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Complexity versus simplicity in water energy food nexus (WEF) assessment tools

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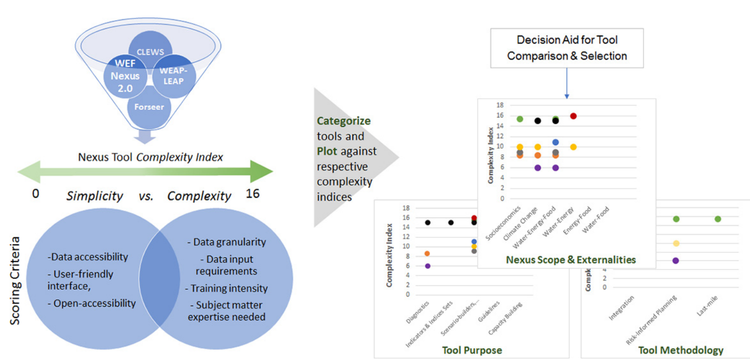
HIGHLIGHTS

- Water-energy-food nexus assessment tools vary in complexity and applications.
- A *complexity index* is created as a measure of complexity for nexus assessment tools.
- Scatter-plots are created that categorize tools and quantify their complexity.
- Such plots serve as a guideline to select tools specific to user objectives.

GRAPHICAL ABSTRACT



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ABSTRACT

Approaching water, energy, and food, as interconnected system of systems, as an alternative to traditional silo-based resources planning and management approaches continues to fall short of expectations of its research-backed benefits. The lack of nexus applications in policy and decision making can be related to numerous factors, with the main barrier being the complex nature of "nexus" systems combined with the disarray of tools attempting to model its interconnections. The paper aims to provide a method for comparing the perceived complexity of nexus tools identified by international organizations as well as primary literature sources. Eight separate criteria are introduced and discussed as measures of a tool "*complexity index*" and used to score the relative simplicity, or complexity, of a given tool. The result of this process is used to identify trends within existing nexus-assessment tools while guiding potential users towards appropriate tool(s) best-suited for their case study needs and objectives. The main objectives of this paper are to: 1) categorize nexus assessment tools according to a criteria-set which allows for suitable tool selection; 2) identify a method for rapid evaluation of the trade-offs for choosing different tools (simple-complex spectrum). The results of the comparative analysis of the selected nexus assessment tools concur with literature citing a growing gap between nexus research and applications in actual policy and decision-making settings. Furthermore, results suggest that tools receiving higher complexity scores, while being able to capture details to specific resource interactions, are unable to cover a larger number of interactions and system components simultaneously, as compared to lower complexity score tools. Lastly, the outcome of the analysis point towards the need for integrating more preliminary assessment capabilities, i.e. diagnostics, guidelines, and capacity building, into existing tools that improve the communication and translation of model outputs into policy and decision-making.

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1. Introduction

The water-energy-food nexus is an integrative approach to resource planning and management that involves high complexity of scale, multiple stakeholders, and many processes. Different "resource hotspots" have unique characteristics and complexities defined by physical resource constraints, stakeholder nature, and the critical question being addressed. Consequently, no single model or tool is able to cover the entire range of complexities. Different methods for conceptualizing the interconnected system of resources systems have emerged in the past decade, as have large numbers of tools that address resource allocation challenges. IRENA (2015), FAO (2014), and others have worked on compiling nexus assessment tools and attempted to compare their uses. Despite the availability of such tools, the lack of consensus about best methods and approaches to the multi-dimensionality of resource hotspots persists (Byers, 2015; Daher and Mohtar, 2015), pointing to the need for further effort towards making nexus methodologies and concepts more accessible and usable by policy and decision-making communities (Leck et al., 2015; Bazilian et al., 2011). Due to "the confusing sea of available tools" (Mannschatz and Meyer, 2015) and their imbedded complexities, institutions lack the resources and motivation to apply and benefit from using the nexus approach (Bazilian et al., 2011). In the last decade, several approaches have dealt with the disarray and the abundance of tools. Ness et al. developed a framework to classify sustainability assessment tools based on their approaches and focus areas. The framework is then applied to quantify the tool's ability to capture various dimensions of sustainability (Ness et al., 2007). The Nexus Tools Platform developed by Mannschatz et al. (2016) is a web-based platform that uses interactive filtering to determine suitable tools for specific water-soil-waste nexus modeling objectives. The United Nations, with affiliated governmental organizations, has established the *Localizing the SDGs Toolbox* and *SDG Toolkit*, which use a filtering mechanism to identify tools that can assist stakeholders in achieving certain components of the SDGs. While these approaches are useful in tool selection, the role of complexity in tool use is not directly considered by the developers.

