Science of the Total Environment 693 (2019) 133662

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Ten principles to integrate the water-energy-land nexus with climate services for co-producing local and regional integrated assessments

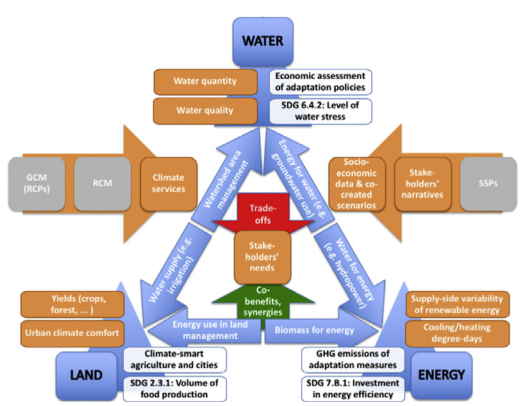
Roger Cremades[a,*], Hermine Mitter[b], Nicu Constantin Tudose[c], Anabel Sanchez-Plaza[d], Anil Graves[e], Annelies Broekman[d], Steffen Bender[a], Carlo Giupponi[f], Phoebe Koundouri[g], Muhamad Bahri[a], Sorin Cheval[c,h,i], Jörg Cortekar[a], Yamir Moreno[j,k,l], Oscar Melo[m], Katrin Karner[b], Cezar Ungurean[c], Serban Octavian Davidescu[c], Bernadette Kropf[b], Floor Brouwer[n], Mirabela Marin[c,o]

[a] Climate Service Center Germany (GERICS), Chilehaus Eingang B, Fischertwiete 1, 20095 Hamburg, Germany
[b] Institute for Sustainable Economic Development, Department of Economics and Social Sciences, University of Natural Resources and Life Sciences, Vienna (BOKU), Feistmantelstrasse 4, 1180 Vienna, Austria
[c] National Institute for Research and Development in Forestry "Marin Dracea" (INCDS), Bulevardul Eroilor No. 128, Voluntari, 077190 Jud. Ilfov, Romania
[d] CREAF, Centre de Recerca Ecològica i Aplicacions Forestals, E08193 Bellaterra (Cerdanyola de Vallès), Catalonia, Spain
[e] Cranfield University, Cranfield, Bedfordshire MK43 0AL, United Kingdom
[f] Ca' Foscari University of Venice, Department of Economics, Cannaregio 873, I-30121 Venice, Italy
[g] Research laboratory on Socio-Economic and Environmental Sustainability (ReSEES), School of Economics, Athens University of Economics and Business, 76 Patission Str., GR-10434 Athens, Greece
[h] "Henri Coandă" Air Force Academy, 160 Mihai Viteazul Str., 500183 Brașov, Romania
[i] National Meteorological Administration, 97 București-Ploiești Str., Sector 1, 013686 Bucharest, Romania
[j] Institute for Biocomputation and Physics of Complex Systems, University of Zaragoza, Zaragoza, Spain
[k] Department of Theoretical Physics, University of Zaragoza, Zaragoza, Spain
[l] ISI Foundation, Turin, Italy
[m] Department of Agricultural Economics of the Pontificia Universidad Católica de Chile, Santiago, Chile
[n] Wageningen Research, PO Box 29703, 2502 LS The Hague, the Netherlands
[o] Transilvania University of Brasov, B-dul Eroilor nr. 29, Brașov, Romania

HIGHLIGHTS

- First-of-its-kind guidance on combining climate services with the water-energy-land nexus
- New definition of the nexus based on networks and complexity science
- A set of 10 guiding principles for local to regional cross-sectoral integrated assessment
- Guiding questions to compare nexus case studies

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 15 May 2019
Received in revised form 22 July 2019

ABSTRACT

The water-energy-land nexus requires long-sighted approaches that help avoid maladaptive pathways to ensure its promise to deliver insights and tools that improve policy-making. Climate services can form the foundation to avoid myopia in nexus studies by providing information about how climate change will alter

*Corresponding author.
E-mail address: roger.cremades@hzg.de (R. Cremades).

https://doi.org/10.1016/j.scitotenv.2019.133662

Accepted 28 July 2019
Available online 29 July 2019

Editor: Badea Ovidiu

Keywords:
Stakeholder
Climate change
Multilayer network
Co-production
Nexus
Climate services

the balance of nexus resources and the nature of their interactions. Nexus studies can help climate services by providing information about the implications of climate-informed decisions for other economic sectors across nexus resources. First-of-its-kind guidance is provided to combine nexus studies and climate services. The guidance consists of ten principles and a visual guide, which are discussed together with questions to compare diverse case studies and with examples to support the application of the principles.

1. Introduction

The water-energy-land nexus, prominently including food among its multiple ecosystem services, is a methodological approach to resource management that draws attention to the complex, linked, and limited nature of resources that are used to achieve competing objectives. The approach has been developed in order to support the provision of coherent and sustainable policies touching upon multiple resource uses and linked ecosystem services (Cremades et al., 2016; Conway et al., 2015; Hoff, 2011). Climate services are provided by transforming data from climate models, together with data from local and regional socioeconomic and environmental systems, into products and information useful for individuals, organisations, and decision- and policy-makers. Climate services are co-developed with diverse societal actors mostly to support adaptation to climate change, but also to mitigate the emissions of greenhouse gases (Street, 2016; Hewitt et al., 2012).

