrated management is, from my point of view, more constrained, static, and tailored to a specific need rather than creating a flexible research framework. However, there are similarities between integrated management and a nexus approach, so that the nexus approach might implement well-explored methods from integrated management systems.
r. To me Integrated management is a part of NEXUS system, mostly linked to the operational part of productive systems while NEXUS appeared to me more focused on greater system’s complexity spanning from interlinkages to feedbacks. The challenges of a NEXUS could be more holistic, while integrated management is usually oriented to optimize resources for specific production systems. It is clear however that a clear distinction between integrated management and Nexus is not evident ….. and the paper may give some interesting feedback.
s. Despite I do not feel capable to correct approach this question I believe they are not the same but maybe nexus approach has derived from integrated management, maybe noticing a lack of attention on the nexus system.
t. Also, the term ""nexus"" is applied to all kinds of synergistic interactions and tradeoffs (e.g., the ""environmental nexus"" of water, food, climate, biodiversity). To me, the term ""nexus"" speaks to the identification of synergies and tradeoffs at the intersection of various sectors. ""Nexus management"" then is employed where synergies can be

exploited, and tradeoffs avoided (goal-oriented), whereas the term ""integrated management"" is process-oriented, and speaks to the management across sectors without only focusing on the exploitation of efficiency gains. For example, Integrated Water Resources Management has been defined as ""‘‘a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems’’ (German Water Partnership, 2000, cited in Kalbus et al. 2012). Kalbus E, et al. (2012) Integrated Water Resources Management under different hydrological, climatic and socio-economic conditions. Environ Earth Sci 65(5):1363–1366."

u. The nexus approach should be used for the management of water, food, energy, ecosystems. The management based on the nexus apporach may be effective if it is integrated.
v. Both approaches seeks the same and have the same core. Nexus is more specific, regarding sectors and tools to be implemented. Integrated mgment can be applied more widely.
w. In theory, yes, "nexus" is different. Integrated management is a broad approach (umbrella) that can utilize "nexus" research and applications. Specifically, nexus is the inter-dependences and feedbacks among systems - this may or may not be captured in integrated management. The benefits of nexus is the simultaneous consideration of multiple systems.
x. I think nexus thinking can lead to integrated management but not the other way around.
y. According to Duran-Sanchez et al. : ”Integrated Water Resources Management is a process that promotes coordinated development and management of water, land and related resources, in order to maximize economic and social well-being in an equitable manner and without compromising, in the present or future, the sustainability of vital ecosystems.” (1). While this definition is specific to the domain of water, it appreciates the influence that water has on, and the influences from, other resources such as land, biodiversity, etc. In my view, the intention of integrated resource management is to promote a holistic framework that seeks to coordinate and integrate the functioning of multiple resource systems, with the intention of improving the sustainability of a resource such as water, without detracting from the sustainability of another resource. Thus, it is specific to the activity and challenge of management. “Nexus” on the other hand, still seems as more of a nebulous work, that merely indicates that there are critical connections and interactions among systems. Bleischwitx et al., which grapples with the question of whether or not the nexus perspective is meaningful, proposes a five-node “nexus framework” to address the goals of the UN’s SDG’s, which seeks to define the linkages across systems in order to assess tradeoffs and identify potential synergies between systems. Defining these interlinkages is challenged by issues of spanning scales and bounding scope (2). Considering these perspectives, I think defining the interlinkages in a “nexus framework” must preempt integrated resource management. I see the utility of “nexus” thinking as understanding the problem in the context of the complexity of the world (i.e., a mapping of the space with n

interlinkages), and “integrated resource management” as the actionable framework that should come as a reaction to that mapping. (1) Water 2018, 10(9), 1191; https://doi.org/10.3390/w10091191 https://www.mdpi.com/2073-4441/10/9/1191/htm; (2) https://www.nature.com/articles/s41893-018-0173-2

4. How do you make decisions in your nexus-oriented research about how to demarcate the spatial, temporal and sectoral boundaries of the systems you will consider, given that almost everything is connected in some way? How do you move between scales (e.g. from the globe to cities and from decades to seconds)?
    a. This is problem-specific, depending on the questions I'm interested in asking and often constrained by data availability.
    b. We have a downscaling and upscaling methodology. With our approach we start at one side from the global scale and then downscale to continental/regional level. From the local part we can upscale to this same level.
    c. We are trying to address the city scale, and find that we often have to downscale national data. In our case, energy sources have changed quite rapidly over the past two decades (and water usage also, due to prolonged drought), so the temporal aspect is quite interesting and relevant to document. But again, the difficulty has been in getting adequate data to parameterize the temporal changes sufficiently.
    d. This is of course a very complex question. In general, as in many other topics, we should work with a hierarchy of decision-making processses, from the global to the local, from the long-term to the short-term, and backwards. Some issues will require looking only at the global, long-term elements; other may just need looking at the local or short-term; and others may need all.
    e. There are at least two factors that would limit the boundaries of the research. First, the applied methodology/model/approach would be the first limiting element. Then, given the mentioned complexity, I believe that the first important step is to define the problem and try to justify why is it inetersting for the audience or for the stakeholders.
    f. I strongly believe that the nexus is applicable at administrative boundaries. Right now, I apply it to a national scale (Egypt) and at the Canadian Provincial scale (Saskatchewan). This way, it is easy to identify boundaries with input and output, including imports and exports. I partially connect to Global scale through trade connections (no complete coupling), but still long way to go on this. We use multiple scales, we handle water, including hydropower, irrigation,..etc at daily/weekly scale, municipal water use at monthly scale, and aggregate certain things (crop yield and agricultural production and consumption) to annual scale. Again, long way to go on this issue.
    g. This question might deserve more discussion. From my perspective many choices on scales are arbitrary and sometime are the main source of uncertainty. Some valuable criteria for choosing the right scale is: -useful scale for the question analyzed (global, national, local); - scale of interest for stakeholders; - important scales for technical modelling (basins, administrative boundaries, AEZ); - Other technical requirements for fine representation (i.e. hourly renewable energy, seasonal water dynamics)
    h. In my work, I have defined the boundaries both strongly (e.g., using a specific hydrogeopolitical boundary, using a specific timeframe) and loosely (e.g., the city's

metropolitan area, the present) depending on the importance of the boundary for examination. Defining boundaries is important to know what to include and what to exclude, but sometimes becoming so focused on keeping to your defined boundary can allow you to miss major interactions (e.g., the relationship between the urban metropolitan area and the neighboring agriculture area would be missed if you forced yourself to remain within the political "city limits). Thus, I generally set some specific boundary surrounding the urban scale and allow myself the flexibility to consider how the things in the boundary directly relate to nexus interactions just outside the boundary if relevant for the current investigation.

i. I like to use existing tools for existing scales and boundaries and then find a way to connect those tools. I feel trying to use one tool for every spatial and temporal scale often leads to too many degrees of freedom, making the research not as useful. Again, nexus research should focus on the tools that connect scales, rather than tools on the individual scales.
j. I start from the question/problem to answer/solve. I try to define the boundaries of the system so to minimise the effect that changes within the system have outside the system but I do consider how changes outside the system affect my system. Should my system include very different ecosystems (urban and forests) I create a sub-model for them and include interaction between the two. This is relevant for the spatial scale. For the temporal scale I might use a temporal scale for the exogenous inputs (e.g. annual GDP trends) and a different more fine temporal scale for the process inside the system. Note that the the different components of the model/analysis may use different temporal resolutions.
k. Currently, I am focusing on a national scale (e.g., Sweden) and I´m integrating water, food and energy sectors by identifying interrelationships, modelling them and optimizing allocation of resources. This is done at a daily time-step. I would say that research is limited by time and data (and thus computing power). The decisions on space and temporal constraints are mostly due to time allocated for research, data availability, and computational constraints. I personally think that in our interconnected world and keeping in mind the concepts of embodied energy-CO2 emissions and embodied water, researchers should focus on developing global scale WFE nexus model at an accurate time resolution (i.e., weekly or daily) to guarantee the achievement of the SDGs. I like the approach from NASA by using remote sensing dta for nexus and SDGs. But I still think that models should be included to provide optimal solutions, address global problems and support policies.
l. The spatial, temporal and sectoral boundaries depends on the scale of the problem. Maybe a first cualitative analysis to determinate the most influential variables and their scale. In general, there is a limitation given by the available data."
m. The decision of scale is like the decision of defining Nexus interactions, it depends on what are the dynamic interactions between elements.
n. Often my nexus studies are around optimising interventions, infrastructure and its use. As such, temporal boundaries are based on the economic period considered for optimisation (eg. large infrastructure that lasts decades requires analysis of climate related future resource availability, and so is linked with global climate models, and so is

connected with models global concern. Spatial boundaries are made based on administrative and resource boundaries (eg.1 a city boundary and simplification of material flows as boundary conditions for an urban nexus problem, eg. 2: a spatial consideration of a whole basin in transboundary river problems). The move between scales is often posed using hierarchical approaches, where outputs from higher spatial scale data are posed as boundary conditions to smaller scale nexus models. Foot printing of material flows is also used to link different scales in my work. I also use hierarchical approaches to connect long-term infrastructure decisions (eg. decades long and multi-year time steps) to operational testing of spatially explicit nexus models over smaller time steps (constraints and performance guarantees over days and months).

o. Decision making in nexus-oriented research in order to demarcate the spatial, temporal and sectoral boundaries of the systems to be considered, could be done by means of the application of a multi criteria decision making tool or the design of related models. In the case of the multi criteria analysis (MCA), alternatives of "nexus" integration categories should be determined, as well as the criteria for valuing them that reflect the values associated with their consequences. In order to manage different spatial and temporal scales applicable to a specific "nexus" study or research, it is fundamental the analysis of possible goals, targets and indicators, which could be part of the structure of models, as in the case of themes of water modeling with regards to the nexus and SDGs, or hydrological and water resources models applied for different spatial or temporal scales.
p. In general, choosing the scale is very case-specific, and giving a blueprint on how to choose the right scale might not be possible. However, keeping in mind that the nexus approach investigates SDG interactions the scale should be broadened as the overall question is rather global. Of course, local findings must be considered and included in the analysis. However, the actual relevant interactions are rather to be found on a global level.
q. There is clear strong dependency on data availability and its characteristics. Dynamical processes linking different time and spatial scales are feasible (especially if analyses are spatially/temporal explicit). There is however, a large difficulty to link biophysical modelling processes to macro-economic modelling output. Biophysical modelling outputs are often explicit over time steps, while several Economic General Equilibrium Models represent a convergence at a specific point (only) in time. Then it is extremely difficult to link result from time/scale explicit biophysical models and macro economic models relying on general equilibrium.
r. In general nexus studies are based on a main field. Most of the studies are not able to weight equally the different systems. Many reasons are associated with this, from lack of data to lack of knowledge and interest by the researcher. I use to adjust temporal and spatial resolution to the most fundamental and basic resolution of the studied systems. Therefore it is important to evaluate all available data in order to understand your possibilities and the question the study is approaching. By evaluating carefully those 2 aspects it becomes much easier to define the resolution and boundaries of your system. It is not unusual that one of the systems demands a higher spatial or temporal resolution in order to be better evaluated, however there is not enough data to do the

same with other important system that is affected by the former on. Finding the best manner to deal with those trade-offs are the key challenge for most studies and its depends on the general and specific objectives of the analysis.

s. Drawing system boundaries arbitrarily, or ""out of convenience"" can be dangerous, and has severe consequences for the sustainability of human livelihoods (e.g., climate change, biodiversity loss). It is crucial that, in a globally connected world, we draw the spatial boundaries of our resource systems at the global scale, and that the temporal scales of analysis consider feedback mechanisms, lag times, and cross-scale interactions. And we now have the methods to do so. For example, to account for global scale impacts of local resource consumption, footprinting methods (e.g., water footprint (Hoekstra and Mekonnen, 2012), ecological footprint (Borucke et al. 2013)) have been applied to urban water supply systems (Krueger et al. 2020). With increasing frequency and magnitude of shock events, such as floods, droughts, storms, wildfires, etc. new modeling approaches now allow the investigation of system resilience in response to repeated shocks, the loss of resilience, and therefore the unsustainability of current resource systems (Klammler et al. 2018), which has also been applied to urban water supply systems (Krueger et al. 2019). Borucke M et al. (2013): Accounting for demand and supply of the biosphere's regenerative capacity: the National Footprint Accounts' underlying methodology and framework. Ecol. Indic. 24 518–33; Hoekstra A Y and Mekonnen M (2012): The water footprint of humanity. Proc. Natl Acad. Sci. 109 3232–7; Klammler H, Rao PSC, Hatfield K (2018) Modeling dynamic resilience in coupled technological-social systems subjected to stochastic disturbance regimes. Environ Syst Decis 38(1):140–159; Krueger EH, et al. (2019) Resilience Dynamics of Urban Water Supply Security and Potential of Tipping Points. Earth's Futur 7(10):1167–1191; Krueger EH, Borchardt D, Jawitz JW, Rao PSC (2020) Balancing security, resilience, and sustainability of urban water supply systems in a desirable operating space. Environ Res Lett 15(3):035007.

t. The spatial resolutions of the model are different depending on the systems (physical, social, economic, ecological). The physical and ecological model have grid (about 0.5 deg) resolutions. On the other hand, the social and economic model (land use model) have resolution of economic regions (17 economic regions globally). They are connected by the down-scaling technique in the land use model, in which the economic regions are downscaled into 0.5 degree grid resolutions. One of the method to move between different scales is such down-scaling technic where some rules for the downscaling is assumed.

u. This is quite one of the most difficult things in the research. We thought about the goal of the project and the availability of the info. For example: the goal was about hydrological basins and we seek for info at that level, which was extremely challenging so we had to "treat" the info.

v. The question and hypotheses should drive the scales and system boundaries and connections of interest. We cannot consider all connections, nor should we - because not all will be relevant to the question and will play minimal roles (this can and should be justified reasonably). Making assumptions is a clear requirement of nexus research.

Jumping scales should require mechanistic linkages, if possible - or justified assumptions.

w. In my opinion the demarcation of the spatial, temporal and sectoral boundaries of the systems will be limited by the invested research efforts (time, funding, human resource, etc.), data availability, and computational power. Given that almost everything is connected in some way, I think the nexus research at the global scale and national scale would be most applicable because of the data availability at the current stage.
x. Decisions are guided by the research question, which are partially guided by observed phenomena that are concerning. Scaling is hard, but presently done by aggregation / disaggregation.
y. For us it is easy since Alaskan communities are already isolated. However, I would extend it to each river basin, which shares a salmon resource.
z. This question addresses the most difficult part of nexus research, bridging scales with imperfect datasets; your analysis is really only as good as your most coarse dataset, so it is absolutely critical to really understand what data you have, the spatial-temporal scales, unit definitions, etc. Then, it is critical to be honest as you to analysis across scales, where you lose resolution in the data. If I am doing research in the US, I really only have national water data that is published every 5 years, across 5 or 6 economic sectors, and these water data are merely guesses. Energy data, on the other hand, are much more available and typically much more precise. However, if I create a unit of analysis that integrates the coarse water data with the accurate energy data, the out come is really only as good as the poor water data. This same analogy can be extended to boundary definitions. I think as long as researchers are really honest on where uncertainty and error enters the analysis, we can maintain some confidence in how much credibility a solution has. Unfortunately, I think the most dangerous trend I see in "nexus" research is that researchers are dabbling with datasets in domains that they don't understand, and these caveats are lost. I fear that as the "nexus" gets larger and larger, the less useful the answer potential becomes. Thus, I think there is merit in thinking a lot more in this space about frameworks to avoid these issues.