Modeling interconnected resource systems is a complex task that requires extensive data inputs and makes modeling and simulating the nexus of water, energy, and food systems challenging (Kaddoura and El Khatib, 2017). Governmental institutions struggle to implement a nexus approach into policy and decision-making due to the absence of effective resources that can help overcome these inherent complexities (Bazilian et al., 2011). The lack of consensus regarding the best methods and approaches for addressing the multi-dimensionality of the nexus persists (Byers, 2015; Daher and Mohtar, 2015), and highlights the need for further efforts to streamline nexus methodologies for policy and decision-making communities to make them more accessible and usable (Leck et al., 2015; Bazilian et al., 2011). Researchers within the WEF nexus research community have addressed these challenges with suggestions to couple existing frameworks and tools (McCarl et al., 2017; Bazilian et al., 2011; Kaddoura and El Khatib, 2017; Byers, 2015; Mannschatz and Meyer, 2015). The integration of existing methods is both time and cost effective (Mannschatz & Meyer).

Thus, the purpose of this paper is first, to provide a method for comparing widely applied nexus tools identified by international organizations (UNDG, 2016; IRENA, 2015, FAO, 2014) and in primary literature sources (Kaddoura and El Khatib, 2017). The second component is to construct a set of criteria motivated by systems engineering and user-experience (UX) concepts to measure the respective 'simplicity' or 'complexity' of the tools. Among other factors discussed in this paper, the methodology assumes usability to be a key component contributing to the overall complexity level of a tool. Specifically, we: 1) categorize nexus assessment tools according to criteria that allow selection of suitable tools; and 2) identify a method for rapid evaluation of the trade-offs in choosing between different tools (simple-complex spectrum). The outcomes of this process are used to draw relationships and identify trends from existing nexus-management tools and to use these to help users identify the tool(s) best-suited for their individual needs and objectives.

2. Nexus tool challenges: defining tool complexity

The basis of the water, energy, food nexus approach to resource management lies in accounting for interactions at the interfaces of resource systems, while holistically assessing the impact of specific scenarios or interventions from environmental, financial, and sociocultural perspectives (Daher et al., 2018). Quantitative tools can be leveraged to gain further insight into the nexus implications of sectoral policies and to guide stakeholders towards more environmentally and resource-conscious solutions. Different potential users of these tools have different specific questions that need answers. Those users may come from government, business, or civil society agencies, and be interested in different levels of detail and information regarding their resource allocation questions. Also, these different users may operate within different constraints of time, finances, and human resources. In such cases, simplified or 'rapid nexus assessment' tools tend to be more suitable and provide valuable initial assessment, which can then bridge to the use of more advanced tools. While no one tool could address all types of questions, at different institutional and physical scales (Daher et al., 2017), the growing number of such nexus assessment tools could result in challenging users to identify which tool might be most suitable for their required assessments.

According to the nexus assessment tools presented in IRENA's (2015) report "Renewable Energy in the Water, Energy, and Food Nexus", only two of the eight tools surveyed met its criteria of a 'simple' nexus tool. Those two tools are: the WEF Nexus Rapid Appraisal Tool (FAO) and WEF Nexus 2.0 Tool (Daher and Mohtar, 2015). Complex tools are defined by their significant data requirements and resource intensity "in terms of time, capacities, and financing" (IRENA, 2015). Comprehensive tools generally have significant data needs and are resource intensive in terms of time, capacities and financing (IRENA, 2015). The scaling of simple and complex tools may help identify areas of overlap, in which tools might be coupled for improved, integrated nexus assessment and analysis. Liu et al. (2017a,b), Byers (2015), and Howells et al. (2013), cite the importance of developing integrated modeling approaches for nexus studies. However, the complexity of such an integrated modeling framework could make its development and application both difficult and costly. Extensive data needs and high data resolution are commonly seen as indicators of tool complexity. Thus, it is evident that coordination between the stakeholders relevant to addressing specific resource challenges is necessary to generate the data required to quantitatively assess the synergies and trade-offs involved in the WEF nexus.