A major risk of using the nexus approach without considering data from climate models is that climate change may gradually alter the balance between the resources involved in the nexus, and even

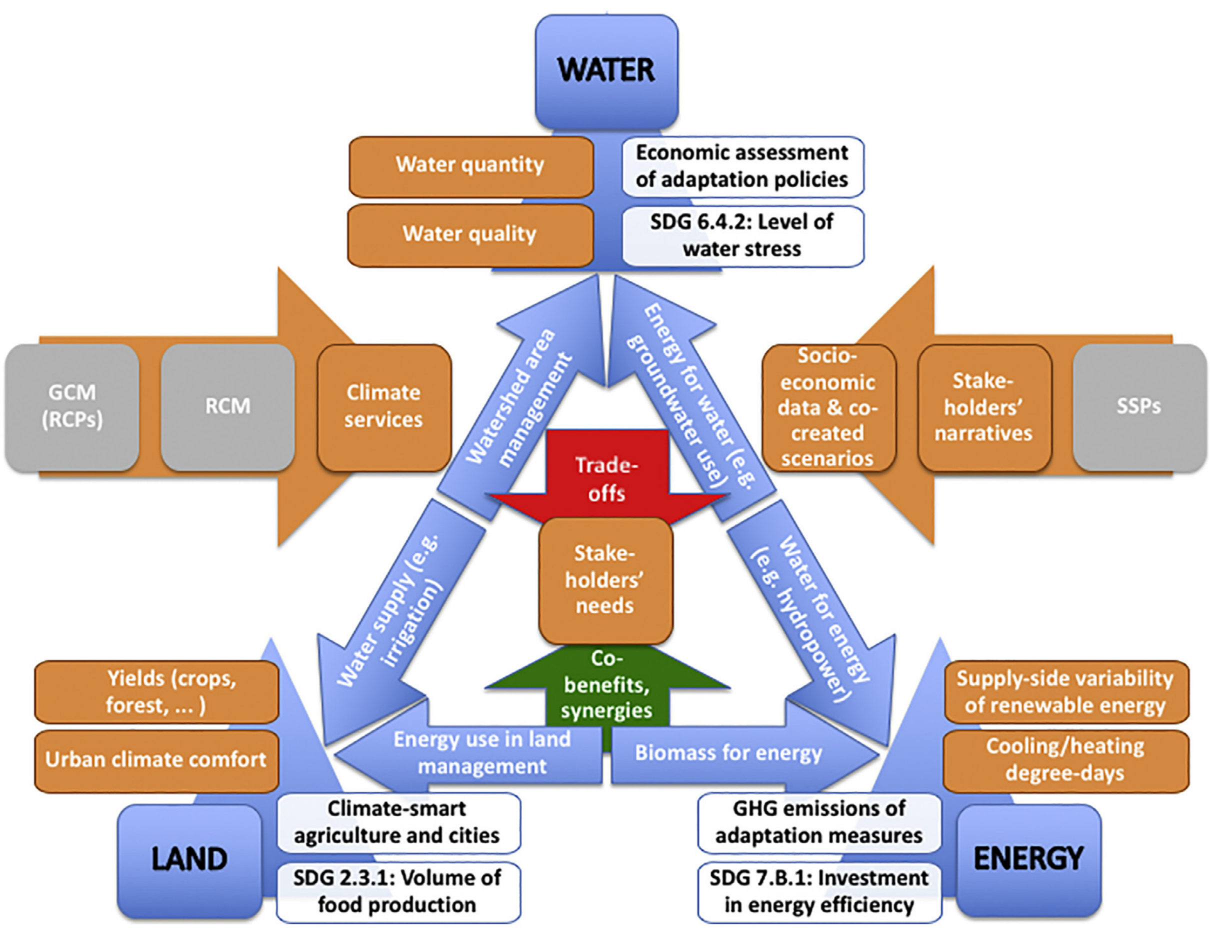


Fig. 1. A visual guide with examples integrating data from climate services in nexus-related assessments and analyses with relevance to sustainability policies. The ultimate goal of using climate services and the nexus together is to fulfil stakeholder's needs (centre of figure), which involve economic activities in multiple economic sectors that are relevant for the achievement of environmental targets like the SDGs (Sustainable Development Goals) and for the design of pathways towards these targets. Pursuing synergies when possible, and managing resource scarcity and trade-offs across multiple activities (centre of the figure), become a necessity across linked resources. A diversity of non-exhaustive examples of activities linking the resources of the nexus (blue arrows) is shown. All elements related to climate services appear in orange. For instance, they include the central role of the needs of stakeholders, the incorporation of their narratives in scenarios, and the transformation of the relevant climate data into impact data approaching the stakeholder's variables of interest. There is a particular reference to examples of climate services (orange, next to each resource) for water, land and energy that can be expected to require a nexus integration. The white boxes, again next to the resources, exemplify nexus-related assessments and analyses related to sustainability policies and the SDGs. Data from climate models (GCM, RCM) and international scenario frameworks for climate and society (RCPs, SSPs) appear in grey. Note: GCM stands for general circulation model, RCP for representative concentration pathway, RCM for regional climate mode, and SSP for shared socio-economic pathway. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the nature of their interactions. Likewise, a major risk of developing sector-specific climate services without considering the nexus, is that trying to adapt a sector to climate change could have unintended and undesirable consequences across economic sectors and scales. The risks here are unexpected trade-offs across resources (see Fig. 1) impacting negatively across stakeholders, sectors and even societal goals. These trade-offs across economic sectors and resources cannot be evaluated without understanding, and often quantifying, the nexus between resources shared by different sectors and activities.