Supplementary Note 6. LIST OF ORIGINAL ANSWERS TO NEXUS METHODOLOGY QUESTIONS

1. To what extent do you think nexus data collection can or should be standardized across multiple sectors, spatial boundaries and temporal scales? How would we ensure data quality and reliability? Are there examples of other community databases we could follow? Who would host such an effort? Can/should AI or IoT play a role in data collection?
    a. In my view the biggest step for nexus thinking and data collection is based on units/dimensions of the data. For instance if you produce food (kcal), how much water is needed to produce1 kcal? And how much kWh is needed to produced the 1 kcal. For this we need to look to the whole chain, so not only the water needed for irrigation but also for producing the food to such a way that it can be directly taken up. Same hold for feed of course. The question is can we standardize this? I fully agree that we should do this, by using as much as existing data bases. At a larger scale, we have tried to do this in a

paper of a few years ago, Bijl et. al GEC 2018, "" unpacking the nexus"". Here you can see that we mainly rely on our Integrated Assessment Model data combined with FAO"

b. I think standardization would clearly help in making models compatible at different temporal or geographical scales. As for data quality and reliability I cannot say: public statisticians should be consulted, since I think the effort should be hosted at public (be it national or international) institutions. AI might play a role in reconstructing data or ensuring its validity.
c. I think that should be standardized but is quite difficult because of the differences between the countries and/or sectors. Data quality and reliability is one of the key to success so I think focus should be really put into this topic... the effort should become from the public agencies and AI / IoT definitely would play a role.
d. Part of the nexus "challenge" is fusing disparate data. Nexus research is so broad that I can't see how such a standardization would actually be practical for some of the sources of raw information (e.g. private (utilities)). Government data is already provided in formats that are standardized (e.g. EIA), but perhaps not at highest granularities that we would desire. So, I think pushing towards data quality and reliability actually makes a great research opportunity for data development efforts by scientists producing intermediate data products for the scientific community, rather than forcing primary sources of raw information to adhere to principles that may be too strict for common good. All that being said, so much data is currently unavailable (e.g. urban-water use) that any data availability is actually a good thing. Yes, AI should play a role."
e. Current method and technologies allow us to work with data at very fine spatial and temporal resolutions, which could then be used for analysis at very different scales. I think it is important to have widely open and sharable data sources that could be verified, updated and used by a large number of users, working also on different application and different scales. AI and IoT already play an important role in elaborating and generating new data, that were not imaginable few years ago. This methods need to be take forward and need to assimilated into research workflows. Often single sector data, stored by individual specialized institutes, are used to start Nexus analysis. Platform that store and provide access to multi-sector data are still rare, but could significantly easy the work of researchers that normally struggle in gathering and tuning data from different sources.
f. As said in previous rounds, in my opinion, the main strength of the Nexus studies is the multi-level nature, specially the stakeholder engagement. To generate databases with big amounts of energy-land-water-emissions data for different countries and sectors is something already done by the IAM community. Therefore, I believe the harmonization for ensuring quality in Nexus studies should be more ""process-focused"". I mean: how to engage different stakeholder groups, which are the interconnections that should be incorporated in different regions that may not be considered by stakeholders...
g. As I don't see the need for producing big harmonized homogeneous databases, I don't think that AI technologies would help for this, but I am not familiar with those techniques at all.
h. I think all available data sources could/should play a role. It would be fantastic to have a standardised dataset; but I'm not sure this is possible. For example, the water data in

Australia, at least, is usually obtained from public enterprises owned by the government of each state; while similar, they such enterprises are not the same in each state and so reporting is different between them (but actually, it's at least not too bad trying to get the data from the few states). In the U.S. it seems that water distribution is even less standardised. So it would take a major effort to get a database with the necessary information to really understand and compare water use and how it relates to energy consumption, etc. In other parts of the world, water use isn't even metered. To study the Nexus, we ask for data that isn't normally put into public databases (for example, I asked our water enterprise how much energy they consume for different activities). So I imagine data collection at this level will continue to be quite an effort for the foreseeable future.

i. I don't think all nexus data needs to be standardized across sectors, boundaries, and scales. However, being able to do some in some cases it would allow for greater comparison (especially of empirical studies). Standardization could also be useful for considering the three pillars of sustainability--economic, social, environmental--where standardizing outputs from an analysis into dollars, social/political capital, and/or ecosystems services--which would be an interesting perspective from which to analyze FEW nexus impacts.
j. Standardized as much as possible. The climate community has done really well in this. IIASA has created a nice standard for modeling, and perhaps data can be merged with that too.
k. It depends on the type of analysis intended. For national comparisons, or sub national within the same region, then there is a need for some standardisation of data. Perhaps through national reporting agencies. However, the reality is that Nexus related data are collected in a range of different forms and need to be reinterpreted for Nexus type analyses. Furthermore, hardly any metrics that represent a Nexus between WFE exist - they are almost always for water, food or energy, not an integration of these.
l. This very much relates to the definition of nexus itself. Till this point, there is no prescriptive definition of its scope and scale, and perhaps there shouldn't be unless we can really reach a consensus here. Therefore, data needs will be different for each study. I cannot see special data need for the nexus; we need the same data that we typically use in sector-specific studies but from multiple sectors. Researchers (users) just need to homogenize the existing data to suit their method or modeling framework. In places like USA and Canada, and several other countries that publish detailed statistical year books, a lot of data are available for nexus researchers; at least as a starting point
m. There are multiple community examples that can be used towards data standardization for many of the commonly used datasets (e.g., land use, topography, climate, etc.). However, the context of nexus problems many times requires use of specialized data or unique data that are not easily amenable to existing community models. Efforts towards standardization of such data will have to be a bottom-up effort of the research community. In fact, IoT and AI should certainly play an important role towards identifying new data, hence even more crucial to let the standardization of new data types be a flexible and open-ended effort in the research community.

n. Data availability is a bottleneck for many nexus studies and methodologies because they are not available in the same temporal and spatial scale for all sectors. It is natural since always all data have been collected by and for each sector to answer the question regarding the sector specifically. I believe communication is the key word to standarize data collection. Sectors must indicate which temporal and regional scale they get the data, then all sectors will know the level in which they must provide data in order to attend the other ones. It raises questions regarding how to offer data in temporal or spatial scale in which there is no data availability, or who will pay for the additional investments to collect all necessaire data. There is no easy or unique answer for those issues but technology development has been improving the capacity to collect data across diferente levels, hence I hope AI and IoT can play a significant role to reduce the distance between sectors data collection.
o. I think satellite data at global scale should be developed for water food energy nexus purposes (water resources availability, food production, wind, solar and other renewable energies). Countries should develop databases of water, energy and food flows on regional and preferably at sub-regional level with at least a daily temporal scale and preferably at higher resolution. IoT technologies can be used to increase the amount of information at an advantageous price and AI can be used for data quality, reliability and missing data. AI can also be used to better identify/understand interrelationships and discover hidden interrelationships. References: McNally, A., McCartney, S., Ruane, A. C., Mladenova, I. E., Whitcraft, A. K., Becker-Reshef, I., ... & Uz, S. S. (2019). Hydrologic and Agricultural Earth Observations and Modeling for the Water-Food Nexus. Frontiers in Environmental Science, 7, 23; Zaidi, S. M. A., Chandola, V., Allen, M. R., Sanyal, J., Stewart, R. N., Bhaduri, B. L., & McManamay, R. A. (2018). Machine learning for energy-water nexus: challenges and opportunities. Big Earth Data, 2(3), 228-267.
p. I believe the nexus research will benefit by a somewhat standardized data collection, which includes the framework of data that need to be collected and their units. The framework of data would depend on the definition of ""nexus."" which might be different in scales, regions, and disciplines. I think the input/output datasets and/or the supply chain datasets would be most relevant to the FEW Nexus studies.
q. For the regions in developing countries like India, data collection should be standardized. For standardizing the data collection, providing central hubs like open dashboards from government agencies is a good option. For example, the state of Andhra Pradesh in India facilitated the Dashboard to know the streetlights working system. It helps to know the working condition of streetlights over the state from any remote place. This dashboard also provides information about government schemes and ration supply system. But it doesn't consist, information about imports and exports of goods, it should be incorporated in the dashboard systems and access should be given on public platforms with proper security to data.
r. An example might be the Inter-Sectoral Impact Model Intercomparison Project (ISMIP) https://www.isimip.org which developed a framework for consistently projecting the impacts of climate change across affected sectors and spatial scales. The framework defines the format of output data and assumptions that the different member models

have to comply with, so that the results can be compared and use as input to other models. The data is shared through a common catalogue and modelling groups can join the community. The data catalogue contains many data related to the WEF Nexus (e.g. hydrology, land use, crops, fertilizers). The common format for data output is raster files with a temporal dimension, as this is easy to adapt to the local, regional or global scale.

s. I believe data can be standardised to an extent that models that use the data can be standardised. Just like global community models(CESM models) have been able to standardise, archive and share data, it may be possible for data that have been collected and validated in nexus studies to be standardised and archived for sharing. However, the increasing sensitivity of land and water resource data, especially at more localised scales, and where transboundary or competing multi-user issues arise, would be a hurdle. Something as simple as historical agricultural inputs and yields are difficult to find, access or validate at scales relevant for intervention optimisation. It could be hosted by publicly funded research organisations. AI can help and should play a vital role bridging the data unavailability. Some researchers are already going towards AI approaches to estimate WEF resource availability and flows that are either not directly measured, or ones where the data stewards/owners are not willing to share.

t. From an urban water perspective, data on the nexus is often formulated in terms of energy requirements in the water sector, or vice versa. For example, for urban water supply, sometimes categorized into upstream (extraction/production, treatment, and distribution of water), in house (heating, pumping), and downstream (wastewater pumping and treatment) energy requirements (e.g., Venkatesh et al. 2014; Radcliffe, 2018). Other nexus approaches go beyond that and consider all resources produced, consumed, and lost within the production, consumption, and disposal cycle, similar to Life-Cycle Analysis (LCA) methods. For example, energy contained in/ (potentially) produced from wastewater (methane, heat), nutrients extracted and used for fertilization of soils, and water recycled for secondary purposes (irrigation, toilet flushing, etc.), and energy and pollutants emitted into the environment (e.g., Gárcia-Sanchez and Güereca, 2019; Lane et al., 2015). However, while the aim of LCA is process optimization, nexus research additionally aims to identify synergistic management potential. With its roots in the arena of Integrated Water Resources Managament (IWRM), nexus research could go beyond resource management optimization/coordination, and develop governance approaches that use this potential. So beyond data collection of resource cycles and interconnections, nexus research needs to collect social science data on governance and management. In terms of scales: Certain resources can be more readily transported (e.g., food, energy) than others (e.g., water, land). Flow diagrams (e.g., Sankey diagrams) and footprinting methods that use a combination of consumption footprints with the location of the production/pollution footprint and temporal trajectories that show the evolution of systems and their footprints over time (years) could be adequate for the resource-side of data/scaling. This needs to be combined with multi-level governance data that accounts for the local-global connections that emerge from the resource-flow connections through global trade, atmospheric transport, transboundary interactions (e.g., transboundary water basins), etc. References: Venkatesh G, Chan A, Brattebø H (2014) Understanding the

water-energy-carbon nexus in urban water utilities: Comparison of four city case studies and the relevant influencing factors. Energy 75:153–166.; Radcliffe JC (2018) The water energy nexus in Australia – The outcome of two crises. Water-Energy Nexus 1(1):66–85. García-Sánchez M, Güereca LP (2019) Environmental and social life cycle assessment of urban water systems: The case of Mexico City. Sci Total Environ 693. doi:10.1016/j.scitotenv.2019.07.270; Lane JL, de Haas DW, Lant PA (2015) The diverse environmental burden of city-scale urban water systems. Water Res 81:398–415.

u. Standardization and uniform collection would be ideal and perhaps necessary for efficient analyses. It would be useful if individuals could be incentivized to contribute to a repository that would be managed.
v. I think standardization is only possibly among similar communities. Similarities in size and economic development level are even more important than similarities in culture. To define common parameters between rural Alaska and New York would be a stretch. But there are probably common parameters among New York, Hong Kong, and Paris.
w. I don't see this as practical. As I mentioned in a previous prompt, nexus research can only be as precise as its most coarse dataset. Technology readily enables some data to be collected easily at very fine spatial-temporal resolutions, and other spaces are currently much more limited. If we were to standardize timescales, I think we would reduce the potential for technological or data resolution improvements, or analyses in regions where data are particularly good (or bad). On the other hand, I think that the standardization of notation, unit reporting, etc. would be very helpful. In the energy literature, for example, publications are very sloppy in distinguishing between electricity and primary energy, MW_e vs MW_thermal, etc. Emily Grubert and I wrote an entire paper about this topic: https://ascelibrary.org/doi/full/10.1061/%28ASCE%29WR.1943-5452.0001241. Ensuring data reliability is a difficult issue. I think creating codes and standards around reporting would be useful to help ensure standardization (e.g., https://www.greenbuttondata.org/). This is not my area of expertise, but I think we must get much better at this. The challenge becomes restricting public access to datasets that might not be in a specified format. In other words, today there are a plethora of datasets all over the internet of various qualities. It would be fantastic if we could somehow standardize these so they are interchangeable and discernable, but that might come at the cost of access in the first place. It seems like national repositories, mirrored after something like EIA.gov or USDA's ERDS would be helpful as a storage site for all data abiding by rules. IOT will be absolutely critical in this space, and since these technologies can be scaled and disseminated across regions with identical data collection, data reporting standardization will be facilitated (as opposed to thousands of water quality scientists, for example, reporting physical measurements to a central database).