2.1. Complexity and usability

The large array of stakeholders involved with WEF nexus hotpots include a conglomerate of skillsets and backgrounds. Therefore, *tool usability* is an important feature for stakeholders to consider in selecting suitable nexus assessment tools. Usability is an element of the broader field of user-experience design (UX) (Soegaard, 2018) and can be understood as a function of user goals and objectives in addition to the user's 'environment' (Brooke, 1996). The ISO (International Standardization Organization) has incorporated usability into its standard ISO 9241-11, 'Ergonomics of Human System Interaction,' which distinguishes between usability dependent on human-tool interaction and traits of the tool itself (Bevan et al., 2015). The standard defines usability using three contextual components:

1. Effectiveness: the accuracy and completeness with which users achieve specified goals
2. Efficiency: the resources expended in relation to accuracy and completeness with which users achieve goals

3. Satisfaction: the freedom from discomfort and the positive attitudes towards the use of the product (Adapted from (ISO 9241-11, 1998))

Brooke (1996) introduced the System Usability Scale (SUS) as an open-source tool for assessing the perceived usability of computer software and commercial products (Grier et al., 2013). The tool, organized as a questionnaire of 10 five-point items (Lewis, 2018), is commonly applied in user-experience (UX) studies (Brooke, 2013). Fig. 1 shows a sample standard SUS questionnaire adapted from (Lewis, 2018). The methodology of this study follows in the steps of the SUS in that it defines complexity and usability criteria and uses simple metrics to measure perceived complexity of a given nexus tool.

Mützel (2017) discusses the results of a study on *feature fatigue*, conducted by Thompson et al. (2005), which supports the idea that perceived tool usability is related to its inherent complexity. The study finds a negative correlation between the number of features in a tool and its usability. This correlation is then related to the extensive time required for the user to learn the tool's functionalities (Mützel, 2017). Previous nexus management tool surveys identify characteristics that contribute to the complexity of a tool, most of which relate to this concept of usability. Simple tools are classified as having less stringent resource requirements while providing "valuable preliminary assessments and incorporating explicit context-specific input from decision-makers" (IRENA, 2015). Simplicity is based on accessibility to input indicator requirements and offers an easy-to-follow framework and guidelines for the user (such as pre-set policy interventions). It provides output data that is understandable to the layman. While the general question may be "how to choose the right assessment tool for my nexus analysis," another significant factor is the correlation between the complexity and the capabilities of the tool.

In coupling tools, however, the challenge lies in identifying the compatible tools to integrate in accordance with the stakeholder's objectives (Mannschatz & Meyer). Adding to the complexity, the absence of a collective platform to organize the abundance of tools has led to information and tools that are "scattered, inaccessible, incomplete, out of date, [and] static" (Mannschatz and Meyer, 2015). The overall objective of modeling is to find simple models that convey the components of a real system at a certain space and time (Holzbecher, 2012). In the perspective of environmental modeling, Holzbecher (2012) points out that adding complexity to models does not necessarily improve results or accuracy. Simple models can be improved by the integration of complimentary models, as was the case of the extension of CropWat (FAO) into WEAP (SEI), and the coupling with energy model, LEAP (SEI). However, 'an improved model design increases the quality of the model but further extensions of the improved model may finally lead to a situation in which the increase of model complexity is counter-productive' (Holzbecher, 2012; Jørgenson, 1994; Contanza and Sklar, 1985; Chwif et al., 2000).