In this discussion article the authors claim that integrating climate services with the nexus is essential to support local and regional integrated modelling approaches across different scales, resources, and economic sectors, and that their joint use is fundamental to increase the societal understanding of trade-offs and co-benefits of actual or proposed policies and scenarios (Cremades et al., 2016). This integration is absent in the literature to the best of our knowledge. The discussion article provides guidance on developing the integration of climate services and the water-energy-land nexus, and in particular, it aims to:

i) justify the need for combining climate services and the nexus approach for cross-scale and cross-sector policy, sustainability and resilience modelling and assessment;
ii) provide a knowledge-base for a scoping analysis in specific cases, to decide whether climate services and the nexus approach are necessary complements to prevent negative trade-offs and maladaptation, defined as "an action taken ostensibly to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems, sectors or social groups" (Barnett and O'Neill, 2010) or as actions that could "have detrimental impacts on the territory, sector, or group of people conducting the initiative"(Magnan et al., 2016);
iii) provide first-of-its-kind guidance on how to explore the co-beneficial space across the linked use of multiple resources across economic sectors and scales, and their related societal goals, like the Sustainable Development Goals of the Agenda 2030 (Boas et al., 2016) under climate change and diverse socio-economic development pathways represented in scenarios, and
iv) advise how to co-produce new tools with societal actors by improving the level of detail and usability of integrated assessments based on modelling of adaptation to, and mitigation of, climate change at the local and regional scale, accounting for the multiple sectors involved and for the links to the global scale.

2. A knowledge base for determining when to combine climate services and the nexus

Decisions involving adaptation to climate change impacts and mitigation of greenhouse gas emissions involve potential trade-offs across economic sectors and temporal and spatial scales; these trade-offs might include increased greenhouse gas emissions (Cremades et al., 2016), feedback loops between increased water supply and urban growth (Nair et al., 2014), social inequality (Romero-Lankao and Gnatz, 2019), or other unintended negative consequences affecting one or many SDGs, which need to be considered to avoid maladaptation. The water-energy-land nexus offers a window of opportunity for modelling, understanding, and in some cases preventing, these trade-offs and their interdependencies across stakeholders, sectors and anthropogenic and natural systems, and thus helps to provide comprehensive climate services that avoid maladaptation. A scoping activity is required when considering the nexus, to evaluate to which extent its resources and their interactions could be affected by climatic and socio-economic change, and to evaluate the future validity of the nexus insights provided under current and past climatic conditions.

By integrating stakeholders' knowledge and requirements with multiple socio-economic and environmental data sources to support societal decision-making, climate services use data from climate models to co-design solutions with inputs and data from various sources, and answer questions related to climate change adaptation and mitigation from policy-makers, decision-makers, business people and practitioners (Street, 2016). These information sources can be the basis for mathematical models, decision-support tools and tailored information that aim to reduce climate risks, to generate favourable social and environmental conditions, and to create economic benefits across sectors and temporal and spatial scales, by preventing and reducing the cost of damages and inaction, and by supporting new opportunities.

This discussion article presents a novel set of ten principles to integrate the water-energy-land nexus with climate services. This integration aims at generating climate services with quantitative cross-scale and -sector policy modelling and assessment to support the achievement of sustainability targets and co-design pathways leading to them. This integration involves the use of the water-energy-land nexus approach to tackle the diversity of stakeholders' needs. These needs include their policy, practice and business challenges related to planning and management of natural resources under climatic and socio-economic change within and across economic sectors and systems, e.g. water, urban, tourism, forestry, energy, and agriculture.

These ten guiding principles are based on the experience of the authors on the water-energy-land nexus and on climate services, on the lessons learned from case studies and approaches in several climate services and nexus-related projects (e.g. CLISWELN, DAFNE, NextAg, SIM4NEXUS, EU-MACS, ADMIT), on stakeholder-related activities of co-design, co-production, and co-dissemination in these projects (Mauser et al., 2013), and on multiple related articles produced by the authors on these topics (Zou et al., 2015; Schönhart et al., 2018; Morales et al., 2005; Reed et al., 2009; Kulak et al., 2013; Bowyer et al., 2015; Benson et al., 2017; Gain et al., 2015; Ioja et al., 2017; Pardoe et al., 2018; Fercovic et al., 2019; Brouwer et al., 2018; Cremades et al., 2016; Koundouri and Rulleau, 2019). Albeit this is a thought piece in the shape of a discussion article, from a methodological perspective the principles below summarize the knowledge acquired during these projects, interactions with stakeholders, and articles. The lessons learned during these activities are generalised into principles, and include suggestions about the interaction between climate services and the nexus that have not been put together before. These principles are intended to be applicable across world regions and their related nexus and climate change challenges. Overall, these principles bridge the gap between climate services and the nexus by discussing approaches to a degree similar to those of the integrated assessment community, and make suggestions better suited to local- and regional-scale modelling. We use the term region to refer to the sub-national scale. These principles are supported by the visual guide above (see Fig. 1) and with the practical examples of application provided for each principle in Tables 1 and 2.

3. Ten principles for integrating the water-energy-land nexus with climate services

After these initial considerations, this discussion article presents the ten principles to integrate the water-energy-land nexus with climate services for cross-scale and -sector policy and sustainability modelling and assessment:

1. **Stakeholders and their needs should be carefully selected and integrated**. On the one hand, information should be developed upon the identification of stakeholders and their needs characterizing the nexus case under climate change (see Reed et al., 2009). On the other hand, it is necessary to integrate

Table 1
Examples about how to apply the principles 1 to 5 for integrating the water-energy-land nexus with climate services at different scales. Note: RCP stands for representative concentration pathway, and SSP for shared socio-economic pathway.