2. A large number of nexus frameworks and methodologies exist and continue to be developed in addition to several nexus review papers. Do you think there is a need and if so how can we coalesce and compare across frameworks? In your opinion what is the largest modeling gap left in nexus methodologies?
    a. In my opinion it is the scale of interest and how they are linked

b. The largest modeling gap in my opinion is the compatibility between sectoral, geographical and temporal modeling. A framework in which researchers might place their inputs would help a lot in progressing. A first step might be inspired by the work done at the Energy Modeling Forum (https://emf.stanford.edu/)
c. That comparison and integration can really work!!
d. Yes, comparisons of model frameworks and potential coupling (biggest gap) would be a valuable effort.
e. I think that development brings innovation. All tools that I know have limitations that new teams might overcome. Moreover, it is sometime easier to develop new tools, rather than using some developed by others (if time and resources allow). Same frameworks (i.e. CLEWS) allow development of new methods and linkages while keeping an overall common framework and sharing platform. This seems to be one of the more effective ways to spread new developments and innovate them.
f. I am not familiar with these frameworks so I don't have an opinion about these modeling gaps.
g. I am amazed by how many of the frameworks are purely theoretical. This is starting to be filled in with quantitative examples, but still more are needed. There still aren't any standardised, quantitative models that are commonly used (that I know of), so these kind of Nexus assessments can't be conducted routinely or predictively (and are therefore less useful for management of resources). There are so many "entry points" for these studies as well, all of which handle different sectors in various detail. This gives us different perspectives. As an emerging field, review papers help synthesize the burgeoning body of literature... and are quickly out of date.
h. While I believe there is a general consensus now in terms of the definition of the FEW nexus, there is still some debate about defining the system limits and components. I believe that nexus frameworks and review papers seek to overcome this challenge by synthesizing existing conceptualizations. The challenge with the growing number of review articles, however, is that a standard framework has not yet been established as a gold-standard. This may be okay, as the conceptualizations of the nexus differ from one another (e.g., nexus governance differs from evaluating physical flows and trade-offs of nexus resources), and these require different methodologies. But establishing a single baseline framework or theoretical conceptualization from which future research builds off of would be useful to compare across studies, to increase empirical research, to understand nexus governance in practice, and to move the nexus concept forward.
i. Comparing methodologies might not be too important.The largest modeling gap is social science and political science within these models. Migration is also an issue that hasn't been addressed well.
j. Not sure I follow this question. I don't think there is a need for another framework of review paper if that is the question. Modelling gap.. Probably links to development pathways that are linked to meaningful and realistic policy scenarios, rather than those that are unrealistic/ idealistic.
k. There are two issues here: (1) The different available methodologies emerge from the fact that different researchers defined the scope and the scale of the nexus problem differently, and thus, they might have needed different

methods/approaches/frameworks. (2) The nexus modeling (accounting) is similar to any other modeling problem. Why did people developed so many different models? Various reasons: (1) special need for a new tool to perform certain tasks; (2) Convenience, because existing models are too difficult to understand and use, too expensive, or too data-intensive; (3) existing tools are place-specific and difficult to transfer to other areas; (4) academics who are always under the pressure to publish. Many of them believe that they cannot publish (or earn a degree) unless they develop their own thing! We all, as researchers and reviewers, contribute to the problem as much as we love to contribute to the solution. Many researchers who wrote review articles compared different methodologies, but I am afraid that these are not comprehensive comparisons. One ambitious project is to develop a standard (and real) database of a case study, and apply different frameworks to it in order to analyze pros and cons of different frameworks. I doubt that this can be achieved in the foreseeable future!

l. While many frameworks and methodologies have been proposed, a big gap that exists is the implementation and evaluation of such methodologies by stakeholders.

m. The nexus gap relies on value the sectors equally. In general studies about nexus emphasize as specific sector, while the others are considered to stablish a relation between them. Due to this gap it is not easy to define which model is the best o answer each question. In general they are used to provide outcomes about all possible questions related to the comprised systems, but actually they should make clearer for which purpose it was developed and which problems it is most suited to. That is also one of the reasons it is so difficult to compare different frameworks. To my knowledge there is no way to classify a nexus model as a more energy centered model, or water centered model, it would make easier to compare different model with no need to develop and detailed analysis about model assumptions and methodologies. "

n. I think more open-source oriented approaches to research and development will help to create a community (and/or few communities) that work on few frameworks/models. Most of the models available so far show the same gap, they focus only on few aspects of the nexus and on a small scale. Very few models and tools integrate the complexity of political, social, economic and resources aspects. References: Kaddoura, S., & El Khatib, S. (2017). Review of water-energy-food Nexus tools to improve the Nexus modelling approach for integrated policy making. Environmental Science & Policy, 77, 114-121; Dai, J., Wu, S., Han, G., Weinberg, J., Xie, X., Wu, X., ... & Yang, Q. (2018). Water-energy nexus: A review of methods and tools for macro-assessment. Applied energy, 210, 393-408; Shannak, S., Mabrey, D., & Vittorio, M. (2018). Moving from theory to practice in the water–energy–food nexus: an evaluation of existing models and frameworks. Water-Energy Nexus, 1(1), 17-25; Endo, A., Yamada, M., Miyashita, Y., Sugimoto, R., Ishii, A., Nishijima, J., & Kumazawa, T. (2019). Dynamics of Water–Energy–Food Nexus Methodology, Methods, and Tools. Current Opinion in Environmental Science & Health.

o. In my opinion, there are two major modeling gaps that need to be addressed in nexus methodologies. One relates to the unclear definition of nexus which leads to various frameworks of nexus models. Consequently, it is difficult to coalesce or compare across different nexus systems. The other relates to the dynamic nature of the nexus systems. The nexus systems are dynamic not only at the flow level, i.e., the flow of food, water

and energy, but also at the system-structure level, i.e. the interrelationships or the supply networks of FEW changes over time. However, most of our current model techniques simulate only the dynamics of flows not the structures, i.e., the models are not able to adjust their structures themselves and will be outdated soon because the reality never stops changing.

p. Nexus approach is a data-driven approach, variations among the nexus methodologies at the development stage is to overcome the data and scale issues at coarse spatial scales. In my opinion gaps in methodologies is due to data and scale issues (in one word: data issues-driven due to spatial complexities). Comparison among the methodologies should be there, but that should correspond to the same spatial scales of study areas (county to county, country to country, and city to city). In my opinion, the largest gap in methodology is, the gap driven by uncertainties in data.
q. The uncertainty linked to the modelling framework can be more important than the uncertainty linked to the biophysical and socio-economic parameters. For example, the SSP database (https://tntcat.iiasa.ac.at/SspDb) shows various parameters (e.g. food production) for different SSPs and different models, and one can see that often a same model will produce similar results for different SSP's, while for a same SSP scenario, different models will be considerably different. Thus, comparing different models helps characterize the uncertainty.
r. I like the idea of a multi-scale nexus modelling framework, where either more localised studies could be plugged in or more sectors could be added. With global IAMs maturing, and multiple regional, national level and urban nexus studies being produced currently, I can imagine a community based initiative to bring all these into one such framework at some point in future.
s. There are many pending questions that research should help to understand, as the meaning of historic data in the scenario of the changing climate conditions or the effect of the time horizon for climate change in the design and operation of projects. In the use of research and information there are factors that facilitate to obtain results on policies and projects, as the coproduction of knowledge that requires the commitment of a wide range of actors with diverging interests and agendas, and the consideration of the level of knowledge and expertise of directors and decision makers on ecosystem services as well as on resources and technological tools. Taking into account that factors as the pressures of population growth, urbanization and climate change are urging attention to the relationship between where and how people live and the resources they need, an ecosystems based framework, could well allow for the application of criteria that reflect the values associated with the consequences of each nexus integration categories, as required baseline information, environment, economic values, legal and policy framework, and socioeconomic and environmental feasibility. Precisely an important modeling gap left in nexus methodologies is the required interdisciplinary teams working together on the research of key interacting factors across sectors.
t. I think that there is a large gap when it comes to the integration of human actors (governance, decision-makers, social behavior) into nexus models. These models are currently focused on modeling resource stocks and flows, simulating past developments and scenarios of their trajectories into the future. What is less explored is how collective

behavior can change these trajectories. See, e.g., Otto IM, et al. (2020) Social tipping dynamics for stabilizing Earth's climate by 2050. Proc Natl Acad Sci U S A 117(5):2354–2365.

u. It is necessary and important for frameworks and methodologies to continue to be allowed to be developed. The diversity breeds more knowledge and insight. That said, analyses of commonalities and differences and gaps of those that exist are also quite important.
v. Yes, I think we should define common terms and common metrics where possible, but ONLY where possible, not forcing definitions where they are not appropriate.
w. This has been a key question I have been asking for many years now. Creating a brand new methodology is a good way to get one more peer-reviewed publication, whereas utilizing one that already exists is not. Thus, I think there is an inherent pull for academics to keep recreating the wheel, even if other good wheels exist. I think a lot more attention needs to go towards testing, executing, analyzing, and scrutinizing the tradeoffs of such methodologies. This would be a key gap for me; going into the literature and completing a rigorous meta-analysis. Otherwise we will just keep theorizing in generalities for many decades to come. I think this is similar to the challenges in LCA, where every study has different data and boundary definitions, which makes studies very easy to publish (because every methodology is novel) but not very useful. But again, this is hard work, that does not maximize the outcomes that academics care about, so I think this is one of the most pressing issues for interdisciplinary thinkers to solve. How do we reward slow research?

3. What strategies/methods/metrics/visualizations exist or can be developed to explore the potential synergies & trade-offs of actions/policies across different sectors? Please share any examples or potential ideas from nexus or other disciplines?
    a. One of the main ways to viaualize the nexus is the Sankey Diagrams It is the challenge to combine the different dimensions/units in the nexus to each other.
    b. Visualizations = power BI?
    c. The Energy Water Nexus Knowledge Discovery Framework (DOE funded) was originally slated to do all of the above: https://www.tandfonline.com/doi/full/10.1080/20964471.2018.1524344; https://info.ornl.gov/sites/publications/Files/Pub106704.pdf; Also, there is NSF FEWSION: https://fewsion.us/
    d. I think that, as in the IAM community, the main outcome of this kind of studies would be the inter-scenario differences. The regional-sectoral assumptions required for Nexus modelling exercises could be argued by different communities, specially when the focus moves from local to regional or global. Even though stakeholders are engaged, they can be biased so there could still be a significant level of uncertainty. Therefore, focusing on policy or shock based inter-scenario comparison would allow to show all the effects in a more robust way. In terms of visualization, diffPlots, or sankey diagrams should be more used than figures showing absolute magnitudes"
    e. In groundwater the most common numerical model used globally is one that is super flexible; different packages can be added in or left off depending on the system,

different boundary conditions or initial conditions selected... but the mass balance at the center of it all remains the same. I'd like to see a model like this develped for Nexus studies as well; what are the fundamental components of water/energy/food that must always be included, but other details/sectors that can be added in if the information is available?

f. Albrecht et al. (2018) conducted a review of the methods used to analyze the FEW nexus. The results show that the majority of methods were purely quantitative with few qualitative approaches. The most common approaches used included scenario analysis, life-cycle assessment, input-output economic analysis, and hydrologic modeling. For FEW nexus governance specifically, social network analysis is a unique way to visualize and analyze the system, as it measures the level of interaction between governance actors between the three sectors. This provides an approach to measuring FEW nexus governance and visualize the level of cohesion (or lack thereof) between the three sectors (Stein et al. 2014; Kurian et al. 2018; Daher et al. 2019; Daher et al. 2020; Kharanagh et al. 2020)."
g. IIASA pyAM is a good example
h. Good visualisation at wefnexusindex.org However, this needs to be taken further to link to identify gaps and identify potential policy changes etc.
i. I am not sure if I understood this question correctly, but I don't see it as a big problem. I have seen radar plots that show how different scenarios (can be policies/strategies) affect different criteria (can be sectors) in an effective way. Anyway, visualization is a big field now and we will be able to find ways to visualize our results effectively
j. Because of the complexity of nexus analysis, strategies/metrics/methods/visualization should involve stakeholders in every aspect of the research and implementation. Hence, easy-to-use and comprehensive decision support systems are vital to this area of work. As an example, the InterACTWEL decision support system is currently being developed to help watershed communities visualize scenarios of adaptation plans for food-energy-water nexus in watersheds. Reference: M. Babbar-Sebens, S. Rivera, E. Abeysinghe, S. Marru, M. Pierce, E. Coulter, M. Farahani, D. Wannipurage, and M. Christie, "Interactwel science gateway for adaptation planning in food-energy-water sectors of local communities," in Proceedings of the Practice and Experience in Advanced Research Computing on Rise of the Machines (Learning), ser. PEARC 19. New York, NY, USA: Association for Computing Machinery, 2019. [Online]. Available: https://doi.org/10.1145/3332186.3333253; InterACTWEL website: https://interactwel.org/
k. Firs it is importante to generate a large number of scenarios in order to get a good feeling of how different policies will impact each sector, how and where. Makes everything spatially explicit or spatially visible can offer a better sense of in which level a sector can affect others. The theoretical qualitative relation between the sectors is well known for many individual actions and policies, now it is necessary to have a quantitative feeling regarding these policies, specially when applied together. Unfortunately most of the countries do not have an holistic approach when developing new policies for specific sector. It is crucial to have more conclusive number to support policymakers in order to avoid implementation of silo policies that are counter-effective.

l. I think that circular graphs represent an important visual mean to identify and quantify relationships. Another important way is to represent relationships and quantify them are Sankey diagrams. References: Urbinatti, A. M., Benites-Lázaro, L. L., Carvalho, C. M. D., & Giatti, L. L. (2020). The conceptual basis of water-energy-food nexus governance: systematic literature review using network and discourse analysis. Journal of Integrative Environmental Sciences, 1-23; Bauer, D., Philbrick, M., Vallario, B., Battey, H., Clement, Z., & Fields, F. (2014). The water-energy nexus: Challenges and opportunities. US Department of Energy; Wang, S., Liu, Y., & Chen, B. (2018). Multiregional input–output and ecological network analyses for regional energy–water nexus within China. Applied Energy, 227, 353-364

m. The water footprint is one useful metric that has allowed to quantify and visualise synergies and trade-offs of energy, agricultural and water policy. It has also helped to explore the impact policies have in transferring water stress geographically.

n. Potential synergies & trade-offs of actions/policies across different sectors are arising to integrate for instance land use and water resources planning that will allow decision making based on the appropriate connections, as is the case of the design and application of a Multi-Criteria Analysis (MCA) model that allows the qualification of key interacting factors and elements for water management and land use planning, determining the levels of relevance of the integration categories in order they should be given the corresponding consideration. A starting point is the definition of land use and water resources integration categories and the criteria and sub-criteria for valuing them. The required or existing information and plans, and socioeconomic and environmental feasibility, reflect the values associated with the consequences of each water and land use integration categories, as water supply assessment and development, regional structures, growth management, and resource use efficiency. Once the integration categories and the criteria have been defined, weights and scores are assigned to derive overall values and ranking by a MCA, that would include a sensitivity analysis. (Castanier, H. 2018. “Integrating Land Use and Water Management Planning with Multi Criteria Analysis”. SIWI. Stockholm World Water Week 2018).

o. Complex network theory could be a valuable path for nexus research, especially in the field of multiplex networks, e.g. (Zhou, X. Y., & Lei, K. (2020). Influence of human-water interactions on the water resources and environment in the Yangtze River Basin from the perspective of multiplex networks. Journal of Cleaner Production, 121783.), with appealing, but abstract visualizations such as this one: http://people.iiti.ac.in/~sarika/Research-Activities-files/Multilayer.png. For a conceptual visualization see figure 1/6 and 2 in (Krueger EH, Borchardt D, Jawitz JW, Rao PSC (2020) Balancing security, resilience, and sustainability of urban water supply systems in a desirable operating space. Environ Res Lett 15(3):035007. https://iopscience.iop.org/article/10.1088/1748-9326/ab6c2d). The upper layer/triangle represents the water sector, only, while the lower layers/triangle, conceptually, shows cross-sectoral interactions (Fig. 2) and impacts in the form of water & ecological footprints (Figs. 1 & 6). Other representations of increasing complexity through inter-sector coordination, but less visual, such as Figs. 5 and 7 in (Ferguson BC, Brown RR, Frantzeskaki N, Haan FJ De, Deletic A (2013) The enabling institutional context for

integrated water management: Lessons from Melbourne. Water Res 47(20):7300–7314.).

p. Network analysis would be quite useful.
q. I think that big data analytics and tools are giving us more tools for mapping networks. For example, many studies are now looking at linkages in citations in the literature, social media, etc. through text scanning technologies. I imagine there will continue to be innovation in terms of using automated methods to map out the connections in papers and data through AI and other data analysis tools that will enable us to go much farther than what we can do now manually.