In a recent review of water-energy-food nexus tools carried out by Kaddoura and El Khatib (2017), strengths and weaknesses of common tools applied to nexus modeling, including the CLEWs framework (Howells et al., 2013) and WEF Nexus Tool 2.0 (Daher and Mohtar, 2015), were identified based on the authors' own analysis. The capabilities and limitations described in the review shed light on the characteristics of nexus tools that contribute to their complexity. Availability of tools at low- to no-cost, web-accessibility, simple data requirements, and user-friendly user interfaces were cited as strengths of the surveyed tools; while integration with other methods and extensive data requirements served as limitations (Kaddoura and El Khatib, 2017). Evidently, from the various options available, there is not one nexus model or tool that captures all involved processes and components simultaneously. Tool selection is therefore context and scale dependent, and data requirements are contingent on the resource hotspot addressed.

			Strongly Disagree				Strongly Agree
			1	2	3	4	5
1	I think that I would like to use this system frequently.		O	O	O	O	O
2	I found the system unnecessarily complex.		O	O	O	O	O
3	I thought the system was easy to use.		O	O	O	O	O
4	I think that I would need the support of a technical person to be able to use this system.		O	O	O	O	O
5	I found the various functions in this system were well integrated.		O	O	O	O	O
6	I thought there was too much inconsistency in this system.		O	O	O	O	O
7	I would imagine that most people would learn to use this system very quickly.		O	O	O	O	O
8	I found this system very awkward to use.		O	O	O	O	O
9	I felt very confident using this system.		O	O	O	O	O
10	I needed to learn a lot of things before I could get going with this system		O	O	O	O	O

Fig. 1. Standard SUS; (Lewis, 2018).

3. Methodology

3.1. WEF nexus tools selection criteria for this study

Numerous attempts at tools that capture relationships and interactions across interconnected resource systems have been developed and continue to be published. Various international nonprofit organizations (IRENA, UN, FAO) and academic researchers have produced 'nexus reviews' that provide readers with overviews of different modeling and management tools that have been applied to nexus studies (Bazilian et al., 2011; Endo et al., 2015; Kearins et al., 2016; Semertzidis 2015; Kaddoura and El Khatib, 2017; Dai et al., 2017). For the scope of this paper, tools selected for analysis must meet the following criteria: a) published within last 10 years, b) include at least two of the three nexus components (water, energy, food), and c) the physical tool must still be active in some form of accessibility (on or offline) as of May 2018. The 10-year time constraint is based on a timeline of landmark events, publications (Hoff, 2011; World Economic Forum, 2011), and networks on the water-energy-food nexus presented in Leck et al. (2015) dating back 9 years, which, for this study, is rounded to 10. This last specification is applied to eliminate tools that may be documented frequently in nexus literature but are no longer in active use (for example, the Diagnostic Tools for Investment in Agricultural Water Management, (Salman, 2014)).

In the case of the 2015 IRENA report, tools covering at least two of the three resource systems were chosen in comparing different nexus assessment tools. The justification for the criteria demanding at least two of the three resources systems is rooted in the holistic approach of nexus thinking as opposed to looking at a single sector individually. The nexus tools identified to demonstrate the *complexity index* scoring, tool comparative analysis, and case-study applications are outlined in Table 1 and described in the next section.

3.1.1. Tool descriptions

3.1.1.1. WEF Nexus Tool 2.0. The WEF Nexus Tool 2.0 is an input-output model developed by Daher and Mohtar (2015) for the purpose of analyzing the national resource requirements associated with different food self-sufficiency scenarios. Users of the tool identify data inputs that provide a localized, contextual basis to the model: local food profile, national water and energy portfolios, agricultural conditions, and food import-export portfolio. As a result, the tool specifies the total water, land, and energy requirements, carbon footprint, financial costs, and sustainability of the user-defined food efficiency scenario. The tool is web-accessible and open-access for users.

3.1.1.2. CLEWS. CLEWs (Climate, Land-use, Energy-Water strategies) is a framework for a cross-sectoral systems approach to nexus challenges developed by Howells et al. (2013). The framework is focused on identifying feedbacks across these systems and uses the interconnections to determine how changes in one sector influence others. CLEWs has been applied to various case-studies across Africa, small island developing states, and European transboundary basins with emphasis on context specific nexus issues, such as (but not limited to) links between water availability, hydro-power production, ecosystem services, and agricultural intensification (KTH, 2017).