Scale	1. Stakeolders' needs	2. Nexus resources and system boundaries	3. Co-selection of climate variables	4. Socio-economic and climate scenarios	5. Time period of the analysis
Local, municipal, county-wide, or similar.	Cortekar et al. (2016) describe the customisation of climate services for urban stakeholders.	Wang and Chen (2016) define a nexus case study in an urban agglomeration.	Horton et al. (2011) co-selected climate variables related with urban infra-structure in New York city.	Koutroulis et al. (2016) analyse cross sectoral impacts of climate change in Crete.	Gaur et al. (2018) analyse the urban heat island in Canadian cities in 2026–2035, 2046–2055, and 2091–2100.
Province, State, or similar, including river basin.	Mehta et al. (2013) explore the climate information needs of stakeholders in the Missouri river basin.	Kibaroglu and Gürsoy (2015) set a nexus case study in a trans-boundary river basin.	Vogel et al. (2016) describe the integration of climate variables in the management of water utilities.	Kebede et al. (2018) apply RCP and SSP scenarios at sub-national scale in a participatory way.	Tan et al. (2017) analyse climate impacts on hydrology for the short- (2015–2044) and mid-terms (2045–2074).
National.	Lemos and Morehouse (2005) explore the co-production process in integrated assessments.	Zou et al. (2015) study the greenhouse gas emissions of water use in agricultural land use at the country scale in China.	Evans et al. (2014) prepared stakeholder workshops to co-design a climate modelling experiment in Australia.	Frame et al. (2018) adapt SSP scenarios for national use.	Mirasgedis et al. (2006) study the influence of meteorology on electricity demand for the mid-term (12 months in this community).
Supra-national, continental, or similar.	Kaspar et al. (2015) explain how SASSCAL covers the weather information needs of several agencies and activities in Africa.	Larsen and Drews (2019) study water use in the European energy system.	Tall et al. (2014) explain how relevant climate variables are selected with farmers in Africa and Asia.	Hejazi et al. (2014) make long-term water projections for fourteen geopolitical regions with ad-hoc socio-economic scenarios.	van Vuuren et al. (2012) discuss the need of scenarios with intervals for short-, mid- (20–40 years) and long-term analysis from present time until 2100.
Global.	Brasseur and Gallardo (2016) provide an overview of the difficulties faced by climate services when dealing with stakeholders' needs.	Rulli et al. (2016) research the nexus of biofuels globally.	Schuck-Zöller et al. (2017) provide criteria for evaluating the co-creation of climate information.	Parkinson et al. (2016) project future municipal water demand at global scale under SSP-RCP scenario combinations.	Schaeffer et al. (2015) provide detailed discussions on the interactions between short-, mid- and long-term in climate action.

stakeholders' knowledge and data (see Voinov and Bousquet, 2010). Tailored models, tools, and information for stakeholders should capture — quantitatively or qualitatively — the nexus linkages between different resources — water, land, energy — and their multiple ecosystem services within and across economic sectors. The focus of these models, tools, and information for stakeholders, should be on those linkages that can have significant consequences in the variables of interest for stakeholders and in the outcome in terms of sustainability under climate change.

2. **The relevant nexus resources and the system boundaries should define the case study area**. With respect to the system definition and delimitation, it is necessary to identify the

Table 2
Examples about how to apply the principles 6 to 10 for integrating the water-energy-land nexus with climate services at different scales. Note: SDG stands for sustainable development goal.

Scale	6. The nexus as a complex system	7. Nexus governance	8. Nexus economic analyses	9. Low-probability high-impact events	10. Synergies, co-benefits, and trade-offs
Local, municipal, county-wide, or similar.	Cremades and Sommer (2019) highlight fractals in the nexus between urban land use and energy consumption from mobility.	Halbe et al. (2015) research governance strategies for sustainability transitions in the nexus in Cyprus.	Wang and Chen (2016) use input-output tables to model the nexus in a metropolitan system.	Abadie et al. (2017) explore low-probability high-impact events in coastal cities.	Miller-Robbie et al. (2017) show co-benefits for water and energy in wastewater treatment plants in Hyderabad.
Province, State, or similar, including river basin.	Bahri et al. (2018) model the feedback loops of the water-energy-land nexus with a focus on urban growth and droughts in nearby river basins.	Pahl-Wostl (2017) highlights the multi-level coordination challenges of nexus governance.	Gaudard et al. (2018) show the interaction between electricity prices, streamflow and revenue under seasonal effects, which can alter the impact of climate.	Prime et al. (2015) show how hazards combine non-linearly in surge-wave-river coastal low-probability events.	Cremades et al. (2016) show co-benefits for lower water application and lower GHG emissions are attainable in irrigation modernization.
National.	Bazilian et al. (2011) suggests the use of systems thinking to address nexus issues in developing countries.	Benson et al. (2015) discuss merging the nexus approach with integrated water resources management.	Perrihan et al. (2017) explore the nexus with a general equilibrium model.	Stern et al. (2013) argue that just information alone cannot solve the challenges posed by climate impacts, and advocate for enhanced vulnerability science.	Pittock et al. (2013) explore inter-sectoral conflicts and trade-offs, and synergies emerging from climate change, energy and water policies.
Supra-national, continental, or similar.	Karlberg et al. (2015) discuss the complexity of the nexus in the sources of the Blue Nile.	Weitz et al. (2017) suggest to use integrative governance to close the governance gap in the nexus.	Cremades et al. (2016) elaborate on the economics of the nexus, with a focus on the adoption of irrigation technology in China.	Challinor et al. (2018) suggest the assessment of complex risk transmission mechanisms with multiple methods.	Conway et al. (2017) show how the correlation of climate risks can create hydropower supply disruption in Africa.
Global.	Scott et al. (2015) suggest a triad nexus approach to adaptive management for tackling global challenges.	Boas et al. (2016) identify avenues for the institutionalisation of the nexus between SDGs in global governance.	Lamperti et al. (2018) provide a genuine bottom-up approach that can be used in nexus global analyses.	Lenton and Ciscar (2013) explore the integration of climate tipping points in integrated assessments.	Mirzabaev et al. (2015) discuss the trade-offs and synergies of bioenergy, food security and poverty.