4. The nexus approach is multi-centric by nature and definition. Have you been able to compare it against uni-centric (e.g. water-centric) and show the benefit of the nexus if any? If yes, benefit to whom? and how did you define benefit?
    a. It is true that a fully multi-centric view is difficult. We should also think then what are the real resources: it is not food but it is probably land available for food.
    b. There is a benefit to a multi-centric approach in that it allows for joint planning of different sectors
    c. Yes, benefit to basin managers. The benefit is that shows and demonstrate an idea that was already in mind of everyone, but well supported and with all points of view integrated.
    d. No, I haven't make those comparisons explicitly, but some of the 'nexus' research I've done implies that a uni-centric focus would result in limited perspective and system understanding or mismanagement. One example of nexus research benefiting water managers and consumers (e.g. civilians, famers), is research that identifies the ultimate drivers (most upstream forcings) that are influencing the final outcome, such as water stress, system vulnerability, etc. This helps focus attention on most meaningful areas for focusing attention.
    e. Benefit for potential policy-makers to avoided unintended consequences and design cost-effective policies by being able to seize potential synergies.
    f. I have been comparing multi-sector policy implication to uni-centric, using a nexus model. The results showed clear differences, which can be motivated with the missing feedback across sectors in the latter method. I don't think it is possible to generalize on who benefits more. It is however clear that uni-centric approaches neglect dynamics that in reality exists and can be captured only with nexus approaches, which should be therefore preferred.
    g. As part of the IAM community, most of my research has focused on multi-sector dynamics, analyzing how the effect of a policy or a shock generates system-wide implications. These multi-centric studies show that different policies create winners and losers across systems. There are very few policies that would benefit the whole economy/region, so the main benefit of the multi-sector approach is that it allows to identify the effects for all the different agents. This could encourage decision-makers to re-design the proposed policy to minimize the damages to different agents or to efficiently compensate the damages."
    h.

i. I think this is one of the research gaps of the FEW nexus thus far, at least within FEW nexus governance. To date, I am not aware of any empirical studies that have directly compared uni-centric approaches and multi-centric FEW nexus approaches to governance to show how an integrated FEW nexus approach to governance could influence outcomes and support (or challenge) the claim that integrated FEW nexus governance provides benefits in practice.
j. I think each of water/energy/food are complex in themselves. The advantage of the nexus approach is that it looks at the connections of the complex systems, which are often ignored.
k. We are working on it now!
l. Ongoing effort.
m. It is not unusual a nexus analysis which does not take into account specific elements that are usually encompassed by uni centric approaches in order to be able to comprise other sector elements that are critical for a multi sector evaluation. Of course it generates a trade-off between what should be included, simplified or removed. Multi and uni centric approach are not able to provide the same outcomes in most of the models I have knowledge. Combine both and iterate over them is a interesting strategy to get the best of both. I have the felling that most of the sectors modelling have more benefit in this kind of approach. Benefit in this case is defined as the capacity of the model provide a large and better set of insights based on its results. For instance an energy cannot provide results regarding land use change unless it is couple with a specific land use model. On the other hand it is very complex to represent all vegetation and land use aspects in a model designed to deal with energy. Therefore a framework that can combine all models, not just the uni centric but the multi centric as well, is a more powerful tool than the traditional silo approach.
n. From a mathematical perspective, multi-objective optimization is set to find the trade-off solutions of counteractive objectives. In the nexus approach, if we limit the number of objective related to only water, we will automatically neglect other aspects of the nexus. A typical example is how to use the water in a reservoir among different water uses: agriculture, drinking water, livestock, power production, industrial production, employment, etc. In my research, we have been applied multi objective optimization in the irrigation sector to find the trade-off between water consumption, nutrients consumption, energy for irrigation and crop yield. We did not directly compared an integrated approach using multi-objective optimization with a more uni-centric approach but the second one can lead to solutions that totally ignore the other parts of the nexus. If a single objective problem is set, for instance to minimize water consumption in irrigation, it means that water for irrigation is not allocated at all even if it leads to crop failures. Concerning the benefit, this can be defined in several ways. Benefits can be direct benefits, both monetary following economic theory of the profit maximization, or can more performance related, for instance maximizing water use efficiency. Alternatively, benefits can be indirect benefits, and in this case, the optimization model is set in a way to maximize indirect benefits, for instance water use for employment in agriculture, or other environmental benefits. Personally, I have been working with direct benefits, both profit and performance related, and we are trying

now to shifts towards environmental and social indirect benefits. In previous research work, we have tried to balance water, food, energy, and nutrients (direct benefits) in the irrigation sector. While solving such kind of optimization model we had in mind framers as direct beneficiaries, but also water management and energy management companies. Some references on multi-objective optimization related to the nexus: Dhaubanjar, S., Davidsen, C., & Bauer-Gottwein, P. (2017). Multi-objective optimization for analysis of changing trade-offs in the Nepalese water–energy–food nexus with hydropower development. Water, 9(3), 162; Davijani, M. H., Banihabib, M. E., Anvar, A. N., & Hashemi, S. R. (2016). Optimization model for the allocation of water resources based on the maximization of employment in the agriculture and industry sectors. Journal of Hydrology, 533, 430-438; Zhang, J., Campana, P. E., Yao, T., Zhang, Y., Lundblad, A., Melton, F., & Yan, J. (2018). The water-food-energy nexus optimization approach to combat agricultural drought: a case study in the United States. Applied Energy, 227, 449-464; Campana, P. E., Zhang, J., Yao, T., Andersson, S., Landelius, T., Melton, F., & Yan, J. (2018). Managing agricultural drought in Sweden using a novel spatially-explicit model from the perspective of water-food-energy nexus. Journal of Cleaner Production, 197, 1382-1393.

o. Most of the nexus components are water-centric elements. These water-centric nexus assessments show the trade-offs between water and other multi-centric nexus elements. And, these are beneficial to policymakers in governments and business managers.
p. We are currently analyzing how using a water-energy centric framework to select energy investments combined separately to a water-food framework used to select agriculture investments, performs against using a water-energy-food framework to select agriculture and energy investments. The goal is to see if the solutions found with the nexus framework perform better than those using silo frameworks.
q. We look at benefits in terms of welfare economic benefits (sum of consumer and producer surplus). This is the easiest common scale to compare impacts in different sectors, e.g. energy supply versus food supply. One challenge is that total economic benefits do not necessarily reflect the SDGs, improved livelihoods, or distribution effects. Environmental or ecosystem benefits are usually difficult to quantify, thus we use constraints reflecting different levels of environmental objectives.
r. Invariably, all nexus studies I have seen have been water centric. I can imagine some works being centred around land-constraints but have not seen any yet.
s. See integration of urban utilities in Q1.
t. I think the comparisons result in identifying externalities and their sources (e.g., harmful algal blooms due to agriculture)
u. The team that I have been doing FEW research with has found that a nexus only makes sense when there are relationships and tradeoffs among the food system, the energy system, and the water system. Some facets of the food system, the water system, and the energy system really do not impact each other.
v. I can't think of a discrete example of this, but it seems as though the unitentided consequences of siloed thinking are vast (e.g., pollution from coal plants, power plants running out of water, water wars, etc.), underscoring the utility of nexus thinking.

Supplementary Note 7. LIST OF ORIGINAL ANSWERS TO NEXUS APPLICATIONS QUESTIONS

1. After almost a decade of nexus research, in your experience, has there been any significant shift towards integrated management in practice? Do you have any examples of applications of nexus concepts in the design, implementation or monitoring of any public policy? Do you have any examples of where ignoring the nexus interactions leads to (very) biased results/policies/infrastructure?
    a. I know the management of hydropower/farming along the Blue Nile has seen a lot of interest, and people are studying Nexus opportunities with policymakers about it. Policymakers have also expressed interest in using Nexus methods, but I don't think it's gotten far enough to say that actual policy has been changed. Here are some relevant projects and papers: https://www.nsf.gov/awardsearch/showAward?AWD_ID=1624335; https://www.nsf.gov/awardsearch/showAward?AWD_ID=1639214&HistoricalAwards=false; Sankaranarayanan, S., Zhang, Y., Carney, J., Nigussie, Y., Esayas, B., Simane, B., Zaitchik, B. and Siddiqui, S., 2020. What Are the Domestic and Regional Impacts From Ethiopia's Policy on the Export Ban of Teff?. Frontiers in Sustainable Food Systems, 4, p.4.; Satti, S., Zaitchik, B. and Siddiqui, S., 2015. The question of Sudan: a hydro-economic optimization model for the Sudanese Blue Nile. Hydrology & Earth System Sciences, 19(5).
    b. I'm not sure of this right now.
    c. Liu et al. (2018) gives some examples to cases in which non Nexus approaches lead to issues that could have been otherwise avoided. These are several case studies worth mentioning, many related to the Water Convention and the use of CLEWS models. Sridharan et al., (2019) is just one of the latest to mention. Also on the Indus basin some studies explore how current international agreements could be dealt differently (Vinca et al., 2020) or focus in particular on environmental flow policies. (Awais et al. forthcoming). However, in some cases it is not clear what is the response of policy makers of investors in response to this research. Liu et al. 2018, Nexus approaches to global sustainable development, Nature Sustainability; Sridharan et al., 2019, The Impact of Climate Change on Crop Production in Uganda—An Integrated Systems Assessment with Water and Energy Implications, Water; Vinca et al., 2020, Transboundary cooperation a potential route to sustainable development in the Indus Basin, Nature Sustainability (under publication); Awais et al., Replenishing the Indus Delta through multi-sector transformation, forthcoming.
    d. Shifts in public policy take time. But my feeling is that the awareness of the nexus is growing, and will eventually result in the widespread use of nexus concepts in public policy.
    e. There have been a few with regard to water management, for example 1. White, D. D., Lawless, K. L., Vivoni, E. R., Mascaro, G., Pahle, R., Kumar, I., ... & Asfora, M. (2019). Co‐Producing Interdisciplinary Knowledge and Action for Sustainable Water Governance: Lessons from the Development of a Water Resources Decision Support System in Pernambuco, Brazil. Global Challenges, 3(4), 1800012. 2. CALVIN for California; 3 Ceara

Brazil -- https://link.springer.com/article/10.1007/s10584-007-9257-0; 4. Germany with the FEW Nexus -- https://www.sciencedirect.com/science/article/pii/S1364032118306075

f. With integrated water resource management models, the focus was mainly on the water demand and use, for current and future. What we now observe is that also in those analyses and model scenarios also the other resources are taken into account. For instance food, how much do we need to produce, types etc. We had some small projects by combining integrated water resource management models with Integrated Assessment models. Challenge hereby is to downscale the socio-economic scenarios to more catchment level.
g. I have read mostly about failures. There are some good examples here regarding why (or why not) nexus approaches are being implemented: Liu, J., Hull, V., Godfray, H.C.J., Tilman, D., Gleick, P., Hoff, H., Pahl-Wostl, C., Xu, Z., Chung, M.G., Sun, J. and Li, S., 2018. Nexus approaches to global sustainable development. Nature Sustainability, 1(9), pp.466-476;
h. I don't have any particular example, but some experience with my national government showed my that public policy is evolving towards a more integrated perspective, continously adding new disclipines/variables to the analyses. This is an opportunity for Nexus research and opens avenues for potential collaboration with stakeholders at different scales.
i. In Australia (at least, here in South Australia), we are quite progressive in terms of sustainable energy. This, in turn, is having a big impact on the nexus. We have examples of very successful food production using concentrated solar to both desalinate water for irrigation and also pump the water to crops. Excitingly, the state's water supplier will also be installing solar arrays to produce energy for it's pump stations, as a large amount of our water is pumped across the state from the only large river in Australia. This will not only save the water supplier millions, but drastically impact the energy for water arm of the urban nexus.
j. In practice, I haven't seen a practical shift towards integrated management on the macro- or meso-scale. However, at the small-scale, I have seen some innovations around nexus implementation. For example, in Nepal there is a community of farmers that use solar-power to pump groundwater for crop irrigation. Additionally, in a nearby community, they process an invasive plant species that often overtakes crop fields to produce a biochar that can be used for household energy and cooking.
k. Limited nexus practice, especially explicitly. Interestingly, I can see implicit consideration of nexus in developing countries where resources are limited; perhaps by necessity but good to see. For example, in Egypt, recognition and awareness have been rising that food and water resources are becoming less available in light of the rapid growth in population. At the same time energy resources (e.g. natural gas) is becoming more available as a result of new discoveries and extraction. On the other hand, hydropower (from High Aswan Dam) capacity has become very small contributor to meeting the national energy demand. Egypt needs to expand its agricultural land for food (crop) production, so it decided to tap on deep groundwater, which needs significant energy for pumping. It decided also to make more of the Nile water available for agriculture by

directing some domestic water demand to desalinated seawater, which needs a lot of energy. The country doubled its electric power capacity (mainly from natural gas), which secures energy for desalination and pumping to make more water available for food production. At the same time, Egypt significantly expanded its solar and wind power to increase clean renewables in the energy mix. The WEF-nexus in Egypt is obvious as policies in water, energy, and food cannot be made in silos.

l. In the (urban) energy transition, we see that CO2 mitigation targets have not explicitly considered impacts on water resources. For example, in our work in the Netherlands, currently considered water scenarios that will result in gas-free energy systems for CO2 neutrality rely on much larger water withdrawals, and comparable consumption for space heating.

m. Maybe a good example of nexus interactions is the Aral Sea (in short): (irrigation - ecosystem nexus): In 1960 the decision to divert the Amu Darya and Syr Darya rivers to massively expand cotton irrigation would lead the Aral Sea, once the fourth largest lake on earth, to dry up within the next 40 years causing a major ecological and social disaster (Saidmamatov et al., 2020). (energy-irrigation-ecosystems): On the other side, the upstream countries used to store water during winter to be released in summer so that it could be used for irrigation in the downstream countries. As hydropower is more valuable in winter for heating, the forgone benefits of upstream countries would be compensated through cheap imports of fossil fuels from downstream countries, which enabled to maximize the economic productivity of the water resource at the basin level. The end of this co-operation mechanism with the end of the Soviet Union further increased the pressure on the water resource (Saidmamatov et al., 2020); Saidmamatov, O., Rudenko, I., Pfister, S. and Koziel, J.: Water-Energy-Food nexus framework for promoting regional integration in Central Asia, Water (Switzerland), 12(7), 1–11, doi:10.3390/w12071896, 2020.