3.1.1.3. WEF Nexus Rapid Appraisal Tool. Developed by the Food and Agricultural Organization of the United Nations (FAO, 2018), the WEF Nexus Rapid Appraisal Tool is an online version the *Nexus Assessment* framework (FAO, 2014). It provides a quick method for assessing specific policy and technology interventions with respect to bio-economic pressures at national scale. FAO specifies the tool's intended use is for communication and awareness raising purposes. It supplies the user with a set of 10 'nexus context assessment' indicators and 30 'nexus intervention assessment' indicators and allows the user to adjust weights applied to each index according to their relative importance. The intervention scenarios currently look at power irrigation, a bioenergy, hydropower and water desalination interventions from the perspective of water, energy, food, labor, and cost components.

3.1.1.4. MuSIASEM. MuSIASEM (Giampietro and Kozo, 2000) is a framework that builds on concepts from bioeconomics and the flow-fund model. Over the years, it has been updated to include water, energy, and food systems, simultaneously characterizing the metabolic pattern of energy, food and water in relation to socio-economic and ecological variables. The framework analyzes the 'metabolic pattern of energy, food, and water' in relation to land-use changes, population dynamics, greenhouse gas emissions (GHG) at both national and subnational scales It has been used for both diagnostic purposes as well to simulate scenarios defined by the user simulation purposes (FAO, 2013).

3.1.1.5. Foreseer. The Foreseer Tool uses Sankey diagrams to visualize and trace energy, water and land resources from source to service, under various socioeconomic and climate change scenarios. Through the online interface, users create customized water and energy policy scenarios while environmental impacts are computed as an output of the tool. To date, Foreseer developers at the University of Cambridge have published one global version of Foreseer, and three national and local scale models applicable to China, the United Kingdom, and the state of California (Allwood et al., 2012).

3.1.1.6. WEAP-LEAP. WEAP (Water Evaluation and Planning System) and LEAP (Long Range Alternatives Planning System) are two software models developed by the Stockholm Environment Institute (SEI). Individually, the tools have been applied worldwide to support alternative policy measures in water resources and energy challenges. The models were integrated in 2014, becoming 'WEAP-LEAP.' The model works by exchanging parameters and outputs, such as hydropower generated or cooling water requirements. Together, they can represent evolving conditions in both water and energy systems (SEI, 2013; 2014).

3.1.1.7. iSDG Planning Model. The Integrated Sustainable Development Goals Planning Model (Millenium Institute, 2017) was developed by the Millennium Institute as a tool to simulate trends towards achieving the SDGs under a business-as-usual scenarios (BAU), to explore potential impacts of alternative scenarios, and to model trends up to the year 2050. Its target audiences are policy makers and government officials interested in modeling the impact of potential policies in the design process and/or analyze effects of current policies with respect to the SDGs.

3.1.1.8. World Bank Climate and Disaster Risk Screening Tools. The Climate and Disaster Risk Screening Tools developed by the World Bank are sets of open-resource tools targeting development practitioners for use in understanding climate and disaster risks in project and national/sector planning processes. The tools help practitioners learn about climate trends and geophysical hazards in a given country or project, flag

Table 1
Nexus tools selected for comparison (*Authors*).