prominent nexus feature(s) of the particular case study, and the resources involved. Furthermore, the use of a nexus approach should be justified by the resource interlinkages, and climate change should be adequately considered for the analysis of the future dynamics. Each particular nexus case study is a subset of an entire human-Earth multilayer network. Fig. 2 displays an abstract representation of such multilayer network with implementation examples. The multilayer network is made of nodes and links forming layers of interlinked networks (see Aleta and Moreno, 2019), such as water flows and infrastructures, energy distribution systems, trade of ecosystem services including food and other material flows, as well as their interaction with economic sub-systems, and social real and virtual networks. The prominent nexus feature(s) of the case study should capture the crucial interactions among the resources involved, and the case study area boundaries should be defined in relation to its inflows and outflows, as well as its natural system boundaries, e.g. a catchment area, a city and its hinterland, or an agricultural region, inter alia. The delimitation should clearly identify prominent links to external networks, for example trade and transportation, the influence of global prices on food, energy and other case-relevant products, and potential global interdependences and "teleconnections" with other world regions (Adger et al., 2009). Besides their usefulness to define the nexus and its system boundaries, multilayer networks are increasingly adopted for global change modelling (González-Mon et al., 2019).

3. **Climate variables should be co-selected with stakeholders**. Climate drivers and variables of interest are co-selected with stakeholders in relation to the most important factors that form the basis of stakeholders' decisions about the relevant resource or system. These factors are represented or proxied in socio-economic models of the area in the context of the main economic sectors to be analysed. Specific advice on the selection of parameters from the output of climate models and their use in climate model ensembles is beyond the aims of this discussion article and the reader is referred to other materials covering this specific topics, like the guidance for EURO-CORDEX climate projections data use (Jacob et al., 2014; Hennemuth et al., 2017) and the Copernicus data store and sectoral tools (Raoult et al., 2017), which represent a comprehensive starting point. Scenarios and time periods are discussed below.
4. **Socio-economic scenarios about plausible futures need to be co-produced with stakeholders and investigated in combination with climate scenarios**. Socio-economic scenarios combining narratives with quantitative information about plausible futures should be co-produced with stakeholders to analyse the potential future socio-economic evolution of the current system. Understanding the dynamics of the water-energy-land nexus as a system and providing advice about its performance under climate change requires more than modelling. It is important to include expert opinion and local knowledge on current societal and technological trends, and also to consider how policies and technologies in other regions and economic sectors could influence e.g. resource availability, market prices or existing competitive advantages. Socio-economic scenarios coming from the shared socio-economic pathways (SSPs; see Kriegler et al., 2012) and from existing local narratives derived from stakeholder elicitation are in many cases not fully in agreement. In case of a bad match between SSPs and stakeholder driven scenarios, it is most informative to explore those stakeholder-driven scenarios, and to concretize for the case study a "SSP 1" scenario to inform stakeholders about the most sustainable options for the case study materialised in a narrative or storyline and in model results. It is suggested to combine socio-economic scenarios with climate scenarios, e.g. the representative