n. I am not a policy expert and I will thus simply express my opinion. In general, I personally think that the WFE nexus approach has been mostly an academic practice as also highlighted in Markantonis et al. [Markantonis, V., Arnaud, R., Karabulut, A., El Hajj, R., Altinbilek, D., Awad, I., ... & Matoussi, M. S. (2019). Can the implementation of the Water-Energy-Food Nexus support economic growth in the Mediterranean region? The current status and the way forward. Frontiers in Environmental Science, 7, 84.] despite the tangible benefits that an integrated nexus approach can bring to the environment and economy. A simple example concerning the difficulty of implementing the nexus approach is for instance looking at the division of the government in ministries. Typically, water, energy and food policies are implemented by different ministries. I give an example for Sweden where I work [https://www.government.se/government-of-sweden/].The water sector is regulated by the ministry of environment [https://www.government.se/government-of-sweden/ministry-of-the-environment/], food is regulated by the Ministry of Enterprise and Innovation [https://www.government.se/government-of-sweden/ministry-of-enterprise-and-innovation/], and energy is regulated by the ministry of infrastructure [https://www.government.se/government-of-sweden/ministry-of-infrastructure/]. I personally think that this kind of management makes the implementation of the nexus

and the development of nexus policies more complicated. On the other hand I can say that in the last years with the set Sustainable Development Goals (SDGs) from the United Nations, something is moving both from an educational perspective (i.e., proliferation of courses related to SDGs) but also policies. That is because a single sector approach cannot achieve the SDGs [Position Paper on Water, Energy, Food, and Ecosystem (WEFE) Nexus and Sustainable development Goals (SDGs). Editors: C. Carmona-Moreno, C. Dondeynaz, M. Biedler, EUR 29509 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-79-98276-7, doi:10.2760/5295, JRC114177]. Moreover, several European Union policies have included the nexus approach in their framework: "An Agenda for Change (2011)", the "New European Consensus on Development (2017), the EU External Investment Plan (2016), "A Global Strategy for the European Union's Foreign And Security Policy" (2016). I also think that the EU policy on circular economy like the EU Circular Economy Action Plan in 2015 [https://ec.europa.eu/environment/circular-economy/index_en.htm] [Kettunen, M., Gionfra, S. and Monteville, M. (2019) EU circular economy and trade: Improving policy coherence for sustainable development, IEEP Brussels / London.] are good example for framing NEXUS policies.

o. Nexus research has contributed to some significant shifts toward integrated management, as the extended concept that water resources use systems start at the basin level and not just from the intake infrastructure, addressing considerations of political and watershed boundaries, between municipalities for instance. Relevant nexus concepts, if not widely, have been applied as in the case of the Metropolitan District of Quito, Ecuador, among others worldwide, with the creation since 2000 of the Water Protection Fund (as a local or city initiative) in order to protect the basins of water sources for its population, and the setting of a monitoring network of water resources availability and quality. In the same scenario of the Metropolitan District of Quito, ignoring nexus interactions has produced biased results, since in the city´s land use plans it is not adequately taken into account the need of sustainable regional structures or inter-institutional agreements and water councils, as an integration category of land use and water management planning, particularly in this case that water sources basins are located on neighboring municipalities, leading to permanent new demands, conflicts and complex negotiations (Castanier, H. 2018. "Integrating Land Use and Water Management Planning with Multi Criteria Analysis". SIWI. Stockholm World Water Week 2018).
p. This is not an application to public policy, we showed that the future land use change (food cropland area, determined by the socio-economic factor) is determined by the changes in climate, water, and it is biased if they are not considered. Our paper is published recently: https://gmd.copernicus.org/articles/13/4713/2020/gmd-13-4713-2020-discussion.html
q. From what I know, I haven't seen a major one in practice in U.S. Midwest.
r. I cannot speak for more urban and interconnected regions, but for rural Alaska, implementing a nexus concept is really challenging.
s. It should be noted that the water-energy-food nexus was a political idea, not a scientific one (see Pahl-Wostl et al. 2018). Its heritage can be found in the discussions around the

implementation of the Sustainable Development Goals (SDGs), in which tradeoffs and interdependencies are acknowledged. While the implementation of nexus ideas in management practice has not yet gained prominence, no current public policy can ignore the impacts of the nexus as global change pressures increase. This can be most prominently observed in urban areas, where the complexity of inter-sector coordination under increasing impacts of population growth and climate change impacts pressures urban managers to shift to nexus approaches, such as when energy and nutrients are recovered from sewage sludge to produce energy and fertilizers, which is practiced in many cities worldwide - without much attention from the scientific community. Nutrients contained in urban wastewater serve agricultural fertilization either directly, without treatment, such as in the case of Mexico City (see Tellman et al. 2018 and Mazari-Hiriart et al. cited therein), or through advanced technologies, such as in Melbourne (Australia) and Berlin (Germany), where energy generated from sewage sludge covers most, if not all of the energy demand in the water sector, making it energy self-sufficient. With incentives arising from public pressure and policy response, such as the European Green Deal (https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en), research is receiving increasing funds to test implementation opportunities of nexus approaches (e.g., https://www.biorefine.eu/projects/lex4bio). In order to address its energy dependence, Jordan's government decided to shift to nuclear power production - a disastrous decision for one of the most water scarce countries in the world, given the water demand for cooling in nuclear power production (see: https://oilprice.com/Alternative-Energy/Nuclear-Power/Water-Shortages-May-End-Jordans-Nuclear-Power-Hopes.html).

t. References: Pahl-Wostl C, Bhaduri A, Bruns A (2018) Editorial special issue: The Nexus of water, energy and food – An environmental governance perspective. Environ Sci Policy 90:161–163. Tellman B, et al. (2018) Adaptive pathways and coupled infrastructure: seven centuries of adaptation to water risk and the production of vulnerability in Mexico City. Ecol Soc 23(1). doi:10.5751/ES-09712-230101.

u. I do not think it has made much progress towards application of nexus ideas. I really do not know any example of nexus application. It is not difficult to find studies that ignore a system that is really affected by the analyzed system, providing then unrealistic results. In Brazil we have some measure in the power system, that relies a lot in hydropower, that might have affected water availability, however there are no specific studies connecting both cases.

v. Absolutely. I am in the energy-water nexus space and I see vast improvements in the way that water utilities and energy utilities consider energy and water, respectively. I have been to many meetings with these utilities who are looking for guidance to integrate their water and energy operations. For example in California, energy utilities recognize water conservation as energy efficiency (https://www.cpuc.ca.gov/nexus_calculator/). Water utilities are also beginning to look towards demand side management to make etra revenue and also facilitate grid reliability. At the US national level, power plants have to report water use, making the power sector one of the most data rich in terms of relatively detailed water usage data. As an example of failures, I think California’s historical absence of rules governing

groundwater extraction has resulted in widespread depletion which has ramifications across energy systems, infrastructure (via land subsidence, etc.). As another example, many countries have offered electricity rate subsidies for farmers, which has promoted over-extraction, in-efficiencies in electricity and water use, etc. (see: https://www.tandfonline.com/doi/full/10.1080/0790062042000206156).

2. How significant do you think increased societal awareness of a nexus approach will be to the success of application of public policies? Do you think nexus approaches, monitoring and analysis should be regulated (e.g. through laws, decrees, mandates) in order to be effective? Should nexus methodologies become a consideration when evaluating future projects for sustainable incentives and financing?
    a. I think societal awareness of systems is important, at least letting society know that the government is thinking according to the nexus. In some ways, the green new deal is a good example of a (expanded) nexus approach, where the policy says climate change isn't just an energy and temperature issue, but a health, food, jobs, and population issue. More policies like this would be good. I don't think we need to regulate the nexus, I don't understand what that really means. We should definitely take nexus and systems issues into account when evaluating projects.
    b. Public awareness and ACCEPTANCE are key... it's not just about awareness, it's about accepting that issues need to be addressed through behavioral change. I do think regulation will be necessary, and it should be well-considered and holistic.
    c. I think societal awareness could improve the success and popularity of Nexus approaches. However, given the complexity of Nexus iterations, it is probably easier to inform a restricted group of already technical experts, rather than large shares of population. At the moment, laws that enforce the use of Nexus approached sound quite far from reality at national or international level. However, it might be already the case for very specific local regulation with well-known issues that can be connected to WEF solution. I hope that this could change in the future, for instance stimulating more Nexus research at various scales. One way to do it could be to incentivize funding to Nexus projects
    d. It will be critical, but not as much as for other issues. In this case, administrations can realize by themselves the benefits of an integrated approach. So I do not think that regulation will be required. As for the evaluation of future projects for sustainable incentives: the nexus should be an integral element, given that, if the sustainability assessment is done based on the SDG, water, climate and energy have to be assessed.
    e. It is a useful way to signal to policymakers what the priorities are of the people who vote for them. It is also a way for people to pressure policymakers.
    f. The answer to this question is how good we are in explaining our results to the public. We should think about clear ways of visualisation and need to learn from IPCC, for instance how they show clearly how much carbon emmission there is possible till the cake is over (this pie diagram). Or how now the issue is lanced: bending the curve on biodiversity loss. Very clear message, in which society and policy can be taken

g. 1) Increased societal awareness is critical, both for conducting the research and having it get implemented. Ultimately, societal viewpoints shape those of the elected officials responsible running decision making institutions and for funding our research. 2) Laws are unlikely to be effective on a global scale. What needs to happen is that the economic benefits of nexus approaches need to become clear to those involved in strategic planning. Money talks! 3) Multilateral development banks should definitely use nexus indicators alongside other metrics they typically use to assess projects. If a project in one sector (e.g., a water reservoir) has the potential to affect other sectors and create complex planning challenges as a result, that should be taken into account before funding a project.
h. I agree that societal awareness is an esential point in public policies. It has been explicitly defined as a dimension in some near and long-term sustainability strategies in my region. However, I don't see why it is more (or less) important for this kind of integrated policies. Same for regulation, I believe that an appropiate tracking is an essential element for the effective implementation of any public policy, but nothing particularly important for this study in my view… Regarding the funding of future projects, I believe that those analyses that consider different systems (Nexus, IAMs) are continously becoming more and more popular, so I think that they are already implicitly considered in evaluation/funding decisions."
i. Perhaps we need to have better data availability (and standardised data) if we want this to be mandated. Otherwise it will just create additional barriers to improvement. I'm not sure societal awareness is needed, but I think policy makers need to understand the vast gains that are possible from taking the more holistic nexus approach. There need to be some well-publicised WINS.
j. I don't think increased societal awareness from a citizen perspective will necessarily lead towards increased application of public policies. Awareness by certain decentralized societal groups (e.g., farmers, water-rights holders) however, may be helpful in leading towards application of public policies. Ultimately, though, the change will most likely come from decision-makers and governance sectors irrespective of public awareness.
k. Public awareness helps, in parallel to making policy makers aware and convinced. Too early to talk about laws and regulations. We need to do a lot more work to present case studies with concrete evidence of its advantages and limitations. We also need to present when it can/cannot help. The first step is that we do more work, the second step is to convince decision-makers, within their power and authority, to demand WEF-nexus analysis. We need to give a chance for the WEF-nexus approach to grow and settle naturally. Recommending the WEF-nexus approach as part of Environmental Impact Assessment (EIA) and sustainability appraisal of future projects is a good idea. Such a recommendation should be made based on solid evidence from our collective research efforts that the nexus analysis reveals what other tools are not presenting.
l. I think Nexus methodologies should become a consideration when evaluating future projects for sustainable incentives and financing. It is necessary that monitoring and analysis should be regulated in order to be effective, but I'm not sure if through laws, decrees or mandates. I think that for a first step could be useful something like a manual

of good practices. Also could be a special requirement in the terms of reference of a new project.

m. It is not obvious to me how nexus approaches could be regulated. May be certification of policy/and approaches by recognised bodies would work (eg. think of extending the green certification to a nexus one). I agree projects could be evaluated on their level of nexus integration and this could help to strengthen the sectoral interactions by diffusing the idea into multiple sectors.
n. I think education is the first step to change society, so I think that educating people and/or making them aware of the nexus and its interrelationships is of paramount importance for better understand the nexus interrelationships and why nexus policies should be favoured. Still, a lot of people remain amazed when during popular science talks I show the amount of water and energy that is required to produce a burger as compared to other daily life foods. I think policies that regulate the nexus are required. EU (see answer above) has provided some frameworks for the EU State Members that consider directly or indirectly the nexus. It is extremely important to regulate/frame such ground to keep working in silos mode. In this context, I think that the SDGs provide an important tools to set targets that can be achieved only by adopting a nexus approach. I totally agree that nexus methodologies should be adopted to evaluate projects. In the last years in Sweden when we present research projects to funding agencies we are forced to contextualize our project aims in the perspective of the SDGs. I think kind of policies, regulation helps the adoption of the nexus approach.
o. Societal awareness of a nexus approach is significant to the success of application of public policies in the framework of existing general laws of territorial organization, and water resources use, that contain legal provisions for the regulation of land use in order to maintain the equilibrium of ecosystems in areas of water protection, and for the priority ranking of water use (human consumption, irrigation/food security, ecological flow, productive activities).
p. Increased social awareness is important to mobilize support and adoption from the governments. I really think the nexus is not well recognized broadly. Whether nexus approaches should be regulated may depend on the country (apparently there is no one-formula-fits-all thing). If nexus methodologies become a consideration to be incentivized, I personally expect better adoption and innovation.
q. I don't know.
r. The last question: Yes, absolutely.
s. It is important to spread nexus studies to the society. Communication in science must not be focused on politicians exclusively, all people should be able to know and understanding new science findings. In many places population pressure has more capacity to drive public policies than science, therefore it is necessary to make nexus studies to reach regular people in order to check how it will appeal to the societal. I believe regulation is one of the ways that can be used to implement nexus policies but it is not the only one neither the most effective for all cases. There is a need for a foundation framework to support nexus implementation. It must be much more discussed. There are a lot of studies trying to understand the complex interactions between nexus systems but very few studies about how to implement and regulate

nexus approaches. First it must be clear that different nexus methodologies will provide different results, then it is fundamental to specify the advantages and the flaws of each nexus approach. Despite that it would be very good to include nexus evaluations on sustainable projects and even on private companies' sustainable reports. It would prove how environmentally friend measures are affecting linked systems others than main one. For example, an electricity company should provide in the yearly sustainable report how much energy some power plant generated and how much water was used. It would be a good source of data as well.

t. Societal awareness of a nexus approach certainly helps the success of the application of public policies. Regulatory supports on nexus application is important, but well-designed business models that make nexus approaches profitable will be even more powerful when implementing.
u. I think increased societal awareness is critical, since many people do not see the interlinkages between systems. Once they become aware, policy makers must become more accountable, and I think there are examples of this we can point it. There are many examples where nexus issues are already regulated. For example, a power plant needs a water permit to operate in the US. However, there is a lot of room for improvement. I think the most difficult thing is creating frameworks that do not create unmanageable amounts of bureaucracy. Efficient policy mechanisms exist, like pollution taxes, that could have the unintended benefits of better nexus outcomes.

3. To what degree do you think the Nexus is an academic initiative rather than a way of operating public policy? Will modelling/studying the Nexus really have an impact if countries do not implement this Nexus view at a government level? Do we need to train scholars and professionals differently, in order to successfully design and implement nexus approaches?
    a. I think it's an academic exercise so far but I do think that policymakers want to use it as a way to design policy. So I would say the need is there from policymakers, and academics are working on the supply-side of the nexus, and we need ways to connect the two now.
    b. It is often the case that academia needs to beat the drum repeatedly and consistently before action is taken. I think this is the case with the FEW nexus and issues.
    c. The Nexus initiative definitely started as academic, and it is slowly infiltrating into governmental structures. But the Nexus approach should absolutely become part of any management or operating policy planer, connecting and including the current individual sectoral departments. For sure more effort is needed not only to transfer knowledge and methods from academic to professional and governmental environments, but also to make sure the approach is maintained in non scholar environments, so that it develops in the most solution-oriented way possible.
    d. As many issues before, it starts as an academic initiative, and will end up as public policy. Of course, if this is not the result, if the nexus is not incorporated in government policies, our studies will have no impact. And I don't think we need to train scholars and professionals differently.
    e. In my experience, funding agencies have been the bridge between government and academia. These agencies have been important for academia to work with government

institutions to bring together models and actions to better implement policies. The only way these models/studies would have impact on the governmental level is when they are usable and easy to understand to someone in the government who cannot model. User interfaces are therefore important. Another great challenge is seen when governments change, and they do not continue to implement things that the previous government had worked on. It is common especially when the priorities of the new governments are very different. Training scholars and professionals requires very different techniques, and presentations. For example, a scholar would be very interested in the model itself, the equations that went into it, and a case study of how it has worked. But a professional or a government official is more concerned about its usability, and how it could help them in achieving their goal(s) (reducing costs, reducing emissions, creating energy security, etc)

f. I believe is can be used for policy makers. It is a very interesting way to show how dependent you are on your resources and what kind of decisions you can make to have a sustainable future
g. It is currently only an academic initiative. Governments are where nexus approaches are best implemented, because governments are supposed to be responsible for long-term, strategic thinking. Conversely, industry is rightly responsible for looking out for their own best interests, rather than thinking more strategically about how to maximize overall benefits.
h. As said in prevous rounds, the main strength of the Nexus research in my opinion is the effective engagement of different agents (stakeholders, moddelers, governments...), so, although it can be considered an academic disciline, it needs to be directly linked with public-policy-related agents.An active engagement of these public agents by the mentioned training, or any other formation or communication activity, would be helpful for acheiving the link between the two communities.
i. I think we have to highlight the economic benefits of implementing a nexus approach; money talks. I would have thought the Nexus was academic until I started seeing shifts in the nexus at our state level.
j. I believe the nexus, to date, has been a predominately intellectual concept--though not solely academic. In stakeholder engagements I've done, several practitioners and decision-makers stated that they are aware of the FEW nexus and think it is of fundamental importance for resource management. They were interested in learning more about it by independently pursuing webinars and reading research papers on the nexus. However, it did not appear that they were implementing nexus approaches in practice and actively engaging across sectors. It is challenging to coordinate for public policy across such different sectors that operate on different time scales, different governance structures, and different policies and procedures. We need to train professionals to engage in cross-sector engagement and provide practical recommendations of how to do so--more than just getting people from different sectors in a room together to communicate but consulting on actual resource issues and practically advising on how a nexus approach can best address said issue.
k. I am convinced that the nexus thinking is natural and intuitive, and in fact, it is implemented at least partially at the higher policy level (as I presented the case of Egypt

above). It is easier to convince higher-level policy makers because they implement some of it. We need to emphasize the explicit adoption and calling it what it is. In my Water Resources Engineering class at the University of Saskatchewan, I talk about the nexus a bit to make young engineers aware of it. However, it will remain challenging to convince sector-specific officers with it as their objectives is self-interest (maximizing their own benefits). The nexus shows tradeoffs and synergies and sectorial experts will adopt it when it brings benefit to them. It is our job to study the higher level tradeoffs and synergies, then work our way down to make it clear what it means to sector-specific people, then work our way even further down to explain how this concept can move to the details of design and local operations. I strongly believe that it cannot be bottom-up, it has to be top-down approach.

l. Nowaday I think is more academic because it's difficult to convince goverment to incorporate new tools. I think Nexus view could generate an impact, and a way to impulse it could be showing the impact in specefic iniciative with social relevance.
m. I do believe that the Nexus will move into practice just like IWRM did. At the moment, the nexus is also being pushed within developing economies where a single governmental ministry at the national level has the mandate to organise water, irrigation and energy infrastructure (eg, Ethiopia, Sudan in SubSaharan Africa). How well the policy level integration is being done is of course questionable. Thus, training professionals in this way would help if we are to achieve SDGs synergistically.
n. On one side nexus analysis that are ""sector oriented"" (e.g. Integrated Water Resource Management considering land and energy resources) help decision makers to find solutions to their specific sectors that avoid trade-offs and prioritize synergies with other sectors. On the other side if nexus studies can prove to decision makers that it is even better to not just consider the other systems, but directly merge the individual system planning towards a common planning process (so that considers all systems but also possible actions) to achieve even more synergies, we will reach a real nexus way of operating public policies. But this still needs to be proven and put in practice. Few nexus framework in terms of stakeholder management and planning exercise exist, one example could be (De Strasser et al., 2016). De Strasser, L., Lipponen, A., Howells, M., Stec, S. and Bréthaut, C.: A methodology to assess thewater energy food ecosystems nexus in transboundary river basins, Water (Switzerland), 8(2), 1–28, doi:10.3390/w8020059, 2016.
o. I think it is mostly an academic practice because the government are typically organized in a way that keeps separated the three main aspects of the nexus. See the answer to the previous question. I am modelling the nexus, and of course, I am biased in highlighting the importance of identifying nexus interrelationships and model them to provide guidelines. What is missing is bridging scientists with policy makers but of course, in the last 5 years several policies have been implemented to help bridging those activities. See the answer to the previous question. I totally agree in training students and scholars on the nexus perspective. I am coordinating and teaching in course titled “International Energy Systems” where the nexus in one of the 7 pillars. Despite it is course given at the 4th year of a university programme (equivalent to a first year of a master programme) students hear for the first time about the concept of nexus.

Moreover, despite most of them are energy engineers, they hear for the first time about the water-energy nexus (most of them only knows about water-energy relations in hydropower plants). I think that educating people to nexus is fundamental for the development of future nexus policies and nexus implementation. I feel very proud to say that since I have started teaching this course, the number of students who apply for master theses on the nexus (different aspects of the nexus, mostly related to engineering applications, but also some on policies) has been exponentially increased. I feel also very proud that one of my students is actually working in an organization in India that supports the government for nexus policies development.

p. From identified requirements and needs in the practice or in the field, nexus research and academic initiatives are defined and investigated, and if would be the case, their results should be complemented with pilot field demonstrations and adjustments, and the next stage will be the design and implementation of the corresponding policies at national, regional and local levels. If countries do not implement these Nexus views at a government level, modelling / studying the Nexus would have a partial impact, depending on specific societal and stakeholders awareness.
q. Right now, I feel the Nexus is still largely an academic initiative instead of an operating policy. It appears successful examples need to be set up for followers at the government level. Yes, I think naturally scholars and professionals have different goals and concerned issues. Separate training but working together is important.
r. I think sometimes the nexus concept is forced onto situations where it isn't necessarily useful.
s. See response above, about the nexus originating as a political idea. The integration of resource provision and the shift from resource extraction to ecosystem stewardship is the only sustainable way forward.
t. It is a critical issue. Nowadays nexus approach is much more an academic initiative than an implemented strategy to better deal with resources. It is a relatively new, there is a bit more than ten years of studies, and it can take time to evolve to an actual policy driven strategy. Besides a nexus policy implementation depends on integration between different sectors with different priorities. Historically these sectors pursue different goals and have been regulated individually. They do not have the same importance in every country which can lead to disruptions between nexus approach. There are many situations that are hindering nexus to step up to a policy level. In the meantime, its capacity to really impact government decision is small. I am not sure about training scholars differently; I believe there is a need for a better integration between science and policy in almost all fields. It is not an exclusive nexus issue. Then it is always good to improve the capacity of scientists to communicate results and the importance of the studies, but as I said it is bigger than nexus.
u. I am actually seeing a lot of interest by utilities and industry in the nexus. I think these entities are more interested in actionable, tangible frameworks, that ultimately reduce risk. I think interest is coming from the fact that saving resources saves money, and a water or other resource shortage is an economic liability. So I do think this nexus work goes well beyond academia; however, some academic methods are too involved and complicated for industry and governments to utilize. I do think that governments

become more interested in the nexus as social pressure increases for more sustainability and equity across resource systems. For example, fracking was met with so much resistance, the oil companies had to increase their oversight of water. Desalination facilities have to be cognizant of their carbon footprint, etc. In terms of education, I think that there is a big under appreciation (particularly in engineering) for systems thinking. We haven't figured out how to be rigorous in assessment so students think that critical, systems thinking is "easy" because there is less of a "correct" objective answer.

4. In your experience have certain subsets of nexus inter-linkages been easier to implement in practice? Do you think the nexus approach becomes obscure/less useful at certain scales (e.g. at certain smaller scales other factors may take precedence for societal well-being)?
    a. Sure, I think each scale and each subsets have advantages/disadvantages. But if you don't think multi-scale and supersets rather than subsets, it's not really a nexus approach. The whole point of the nexus approach is the connections are more inportant than the individual siloes.
    b. I think the harmful algal blooms in Lake Erie are drawing attention to, and motivating action, to manage agriculture for food production in a way that reduces nutrient run-off that affects water quality. Similarly, in the energy-water nexus there is a fair amount of management to reduce thermal discharge from power plant cooling.
    c. Some inter-linkages, as hydro-power management and irrigation system, have been widely studies with Nexus approaches. In many cases these were two-sector studies, that could be further expanded. However the number of case studies indicates that they are of interested and outcomes could be directly feed into operational instructions. Certainly every scale have preferred focus points and weaknesses. For sure global or large scale studies tend to often neglect social impacts that would be more evident when dealing with changes at local scale. To my experience research around sectors with high human involvement (agriculture in particular) tend to suffer the most this limitation.
    d. Yes. I think country level issues would be much harder to implement OR very small scale/level issues. The large scale has challenges like generalising local economic, political, cultural and climatic problems, whereas at the small scale, there are challenges with what people want to prioritize (economy vs climate, current vs long term goals)
    e. This is a very interesting questions, as if you see the earth as one pixel, then there is no trade of resources. We have done some analyses and thought about that in a paper in GEC (Bijl et al. 2018: unpacking the nexus). In here you can see how resources are connected with travel distances. At a global level, I think that analyses on larger scale (regions to continents) is very usefull, but this is the maximum scale. At smaller scale, it is defintely interesting to analyse those at catchment scales or even with political boundaries in here. But here the boundary conditions of your model (dependencies to global market etc) are becoming more and more important for your results. A set of regional scenarios should help for that, but we are not yet that far"
    f. Water is clearly linked with energy and food. It just makes sense to manage water well if you are responsible for supplying energy and food. Other links can be more obscure.

The nexus approach definitely becomes more difficult at finer scales, because so much of what is produced and consumed is external to the region of interest.

g. Again, the main strength of this research is the interconnection betweendifferent agents. By definition,I think that the main distinction with IAMs is the possibility to be adapted to more regional or local scales, so I don't think that analyzing different (global or local) scales should be a problem at all. I would say just the opposite.
h. As a hydrologist, I am most familiar with the water-energy arm of the nexus, and I think there are many obvious and relatively easy improvements to be made here, at the city, state, and national levels.
i. Integrating the water-energy or the food-water interlinkages have been easier to implement in practice. For the former, with the clear interlinkages such as the generation of hydroelectric power, the water needed for conventional electricity generation, and the energy needed for pumping water through transboundary canals, many stakeholders already have a grasp of the dependence that one can have on the other within certain contexts. For the latter, food and agriculture is dependent upon water, and thus there is a clear interlinkage of irrigation. These types of two-way interactions seem to be easier to implement than a comprehensive full-nexus approach.
j. Indeed, some water-energy, and water-food nexus sub-sets have been out there. In some places, sub-sets might be relevant more than the whole nexus. It is my bias that the nexus is more obvious at larger scales (with some exceptions). But this is part of what I referred to above when I talked about our responsibility to show when it works and when it does not; this includes the various spatial and temporal scales.
k. Yes, I agree. The subset water use for food - agriculture is already implemented in many cases.
l. I find the plethora of literature on 'nexus studies' at household and community level quite diluting (eg. a study of solar powered kW pumping from a river for irrigating a field) and counter productive. The significant synergies and gains to be made are at the larger scales, where long term policy making and sustainable infrastructure development are the drivers.
m. Not 100% sure that I have understood the question. I think that the nexus approach can be easily implemented/understood in the micro scale (i.e., hydropower plant). It is less understood also because it is more difficult to model and data becomes an issue in the macroscale for instance on a regional or national level. In general, I think that it is easier to implement certain subsets of nexus inter-linkages when there is only one entity involved. For instance on the micro-scale, a farmer can easily implement the food-water-energy nexus because the farmer is managing them at the same time and can optimize the fluxes from an economic or environmental perspective for instance. The farmer has also a better knowledge of the direct data involved in this process. At a macro level, different entities (water food and energy management agencies) are involved making the implementation of the nexus more challenging.
n. In order to ensure sustainable withdrawals and supply of freshwater to address water scarcity, and to implement integrated water resources management at all levels (targets 6.4 and 6.5 of the SDGs), an essential baseline is the assessment of available and exploitable water resources at local level, as well as its development feasibility.

Significant variables as the rate of water withdrawal/consumption and the available water supply produce a valuable indicator of relative water use and the ability of water resource systems to provide the services needed. Large uncertainties in current estimates of global water withdrawals complicate good assessments of relative water use (Castanier, H. 2020. “Assessment of Local Water Resources for Sustainable Development Goals”. EGU General Assembly 2020).

o. In irrigation landscapes, the linkage between electricity consumption for pumping and groundwater availability, and the one between crop irrigation demand and irrigation water need can be better implemented if the data is available. I think the nexus approach will work less effectively at the individual scales but more on the regional scales.
p. Yes, certain subsets that occur in larger grids that impact more people. Classic example is water usage in California--hydro vs. salmon habitat vs irrigation.
q. Yes, subsets, such as water-energy, water-food (see above, and responses to Q5a). Unfortunately in most cases, tradeoffs prevail over synergies. For example, energy production from hydropower (e.g., 3-Gorges Dam in China, Assuan Dam on the Nile), water transfers for irrigation/food production (e.g., Iran's Karoun River, Central Asia's Amu Darya River - Aral Sea) are favored over synergistic projects that keep water in the landscape and allow the best use of green water, rather than blue water.
r. I cannot say for sure a situation in which it is easier to implement nexus concepts. I have the felling that since there is data being measured it is possible to start dealing with the problem.
s. I think there has been a lot of improvement in the water-nexus space because there is often a direct economic argument, or an indirect economic argument (e.g., running out of water is an economic liability in a supply chain), so entities are very interested in reducing their energy footprint (i.e., ~carbon mitigation) or their vulnerability to water shortages (e.g., ~climate adaptation). There are win-wins in terms of corporate perception to public, as well as the bottom line. For other nexus interactions, for example ecological or social linkages, I think there is a harder business case, so there hasn’t been as much progress on these fronts. But it seems like public pressure really moves the needle on these issues so more education and awareness is key.