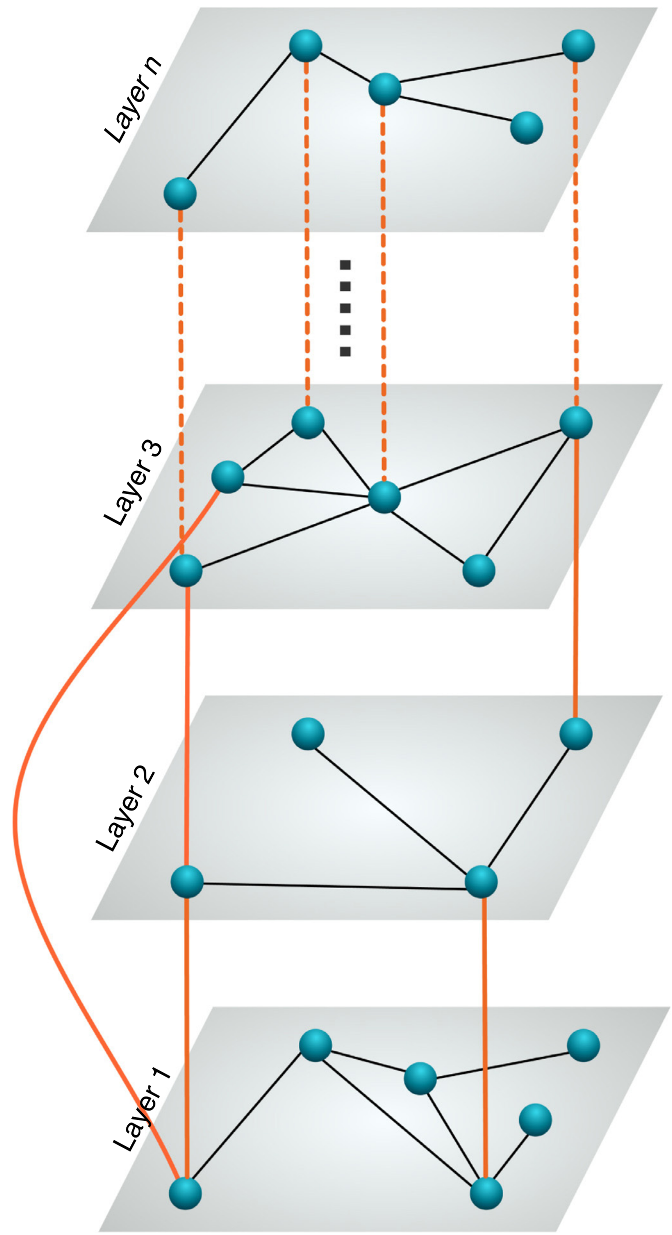


Fig. 2. A generic multilayer network adjustable across case studies (see Aleta and Moreno, 2019; Kivela et al., 2014). The generic multilayer network consists of layers (1, 2, 3, …, n) of networks, each one importantly characterized by the definition of its nodes and their links. Instances of the possible applications of the multilayer network are provided to exemplify nexus case studies within the entire human-Earth multilayer network conceptualised in the 2nd principle above. For example, a layer representing a water network, which links could include i.a. rivers, irrigation channels (linked to a land layer), and urban water supply infrastructure networks (linked to a land layer), and nodes that include springs, consumption points, reservoirs, and hydropower facilities (linked to an energy layer). An energy layer, characterized by networks of energy distribution links and the nodes of production (connected to a water and a land layer), centralised and decentralised, and consumption (connected to a land layer). A land layer, which could be defined with networks of human settlements and their transport systems (connected to an energy and a water layer), by the trade of agricultural outputs, and by the land use change dynamics (Verburg et al., 2019). A social network layer could model the social dynamics underlying the research question in focus, for instance to understand how decisions informed by climate services are adopted across economic sectors, or how innovative governance forms are increasingly adopted across river basins to deal with increasing climate impacts. Social networks, their consensus dynamics, and its implications on decision-making, could be represented for each of the above networks, such as governance networks, investor networks, and networks of resource users (e.g. irrigation associations). All these suggestions are examples for the content of the layers and could be adjusted in a case-study and research question basis.

concentration pathways (RCPs; see van Vuuren et al., 2011), to consider the linkages between climate change, the nexus, the related societal trends, and the relevant policies from directly and indirectly related sectors.

5. **The time period of the analysis should be decided in the context of the future implications of the decisions being made by stakeholders**. To define the time periods in the analyses, we suggest to use the consensus on integrated assessment research, which considers the mid-term around 30 years from present time (van Vuuren et al., 2012), because the implications of greenhouse gas emissions in the energy side of the nexus reach the centennial scale, which is considered long term. While this definition might be compatible with sectors such as forestry, agricultural stakeholders could define the long term as 10 years from present, although the climatic consequences of land cover change towards agriculture and the implications of some agricultural investments reach far beyond 10 years. It might be important to explore short-term (next 10–30 years) time periods in climate scenarios and compare them with a baseline period, because short-term time periods could help to raise interest across broad stakeholder communities. Still, it is necessary to consider that short-term agendas from stakeholders might in some cases dominate their preferences, but that the actual long-term consequences of their decisions go far beyond 30 years and must be taken into account. Perceiving climate impacts in present time could help stakeholders to consider longer time scales and their effects. The time period(s) of interest for stakeholders should be put into the context of the consequences of the decisions at hand, and their potentially related investments and environmental outcomes. Short-term data needs to be combined with data ranging between 30 and 60 years from present time for mid-term climate change, and between 60 and 90 years from present time for long-term climate change. In some cases, besides the analyses of the indicated periods, it might be important to understand how the current system and its potential evolution in future socio-economic scenarios would respond to non-yet-recorded events realized in some of the climate models selected, e.g. what would happen in the nexus system under droughts of a particular length that could appear in climate scenarios.
6. **The water-energy-land nexus goes beyond the classic climate impact modelling chains and there is a need to consider the nexus as a complex system**. The identification of complex system features is important to avoid unexpected outcomes emerging from links between resources and to understand the behaviour of the nexus system in hand. The nexus is a complex system that often includes feedback-loops between the considered sub-systems, in which its interacting elements jointly display behaviours that are not foreseeable looking at its elements alone (Thurner et al., 2018). This complexity conditions the emergence of different sustainability properties, mediated e.g. by feedback loops and non-linear and delayed responses. Some of these complex features can be well captured in system dynamics stock-and-flow models, in network science models, or generally in approaches with a bottom-up design (Verburg et al., 2019; Bahri et al., 2018; Brouwer et al., 2018). All approaches and models have their advantages and disadvantages and the research question would ultimately drive the model choice. Still, a prominent reason for the suggestion of using multilayer networks (see 2nd principle above, and Fig. 2 below) is that multilayer networks are able to connect the micro and macro landscapes and show complex emergent phenomena. A selection of examples of nexus-relevant feedback loops follows: (i) in a context of irrigated agriculture around wetlands valuable for biodiversity, increased irrigation water use under drier climatic conditions can bring groundwater levels down decreasing the wetlands' extension, thus allowing the expansion of agricultural land, which may further increase irrigation water use; (ii) in collective behaviours responding to climate impacts, people might consume more water for storing it, in sight of an announced drought restriction; and (iii) supply-side infrastructure investments making more water available to cope with urban growth enable the creation of further increases of urban land use, which again triggers higher water demands.