Supplementary Note 8. LIST OF ORIGINAL ANSWERS TO CHALLENGES & FUTURE DIRECTIONS QUESTIONS

1. What do you think are the main challenges in applying a nexus approach in practice?
    a. The multiple spatial and temporal scales at which systems are connected and governed have complex implications for decision making; questions like 'for who? What values to optimise? Who imposes constraints?' are never clear enough to demarcate boundaries. This makes ' the nexus approach' difficult, and hence the diversity of 'nexus approaches' seen in literature.

b. 1. Professionals who are in a position to implement nexus approaches have not been trained on them, do not understand them, or have been trained to rely on their own sectoral tools. 2. The design of decision making institutions such as government bodies that does not encourage nexus planning. 3. Nexus approaches can make traditional decision making institutions and people look bad if it shows that the approaches they have previously been taking have been inefficient/ineffective. 4. Institutional inertia--it's just easier to continue doing the same thing than to change. 5. A lack of public awareness and education. Ultimately the public shapes the views and funding decision of elected officials, so if the general population understands nexus concepts, politicians and decision makers will learn to appreciate it as well. 6. The lack of a consistent/accepted approach. Other professions, like medicine, law, and engineering, have "standard practices" that professional societies can confidently recommend. The "nexus" community is diverse and complex, use different approaches and tools, and may be unable to recommend a single toolkit or methodology for approaching problems. Furthermore, all of the knowledge resides in academia, which the public sector tends to trust less, because it's viewed as "experimental" in a sense, rather than fact.
c. The primary challenge is that the food, energy and water sectors are managed independently (and in a segregated way) at all levels of governance (e.g., national, province, municipal). This segregated structure is then replicated by funding agencies, such as multilateral banks, and by providers of services, such as contractor companies. One question that is commonly raised by decision-makers in any of these organizations is how to ""operationalize"" the nexus approach. This basically means how to implement the nexus in practice for every day decision making. This question is raised in part to try to address this challenge."
d. "1) insufficient information due to weak monitoring especially in some sectors: The enrgy sector is very well monitored, the food sector is resonably well monitored, whereas the water sector is very weakly monitored leading to a lack or inaccurate information on botht he demand and the supply side. Digitalization and interoperability of the three sectors would allow the application of the nexus approach. In our work, wea re not considering ecossytems as part of the Nexus and the above is true also for this sector. 2) Understanding and implemening the feedbacks between the bio-physical component of the Nexus with the socio-economic component"
e. "A nexus approach" implies fundamental commonalities among different communities and different situations, and these commonalities do not necessarily exist. We need to decide in which situations a nexus approach is useful, and in which situations it is not. For the latter cases, we need to refrain from forcing academic models onto communities where it isn't useful.
f. I see two major challenges. The first is the reluctance of policy makers and administration officials to join forces and use integrated approaches (which would demand a nexus framework); the second is to develop a common language between academics and policy makers, which would allow both to progress towards nexus approaches.

g. Overcoming lock-in and legacy effects of current systems, both in terms of technological lock-in, as well as in terms of socio-political and cognitive lock-in and legacies.
h. Disciplines and methods are siloed and its difficult to integrate ideas to make decisions. Also, the human dimension of the nexus needs a lot of work.
i. data; not including issues that individual researchers are unfamiliar or ill-equipped to handle (for example: water-energy nexus researchers from engineering might not be trained in investigating equity issues as a fundamental research frame); not having language or disciplinary support for naming and acknowledging value frameworks
j. Data at the right scale. It is difficult to get data on how much water 1 kg food cost, or how much energy for 1 kg food. For all data you need to know these different dimensions, kJ/kg food, M3 water/kg food, kJ/m3 etc. We have done one effort with FAO data on national scale (Bijl et al. 2018, GEC). One of the challenges if moving to more detailed data is also the import/export and the way how you treat virtual water, virtual food and virtual energy. "
k. I think the current main issue is that academic, but also decision and system management environment are poorly structured for allowing Nexus approaches. Sectoral ministries, departments, programs or groups often tend to avoid multidisciplinarity, or try each to come up with in-house simple nexus approaches that are inefficiently replicated. This hinder exchange across disciplines, limits progress on the field and is a waste of resources.
l. Thinking about the governance perspective, I've found in my stakeholder engagements that some of the main challenges in applying the nexus approach in practice come from a few different areas. First, mismatches between the three sectors can cause difficulties in implementing nexus approaches. This includes different decision making timelines between food, energy, and water sectors and different levels of funding or personnel to devote towards cross-disciplinary work. Second, a lack of mutual benefit can be a challenge to implementation. If one organization/sector does not see a near-term and direct benefit from implementing cross-sector approaches (which may take more time, knowledge, and money), the organization/sector is not likely to choose the nexus approach. Decision-makers, resource managers, and other governance stakeholders are the keys to applying the nexus approach in practice, thus overcoming such challenges would provide a pathway towards broader implementation.
m. To develop an adequate detailed methodology that considers all the systems that are of interest for the policymakers/stakeholders requires some time. I find this particularly challenging, given the relatively short time that rulemakers stay in their positions (and assuming there is no continuinity across administratons). Another important challenge is to find an appropiate definiton of the interconnections across systems. It is difficult to see which are the effects and implications of a determined action in every system, particularly for high resolution studies with local or regional dynamics taking place.
n. First, let me say it is interesting to see around some researchers working on the water uptake by plant roots and calling it water-food nexus! So, what I am saying is that if we are talking about “our” systems scale nexus, then it has to be sponsored by a cabinet level authority or a consortium of industry and agencies from all sectors of the nexus. Without this, the nexus cannot be implemented in a comprehensive and sensible way.

Without this togetherness, there will always be challenges of missing data/information and operation details.

o. One of the most crucial challenges in the application are borders. Governmental structures alter which hampers the implementation of measures on the regional or worldwide scale. This is further exacerbated by unstable political conditions, which can lead to a departure from existing conditions at the local level at any time. Besides, bringing academic results closer to practitioners and political decision-makers might remain challenging. In addition, rising awareness in the broader society, particularly in a worldwide context could remain difficult due to a different perception of the world and locally varying relevant problems. On top, abrupt and unforeseeable changes in a system, as the current pandemic, can alter existing patterns, induce migration, and increase the pressure on systems, which can further prevent the implementation of nexus approaches.

p. 1) Reconciling the interests of scientists and stakeholders in a project (ensuring the relevant questions are assessed, managing expectations among); 2) Adequate planning of a project or application (which relates to the first point) by pre-assessing the nexus challenges, engage relevant stakeholders, and gather and/or develop the necessary expertise for meaningful insights (taking into account, for example, data access and availability, resources, and duration of the project); 3) Effective connection of the nexus approach with the policy cycle or the problem solving cycle, by going beyond the dissemination of results and expand the approach to the definition of policies or strategy and respective follow up; 4) development or creation of interministerial or interdisciplinary teams (depending on the context) that can support the policy and decision process mentioned in point 3; and, 5) existence of the necessary capacity and skills to incorporate the approach in decision-making processes.

q. Considering all nexus components or systems and the varying degree of emphasis of each one for specific cases as well as the different levels or scales, and the urgency for action, is fundamental the appropriate characterization of the energy-water-land nexus. For a consistent sustainability planning and decision making across spatial scales, regional and sub-regional economies, levels and sectors of management and policies, is evident the need of the definition of nexus principles and guidelines that would contribute to a management that ensures long term sustainable use of resources and development. The world's energy, water, and land systems are in transition and rapidly integrating, driven by forces such as socioeconomic, demographic, climatic, and technological changes as well as policies intended to meet Sustainable Development Goals (SDGs). The nexus principles for their application in practice should consider that natural resources as land and water are under increasing pressure and are vital for human survival, health and dignity and fundamental for human development, are conceptually finite and have an economic value. A participatory approach should be an indispensable requirement. The nexus approach requires reforms at all stages in the planning and management cycle.

r. I think one first aspect is related to education, people are not educated to integrated management or nexus or at least only few managers. Therefore, extremely related sectors continue to have siloed operational approaches. Most of those sectors are

extremely conservative (i.e., the energy and food management sector) and there is a consistent flux of money involved with strong lobbies that might hinder the application of the nexus approach (i.e., how water allocation is actually performed especially in case of water shortages). An opportunity but also a challenge of the nexus is that the nexus approach is by its nature a multi stakeholders approach (i.e., policy makers, business actors, investors, nongovernmental organizations and the entire society could take part of this process for discussing water-food-energy security issues). This makes things more complicated to manage from a decision making point of view. Besides this power relationships that can hinder the application and operationalization of the nexus there are also other challenges related to data and knowledge gaps and lack of decision support tools to apply the nexus. Decision support tools that not only look at economic aspects (i.e., the water allocation process most of the time is driven by the capacity of the m3 to generate revenues) but also to monetize indirect environmental and societal costs/revenues. Another challenge is related to operationalize/apply and combine the nexus directions with other directions related to meet other challenging phenomena or megatrends such as biodiversity, sustainable development goals, climate change, and resources scarcity. Another challenge is the spatial-temporal aspects of the nexus areas, most of the time they collide to each other. Geo-political (management) boundaries most of the time differs making the nexus areas management very difficult. Reference: Liu, J., Yang, H., Cudennec, C., Gain, A. K., Hoff, H., Lawford, R., ... & Zheng, C. (2017). Challenges in operationalizing the water–energy–food nexus. Hydrological Sciences Journal, 62(11), 1714-1720.

s. Our world has long been divided into different fields, professions, disciplines, departments... etc. with increasing discrepancies in ideology, jargon, technical languages that prevent proper communication and integration. That I think is one of the main challenges in applying a nexus approach in practice.

t. I think one major challenge is to shift from a research mindset of creating brand new methodologies from scratch over and over again, and coming up with strategies to compare, test, and validate the ones we already have, so that we can iterate and improve. This is very slow work, and it is not rewarded with publication, so getting the community to consider this type of exercise is going to be very difficult. But without it, there seems to be very little utility in developing frameworks in the first place.

2. What do you think are the most important questions in nexus research in the next decade and the next five decades, respectively?

    a. 1. What are the biggest drivers and processes that need to be better represented and included in models? 2. What kinds of modeling approaches are working and not working, and in what contexts should they be used? There are so many models and tools and approaches that it's hard to recommend as a community what techniques should be applied in any given circumstance. 3. How can institutions be better designed to facilitate decision making across sectors? 4. How can we effectively capture humans in our models? 5. How can we get multiple disciplines educated on the effectiveness of nexus thinking, i.e., how to better train the next generation of scientists/engineers? 6. How can we educate and communicate with the public and decision makers? The tools

are there, we just need a community that presents a consistent voice about the value of what we offer.

b. Next 10-20 years: fully coupled, high spatial and temporal resolution food-energy-water nexus models, with climate and socioeconomics linkages (the latter around global efforts such as IPCC and SDG efforts; development in parallel with ML/DL/AI and other computing science and technology. Next 50-60 years: expansion of the coupled nexus approach to include other major societal issues such as health/disease, biodiversity, earth system science (rather than solely climate), human development (economic development, poverty, violence). This research will involve conceptualization, model development, operationalization, MEL (monitoring, evaluation and learning) and should improve its connection and involvement of stakeholders and decision-makers across sectors and types of societal actors (public, private, etc)."
c. Next decade: not sure is the most important, but surely relevant, is to understand how soultions for optimal resource efficiency vary with the (local) mix of available resources. Next five decades: implement procedures for a NEXUS compliant long term planning (including ecosystems and socio-economic components) able to account for shocks (both natural as extreme weatthr events and economic)"
d. I think water shortages and changing food landscapes will be bigger challenges than energy. Energy research already has some very bright minds, and a lot of money, behind it. But water will always be a finite resource, and the food-producing capacity of a region will always be a finite resource. So I expect that these two legs of the nexus will create the biggest challenges.
e. I don't see major research questions pending: we have the capacity to model quite well complex nexus approaches (except interactions with climate change). But, as mentioned before, we need to apply our knowledge to real policy issues, and this may require adapting our research to policy makers needs and languages. As for research, as I said being able to connect regionally-detailed climate change models with nexus models will be very important to understand these impacts.
f. How do we redesign current systems of resource extraction, use, and reuse/waste, in a transition towards sustainability? How do we establish adequate governance systems that enable such transitions, which are also inclusive of different stakeholder perspectives and respect environmental justice issues?
g. How will migration alter food, energy, water requirements and impacts? How will climate change impact the nexus in 50 years? How will the impacts of climate change through the nexus be inequitably distributed over the next 50 years?
h. What do we need to focus on beyond GHGs? and how does climate change (including both physical and social impacts) affect our analyses?
i. To couple the work of nexus with the ssp scenarios in a harmonized way so decisions can be taken that show clear consequences on land use, biodiversity, water use, co2 emmissions etc in a fully integrated way. We have done a first attempt (van Vuuren et al. 2019, Nature sustainability)
j. Next decade: 1. How to pursue SDGs in multiple sectors, while knowing trade-off and challenges across sectors; 2. How to include ecosystems in our planning and decision framework for any type of policy; 3. What are the social nd environmental

consequences of findings of Nexus studies. Next five decades: 1. How to pursue SDGs in multiple sectors, in the most efficient way and limiting damaging in each sectors considered; 2. challenges of climate change impact on sustainable development goals across sectors

k. In the nexus decade, I believe there needs to be an increasing focus on implementation: How can we implement nexus approaches be implemented in practice? Additionally, I think there needs to be an increasing focus on empirically identifying and measuring the benefits of nexus approaches over siloed approaches.
l. I think that onekey aspect is going to be to analyze the effects of each policy/action in different systems such as climate, energy (access and security), land use, water (availability and pollution), air quality, agriculture, vegetation as well as the macroeconomic implications (welfare, employment). Although all of them are important, the importance of each system would be determined by the regional characteristics/problems.
m. For the next decade, we will be busy answering the following questions: (1) What is considered a nexus and what is not nexus? (2) Does it really help? How does it matter? (3) water-minded people will keep asking, how different is this from Integrated Water Resources Management?
n. 1) Making the approach accessible in a practical manner to decision-makers, beyond academia and scientific research; 2) Down-scaling applications to sub-national cases with meaningful and useful results; 3) Improving data available for nexus studies; 4) Transferring knowledge across fields of work and sectors in order to support the implementation of the studies and their impact; 5) systematic uncertainty analysis; 6) moving towards dynamic representation of systems (e.g. in partiuclar the impacts to climate from management and policy decisions).
o. The questions in nexus research in the next decade should be focused to advance in the conceptual framework of the energy-water-land nexus, sharing the findings of ongoing research and promoting training at all levels, as well as following up applications in practice, including further research related to the main results. Besides continuing with research questions of the 2020-2030 decade, for the next five decades will be necessary the study and analysis of the most successful applications of nexus approach, as well as being flexible in relation to the adaptation to new research trends, according to the corresponding systems dynamics. Advance and strengthen the design of interdisciplinary models based on successful previous applications, as the case of sustainability planning and assessment.
p. Mapping the data availability and unavailability (considering spatial temporal issues) and promote the building of dataset to bridge this gap. Developing large scale integrated models to study (i.e., model and optimize) the nexus interrelationships across countries, and management units. Operationalize the nexus in terms of developing decision support systems based on the mathematical models developed. Another important research area should be the standardization of procedures, identification of linkages, and open-source codes community based.

q. How do we assess the benefit of applying a nexus approach in practice? What are the risks in this nexus future? What are the core knowledge base / fundamental subjects for students that are interested in this field of research?"
r. How do we design systems that are compliant with the missions of climate mitigation and climate adaptation (which are often at odds), that are also sustainable from economic, social, and environmental standpoints?