7. **The legal framework, established policies and institutions, as well as emerging governance mechanisms, should to be considered in the analysis**. Special attention is needed on policy coherence (Brouwer et al., 2018), on the consequences of siloed policies that ignore the interfaces of the nexus, and on whether all related institutional and administrative mechanisms are sufficiently enforced. The quantitative model or decision-support tool co-created with stakeholders provides a frame for making stress-tests of existing policies and potential innovations, and thus analyse the region's vulnerabilities, e.g. water supply reliability (Whateley et al., 2016). By modelling the performance of adaptation and mitigation plans, infrastructure projects, business plans, and investment options for utilities with their links across economic sectors, and embedding them into socio-economic scenarios that are analysed under climate change scenarios, it is possible to assess their efficiency and characterize their sensitivity and vulnerability across nexus resources. To stress test and assess the efficiency of current and new policies with stakeholders, the model and scenarios analyse how trade-offs, co-benefits and synergies and their dynamics over time fluctuate across societal goals like the SDGs, when are decisions best taken, and what windows of opportunity exists across governance levels from municipality to county, province, country and above. This governance dimension is deemed important to move nexus insights into practice (see Weitz et al., 2017; Boas et al., 2016; Benson et al., 2017). The implications of regional and national regulatory and policy frameworks and the programmes, plans and projects defined by international agreements.
8. **Economic analyses should capture nexus links across resources**. The aspects and variables identified above are modelled with appropriate quantitative methods to capture climate impacts by sector, e.g. crop growth models or hydrological models, and their economic implications. These aspects and variables include (i) climate impacts, like increased drought and flood risks, or decreased crop yields, (ii) adaptation and mitigation strategies, (iii) synergies and trade-offs within and between nexus resources, SDGs, and locally relevant sustainability aspects, and (iv) the resilience and robustness of long-term pathways towards sustainability, consistently with climate and socio-economic scenarios looking at (i) to (iv) and showing differences. It is important to understand the implications of change in one resource into other resources under different expenditure levels for a variety of scenarios, and while the number of innovative tools and models for the nexus with an economic dimension is increasing (see Dermody et al., 2018; Bazilian et al., 2011), the size of the literature including cross-resource nexus analyses and explicit contributions to the economics of the water-energy-land nexus is still very small (see Cremades et al., 2016; Perrihan et al., 2017). It is important to use an approach that differentiates between private benefits in one or more economic sectors, and public interests, e.g. related to adaptation and mitigation or to the long-term societal goals like the SDGs, and their trade-offs, co-benefits and synergies across time scales and regions. Diverse approaches again have advantages and disadvantages, and although it cannot be stated that some methods are always better than others, caution should be expressed about using economic methods with limited skill on capturing the nexus-relevant resource links of each particular case study. One needs to identify the sectors of the economy that use nexus resources and their ecosystem services — and more broadly the nature's contributions to people — as inputs in production processes, or consume them as outputs in consumption processes. Then, for each sector one needs to estimate the impacts on changes in nexus resources and

ecosystem services as per the different climate change and socio-economic scenarios — with different production and consumption patterns — and monetize the impacts of the changes. At this point, one needs to refer to the out of market consumption and use of nexus resources and services, the different aspects of the cultural and economic values involved and the methods that exist to consider them in policy-making and to monetize them (see Koundouri and Rulleau, 2019).

9. **Foreseeable low-probability high-impact events should be considered with as much quantitative detail as possible**. It is necessary to investigate uncertainties related to decisions, and to those aspects not currently captured by scenarios and modelling tools that could create maladaptive solutions. These aspects include the potential role of weak signals and deep uncertainties about trends that might become relevant in the next decades, versus the expected most likely developments currently debated by stakeholders. Besides estimating uncertainties in the data and methodology, and communicating them in the results, it is necessary to research the occurrence of events for which there is no quantifiable information.
10. **The ultimate goal of integrating climate services and the nexus is to search for synergies and co-benefits, and to manage trade-offs**. A quantitative model of the elements of the water-energy-land nexus and their ecosystem services, and contributions to people in the broad sense, allows searching for synergies and co-benefits, and managing trade-offs between societal goals (see Table 2 for annotated examples from Miller-Robbie et al., 2017; Cremades et al., 2016; Pittock et al., 2013; and Conway et al., 2017). When synergies and co-benefits are not possible, the quantification of trade-offs for different co-designed scenarios, and analyses showing the pareto-optimality of variables of interest for different scenarios would provide substantive information for decision- and policy-making. This will help to understand potential reductions of trade-offs between resource uses that could compromise the achievement of the Sustainable Development Goals (SDGs) and other locally relevant sustainability concerns. In some cases, decisions aiming at adapting to climate change can avoid these trade-offs, which could imply higher emissions (Cremades et al., 2016) or drought risks (Bahri et al., 2018). Additionally, trade-offs could have a public versus private dimension.

We provide further information about examples of studies applying the above principles across scales in Tables 1 and 2. Within the limitations of the existing literature, these examples have been selected on the basis of their usefulness to exemplify the application of each single principle. While these studies do not consider the entire set of principles, we find them useful to guide the reader on how each of the principles can be applied to a diversity of research questions and contexts.

4. Discussion

The application of these principles should be tailored to the needs of each particular case and stakeholders' decision variable. In addition to the classic impact modelling chain scheme of general circulation global climate model, regional climate model, sectorial climate impact models, and economic or decision-support model or tool, these principles aim to capture the multiple interfaces, dynamics and feedbacks between resources and economic sectors, and break the siloes that isolate sector-constricted policy-making.

The creation of models, tools and information tailored to stakeholders' needs that embody these principles depends on multiple factors that are challenging, and continuous improvement and interaction between scientists and stakeholders is needed to develop climate services. Some classic examples of hindrances are the coarse spatial resolution of climate and impact data and their lack of skill when representing extreme events, the difficulties of climate impact models when it comes to calibrate their output — e.g. crop yields, or hydrology — to local scales for which there are not sufficient years of data available for all the required land and water management practices, the unavailability of socio-economic data differentiated by multiple aspects like gender or income brackets, or the large amount of funds required to run a diversity of impact models capturing different economic sectors in multiple case studies. Besides, results from nexus case studies are of limited generalizability because there is very rarely an identical situation across them, and often ad-hoc estimation frameworks and models are needed to reproduce baselines and understand the influence of different future scenarios.

By using these principles to build models that reproduce historical data, and making new assumptions for them in sets of scenarios, it is possible to explore whether policies could achieve co-benefits or synergies across the elements of the water-energy-land nexus. This facilitates the selection of sustainability policies and practices under climate change that avoid or minimize trade-offs, and thus do not impede the achievement of the SDGs because of lack of consideration to these trade-offs, which often happen outside the boundaries of mono-sectorial narrow research approaches. These narrow-minded approaches can be problematic for coherent climate services that consider trade-offs across economic sectors and societal goals. Synergies, co-benefits, and trade-offs can be anticipated and managed following these principles, by modelling the planning and regulation of multiple economic activities and resource uses at different spatial and temporal scales under climate change.

Overall, these principles and the accompanying guiding questions below (see Box 1) serve as a heuristic scheme to compare cases and regions in relation to the nexus and the needs of stakeholders (see Fig. 1). By combining ad-hoc quantitative and qualitative techniques, these principles help to analyse how different policies and resource management options configure the feasible space for achieving the

Box 1
Guiding questions to compare nexus case-studies under climate change.

The results of different projects or practical approaches are difficult to compare, because each nexus case-study is often a unique instance of policy-relevant interface between resources themselves and with society. In order to make meaningful comparisons across nexus case studies in the same project or across projects, it is suggested to use guiding questions rather than resource quantities. These questions enlighten interesting debates for comparing and learning across cases:

- *What climate impacts should be taken into consideration and for what time period?*
- *What modulates the feasible space for co-benefits, that is, what makes them possible, and what policies or decisions cancel this space?*
- *What creates trade-offs and reduces the options to achieve the locally relevant sustainability goals or the local or regional contributions to the state-level SDGs?*
- *What trade-offs are unavoidable and need to be taken into consideration?*
- *What policy gaps still exist in the case studies that impede coherent policies across the relevant nexus resources?*
- *What is the political economy of these gaps?*
- *How do policies dealing with the nexus contribute to existing social and economic inequalities?*

related SDGs. It can be often expected that this feasible space is (i) reduced by climate change impacts, (ii) strongly driven by the influence of policies, regulations, trade, and markets, and by land and water use and management, and (iii) mediated through adaptation, although the insights may vary across cases, highlighting other more locally important limiting factors.

The uniqueness of each nexus instance suggests to consider going beyond the difficulties expressed on defining the nexus, and to consider the nexus as a unique instance of an entire human-Earth multilayer network, in which each resource is ultimately part of a global or regional network layer of energy, food, trade, water and virtual water trade i.a., coupled in multiple nodes with other interconnected layers of real and virtual social networks of resource users —e.g. irrigation associations, river-basin stakeholders, lobbies, … — managers, planners, and societal activists contesting their actions when they conflict with long term sustainability goals.

While methodologies tackling the nexus are increasingly available, there are still some gaps, e.g. in the implications of urban land use — and its diversity in densities of population and activities — on flood risks, water and energy consumption, and street-scale energy budgets related to thermal comfort. All these aspects are interrelated and would benefit from climate data input, hence considering them from a nexus perspective would improve climate services.

5. Summary and conclusions

This discussion article provides first-of-its-kind guidance to integrate climate services with the water-land-energy nexus approach. The 10 principles integrate the nexus with climate services for guiding decision- and policy-making with a focus on synergies and co-benefits, and on trade-off management in those cases when win-win options are not on reach. Integrating climate services and the nexus serves to search for synergies and strategies for trade-off management that respond to adaptation- and mitigation-related societal needs from the case study level to the global scale. To produce meaningful analyses, stakeholders need to be integrated since the framing of the research and contribute to future narratives, and researchers need to consider deep uncertainties, feedback loops, and other complex features behind cross-resource and inter-sectoral integration. Besides these principles, questions to compare the diversity of different nexus case-studies and a visual guide can help to picture the similarities across very diverse case studies. Finally, we define each nexus case study as an instance of a network of networks formed by the resources themselves —rivers, power grids, food and material trade, transportation, …— and their interactions, and the links across the human activities directly and indirectly related to them. We conclude that the water-energy-land nexus and climate services are necessary complements when there are shared constrains in nexus resources that have noticeable climate change impacts and that are used across economic sectors.

Acknowledgements

The authors would like to express their gratitude to Declan Conway, Tabea Lissner, Viorel Blujdea and Katharina Bülow for comments that helped to improve the manuscript. Authors affiliated at GERICS, BOKU, INCDS, and CREAF acknowledge financial support from the project CLISWELN funded by ERA4CS. ERA4CS is an ERA-NET initiated by JPI Climate, and CLISWELN is funded by BMBF (DE), UEFISCDI (RO), BMBWF and FFG (AT), and MINECO (ES), with co-funding from the European Union (Grant 690462). FB acknowledges that the work described in this paper was conducted in part within the project SIM4NEXUS; this project received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 689150 SIM4NEXUS. This paper and the content included in it do not represent the opinion of the European Union, and the European Union is not responsible for any use that might be made of its content. AG and OM acknowledge support from the project NEXT-AG, funded by the Natural Environment Research Council (NERC, UK) and the Comisión Nacional de Investigación Científica y Tecnológica (CONICYT, Chile).

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