3. Do you believe that the amorphous scope and breadth of nexus research creates challenges for students in building core disciplinary strengths (i.e. expertise) within a focus area, or does it provide more opportunities? In other words, are we just branding a group of generalist scientists without deep expertise in a subject, or does the nexus, itself, present a separate discipline, where expertise can be developed?
    a. I do not believe we are merely branding generalists; I see myself and some peers as having actual expertise in two or more disciplines, which has enabled work that could not otherwise happen. A "jack of many trades and a master of a few" would be my description of nexus experts. A majority of the experts I have met happen to come from water and energy disciplines with some further expertise developed in computational and governance disciplines. I believe expertise can be developed in the discipline in this sense, going well beyond what you would make of an integrated water resources manager.
    b. The nexus itself represents its own discipline, in the same way that integrated assessment does. Students should train to receive disciplinary depth, such as in hydrology, but should then receive equal training on multi-sector dynamic thinking, to most effectively contribute to nexus research/practice.
    c. Nexus thinking is perhaps a subfield within the more general field(s) of systems thinking, complex systems, and similar. While this may create challenges for students, my sense is that nexus thinking (and corresponding approaches for implementing it in practice) is in itself a discipline (or perhaps a subdiscipline) where expertise can be developed (for instance, nexus modeling tools, nexus monitoring approaches, nexus systems performance metrics).
    d. I don't think we are branding a group of genarlist scientist, rather what we need is scientist that are trained to communicate with scientists of different disciplines. I don't think we need a NEXUS expert that does not have an expertise in any of the sectors, but an expert in one discipline that understands the "language" of the other sectors. In my view, even at governace level, we should not have a single person that knows how to put the pieces together but rather some sort of permanent committee that works together. Perhaps, a framework with similarities woth the Multi-actor approach.
    e. I think subject experts in their own disciplines should work together and share ideas, but I don't think the nexus is a new discipline.
    f. I don't think the nexus is a separate discipline: it is a synergistic combination of several disciplines, which need to work together.
    g. Many of the sustainability issues we are facing are a result of focusing only on narrow expertise, and neglecting a perspective of the wider issues and the context within which this specialty expertise is developed. Expertise at the interfaces between disciplines is

badly needed, and can develop as a field of expertise in itself. The human mind is surely capable of developing depth and breadth at the same time - it is just a matter of educating students in both directions.

h. There is nothing wrong with the "generalist" scientist focused on the nexus. They might be a generalist according to the old definition of disciplines but they have deep expertise in one specific topic, which is the nexus.
i. Expertise can be developed. but we need to retain a specific expertise -- systems analysis, decision analysis, etc. are specific, learnable skills that are not the same as "I looked at both of these issues and determined XYZ." my own opinion is that training should focus more explicitly on method and rigorous applications of specific methods, rather than enabling ad hoc application of quantitative analyses not grounded in specific investigative frameworks
j. The most important part in here is that students need to learn system thinking. Although System Thinking has a large history in environmental and sustainability science (for instance Meadows), it is often seen as a difficult step for students and staff, as it asks for integration and interdisciplinary thinking. Nevertheless I think it is highly important that students learn this skill. (PS Im the director of education of the copernicus institute of sustainable development at Utrecht University which is the largest sustainability institute in number of students in Europe (1800 students both undergraduate and at master level). It is a large ambition to bring system analyses in all programs we have)
k. Given the challenge of existing structure with poorly connected sector-specific compartments, even general scientists who can bridge across departments are important. However, at least my experience show that even people with broad formation tend then to focus their expertise on more focused areas. So I don't think amorphous scope is an issue.
l. I believe the broad scope of nexus research can create challenges for students to develop strengths in specific focus areas. Since students have to focus on three topical areas (food, energy, and water) in addition to the synergies between them, it can lead to generalist science that is not deep within any specific field. However, I believe that this can be overcome by establishing strong disciplinary skills and knowledge that can then be implemented within the context of the food-energy-water nexus. For example, an anthropology student could develop strong methodological training in ethnography but apply that training to a case of household food-energy-water access. In this way, I believe the nexus offers opportunities for students to implement theory and methodology to the tangible and relevant concept of the FEW nexus, though students must make intentional efforts to ensure depth of science within their field beyond just the application to the FEW nexus.
m. I think there should be students with the technical capabilities to develop this kind of nexus models/methodologies. However, as it is happening right now, these researchers would need to co-work with experts in different subjects to develop and improve their methods.
n. Interesting question! There are challenges if the nexus work is conducted by a single student. It is more suitable for large research groups where individuals can be

specialized and postdocs, for example, can lead the synthesis efforts to do the nexus research. However, I have to say that individuals can still do nexus research if perceived as “systems research”. So, students will be experts in modeling, analysis, simulation, and optimizations of systems. Their application area will be “integrated resources management”. So, it is still possible and it opens the door for new opportunities for students.

o. A broad understanding of systems (as a generalist) is critical to see the big picture and allows measures to be addressed in a targeted manner. These generalists will act like managers that cooperate with experts of all fields. They will be able to extract the relevant findings and link all parts together. Hence, creating interdisciplinary experts will not only bring opportunities it is, from my understanding, a key to allow a successful nexus approach implementation.
p. The incorporation of the nexus research in academic curricula depends on the level of studies. In bachelor level studies, emphasis could be given to interdisciplinarity in relation to the core subject under study (e.g. if the core subject is water systems, then an interdisciplinary course could be taught that explores how water is linked to the systems of food, climate, energy and land, or other systems; and how decisions in the different systems affect water, and vice-versa). At the MSc level, the nexus can be studied with more depth by exploring cross-sectoral challenges and the development of nexus case studies; and then we get to the doctoral level, where students will investigate in-depth nexus issues and advance the knowledge. I think it is key to understand what what knowledge and skills should be developed at higher-level education that will be important for future professionals to have, that will likely be the decision makers of the future.
q. Personally, I think the students should have both. I think students should be expert in one field but at the same time be able to relate that field to other fields (to have a system perspective view). After their education, they can decide where to work but still their mind has been shaped to system perspective (nexus perspective). I also believe that the nexus area has potentials to develop specialists in this particular sector and then master courses could be developed to train such students. For instance, bachelor in a specific field and master on the nexus. I think that your question depends also on the market. If the market requires more specialist on the nexus (i.e., professional figures that are able to interact with energy, water, and food specialists, professional figures which have command on their own vocabularies), then of course education institutions should responds to the market with 5-years courses on the nexus. Probably, some of them already exists such as environmental engineering courses were students deal with air, water, and energy (less on food). To summarize, I think it depends on the market to have special courses (5 year courses) on the nexus, but in any case I would prefer to give the students a blended education (i.e., focus on one area and at the same time nexus perspective education).
r. I think we need to develop a balance of both. I do fear that we are creating too many generalists after decades of putting no value on it. We need specialists and then we need people to connect the dots of that work. I see both as critical. I also worry that we are creating a research regime in which too many people are jumping into areas that

they have no understanding of. People that know a generic modeling techniques (e.g., AI, Bayesian stats, etc.) apply those as hammers in domains that they don't understand, with data they don't understand. Whereas, there are a lot of subject matter experts sloppily applying black box models that they don't understand (e.g., AI). Both are really terrible practices. These communities need to come together, but we get back to the issue that academia celebrates fast, frequent publishing, and progress will be made on slow, thoughtful collaborations.

4. Is the potential for innovative solutions sufficiently represented in nexus studies? Are nexus models ready to represent not only incremental innovation but disruptive/systemic change as well as extreme events, shocks, migration?
    a. Yes, in some toolkits/approaches, but not in all. One challenge is that there are so many teams working on so many "nexus" style issues that it's unclear which approaches can handle what kinds of problems. Someone needs to develop almost a typology of the approaches that exist and in what circumstances they should be used. Not a literature review, but more of a guide as to what techniques can be applied in what circumstances, and what the drawbacks are.
    b. I think we have a variety (or spectrum) of tools and models, so the answer here may be ""evolutionary"" (incremental innovation) rather than fully ""revolutionary"" (disruptive innovation). For instance, in a large subset of the newer research on nexus (such as NSF's INFEWS projects), the projects funded aim to ""stitch"" together existing modeling tools (water, energy, and food) rather than develop coupled/integrated models from ""scratch"". My sense is that will start to yield new models that will be used, we will learn from them, and then continue to develop more evolved ones.
    c. Is the potential for innovative solutions sufficiently represented in nexus studies? I think the potential is well represented even if the whole range of possibilities is still not clear. Are nexus models ready to represent not only incremental innovation but disruptive/systemic change as well as extreme events, shocks, migration? See my answer above: I think this is one main research question/challange that needs to be addressed. But many models are ready to do so, at least for some components. Surely, economic models have consolidated procedures and also several methodologies have been implemented to simualte the effects of extreme weather events on hydrology (hydrological risk) and agriculutral production. however, these models only account for a part of the nexus and how the impacts propagate to otehr sectors is largely unknown.
    d. I have not seen this yet. It would be very cool to see.
    e. This is always difficult to represent in many models, and it requires a change in paradigm, not only in terms of the scenarios and dynamics modeled, but also in terms of the solutions found, which need to be robust in the face of this radical uncertainty.
    f. Not yet, the shocks and migrations are yet to be resolved. We need much more research on that. Extreme event research is understood relatively well.
    g. I don't think so, largely because I don't think most nexus practitioners have the expertise to really consider these broader issues. a focus on method and theory could help, I think, but so too can a general emphasis on learning and understanding physical

constraints and specific spatiotemporal considerations that don't make it into large (and often economics-grounded) models

h. No: I think the models are only able to simulate different policy options, they will not able to model sudden events. In a way similar to economic models, only trends and consequences of new policies. We're not able to predict shocks in the future

i. I think the potential for innovative solutions is not sufficiently represented in current nexus outcomes. The proof of it is that many teams, which also develop nexus tools, uses simplified tool for most of their analysis, exploring in this way limited solutions. This is mostly of the time due to the complexity of nexus tools both in development phase, but also for applications. I think nexus tools are ready to include disruptive changes, extreme event, etc., by including pre-existing applications.

j. I think that nexus models provide opportunity for incremental or adaptive change, but I think this is realistic for stakeholders and decision-makers. In stakeholder engagements that I've conducted, decision-makers (e.g., water managers, irrigation district managers, electrical utilities) have noted that they prefer approaches to incremental change over transformative change. The FEW nexus seeks to move resource management forward by considering the synergies between the three resources--but it doesn't present a complete system transformation that would push the system into a new state. However, just because the FEW nexus isn't a transformative innovation doesn't mean it doesn't address extreme events and shocks. Adaptive approaches can provide opportunities for incremental shifts in a system that make the system better prepared to address such shocks, either by leading towards a system with reduced impact from said shock or by increasing the resilience of the system to bounce back faster and easier after it.

k. I don’t think I have seen yet major innovative solutions, but it certainly depends on the location of the study. In certain areas, innovative solutions might emerge based on the nexus analysis. One obvious area in my opinion is transboundary river conflicts, where a conflict over water resources can be reframed under nexus approach, and innovative solutions can be proposed. This can show that in reality we cannot, and should not, attempt to strike deals focused only on a single resource, but rather integrated resources; e.g. water-energy-food resources.

l. I see challenges in the application caused by disruptive changes and extreme events which will induce alterations that cannot be anticipated during the development of nexus approaches. However, as with all models, these kinds of changes almost always lead to a high uncertainty or failure of the model which, on the other hand, cannot be an argument for not developing a model according to the best available knowledge. However, the risk of extreme events and changes should not be ignored, and potential impacts should be described in advance. The application of nexus studies must be understood as a dynamic process that does not stop once the model is implemented. A continuous adaptation to changes (i.e., change management) is crucial to guarantee a long-term sustainable approach.

m. Not really, and this should be explored further. Innovations are limitedly included in nexus studies, which then limits the emerging range of solutions coming out of a study. This can then potentially undermine the perception of the approach by decision-makers and negatively influence its uptake. In the topic of nexus and innovations, I recommend

a recent paper by Davine et al. (2020): Janssen, D.N.G., Ramos, E.P., Linderhof, V., Polman, N., Laspidou, C., Fokkinga, D., Sousa, D. de M. e, 2020. The Climate, Land, Energy, Water and Food Nexus Challenge in a Land Scarce Country: Innovations in the Netherlands. Sustainability 12, 10491. https://doi.org/10.3390/su122410491

n. Being the nexus approach a bridge between disciplines in a coordinated and coherent effort, its potential for innovative solutions is sufficiently represented in nexus studies. In consideration that disruptive/systemic change, as well as extreme events, shocks, migration, are usually the effects of a combination of drivers, the models of the interdisciplinary nexus approach represent adequate tools to better understand and manage these natural or anthropogenic events.
o. To answer this question, I mention again the lack of standards in modelling the nexus and the lack of a community to develop an open-source model can hinder what you are asking. There are serval technologies and applications of several technologies that can significantly affect the nexus but are somehow confined to a close group of researchers focused only on that technology. It might be hard to elevate it at the nexus perspective. For instance, two simple technologies such as PV water pumping system and agrivoltaic can have a significant impact on the nexus but still most of the time are related to a close group of researchers. As concerns your second question, I think that existing models could easily be adapted to simulate extreme events in terms of extreme weather events but more difficult to model how the nexus could be affected by other extreme events such as wars and shocks (also difficult to predicts). Nevertheless, I think that an integrated and large-scale (for instance continent-based) water-food-energy model could quite easily demonstrate where migration are more likely to happen. This can be easily verified with climate data and mass balance models. There are several articles that relate for instance droughts to migration and wars (i.e., wars induced by lack of energy, water and food supply and not by geopolitical issues).
p. In my opinion, there have been significant cases of innovative WFE nexus solutions developed in the past decades, however, many of them refers to general nexus concepts; the others are solutions for specific resources in certain geographic area. The challenge is that there are countless types of resources with various nexus characteristics and we do not yet have a thorough typology for different types of nexus interactions. In my opinion, we have made significant progress in nexus studies, but the disruptive/systemic change in the practice is yet to come.
q. I think that big data techniques, like AI and data mining, will be disruptive, because information gathering and data collection will not be as dependent on the limitations of a human researcher. But like I mentioned before, collaboration between CS and domain experts will be critical to making this successful.