Nexus tools	Author(s) and URL	Sample applications
WEF Nexus Tool 2.0	Daher and Mohtar (2015) http://www.wefnexustool.org/login.php?backurl=http://www.wefnexustool.org/user.php	Sustainability of various food self-sufficiency scenarios for Qatar
CLEWS	Howells et al. (2013) https://unite.un.org/sites/unite.un.org/files/app-globalclews-v-1-0/landingpage.html	CLEW interlinkages in Burkina Faso: an analysis of agricultural intensification and bioenergy production (Hermann et al., 2012); adding value with CLEWS – modeling the energy system and its interdependencies for Mauritius (Welsch et al., 2013); connecting the resource nexus to basic urban service provision – with a focus on water-energy interactions in New York City (Engström et al., 2017)
WEF Nexus Rapid Appraisal	FAO (2014) http://www.fao.org/energy/water-food-energy-nexus/water-energy-food-nexus-ra/en	Solar steam irrigation, Kenya; ethanol production, South Africa; electricity subsidies for farmers, Punjab, India; hydropower dams, Mekong River Basin; The Sahara Forest Project, Jordan & Qatar
MuSIASEM	Giampietro et al. (2013) http://www.nexus-assessment.info/index.php/methodology/musiasem	Food self-sufficiency and biofuel production, Mauritius; potential of Concentrated Solar Power (CSP) and woody biomass for electricity production, South Africa; metabolic pattern of the agricultural sector, Punjab, India
Foreseer	Allwood et al. (2012) https://www.foreseer.group.cam.ac.uk/foreseer-tool/	Land requirements for bioenergy demand under the UK Carbon Plan (Allwood et al., 2016).
WEAP-LEAP	SEI (2012a,b) WEAP: http://www.weap21.org/index.asp?action=40 LEAP: https://www.energycommunity.org/default.asp?action=download	Impact of desalination on water and energy systems and GHG, California (SEI, 2012a,b); future performance of energy-water systems under climate change and policy change, Arabian Peninsula (Flores-López et al., 2016); quantifying cross-sector interlinkages and resource dependence of the energy and agriculture sectors and related environmental impacts, Ethiopia Lake Tana Sub-basin (Karlberg et al., 2015)
iSDG Planning Model	Millennium Institute (2016) https://www.millennium-institute.org	Investments in photovoltaics, Tanzania (Collste et al., 2017)
World Bank Climate and Disaster Risk Screening Tools	World Bank (2014a) https://climatescreeningtools.worldbank.org	Climate and geophysical hazards of a rehabilitation of dams and reservoirs, Vietnam (World Bank, 2014b); climate and geophysical hazards of irrigation, crop management, and water storage, India (World Bank, 2014c)

Table 2
Complexity index rubric.

Criteria	Justification	Score
1. Tool is open-access	Cost is a significant consideration in defining the usability of a tool (Fortmann-Roe, 2014). Open-access provides stakeholders with a higher incentive to utilize a given tool. Along with higher incentives, open-access can provide new users and non-experts time "to experiment with and learn about a simulation and modeling tool" without the burden of cost (Fortmann-Roe, 2014).	[Yes - 0] [No-1]
2. Tool has a web-interface	Tools built with web-interfaces can reach a larger, broader audience. This translates to a higher number of users of nexus management tools, increasing the potential to bring about societal benefits, more sustainable outcomes in resource management, and increased understanding of nexus systems (Fortmann-Roe, 2014; Kaddoura and El Khatib, 2017). Additionally, web-interface accessibility overcomes issues of large, potentially malicious file-downloads related to software packages (Fortmann-Roe, 2014). Tools lacking any interface (i.e. a framework) require the end-user to "make the connection between the description of the tool and the necessary data themselves" (Mannschatz and Meyer, 2015).	[Yes-0] [No-1]
3. Data granularity	Data granularity is the extent of detail and focus of a data point. In general, more granular the data allows the achievement of more accurate and thorough system(s) modeling. The downside of narrow data requirements is that they often are more difficult to find in open-source environments and usually require the use of additional modeling tools to derive estimates (McCarl et al., 2017). *General data* refers to data points commonly addressed in national assessments and reports typically found in international databases, such as those of the World Bank and United Nations. Examples of general data include demographics, gross domestic product, import/exports.	Low [1] = high-level; national-level data Medium [3] = general but with more sector-specific data High [4] = localized sector data and localized technical data
4. Data accessibility	Accessibility to data is a major challenge for accurate modeling: data input requirements for nexus models usually outnumber the data available in an open-access environment (McCarl et al., 2017). Accessibility is highly related to data granularity (harder-to-find data points are more likely to be more detailed and difficult to measure). Where data is not accessible, data can be obtained using more costly and time-consuming methods, such as observation, experimentation, estimation through use of other models, and data engineering (McCarl et al., 2017).	High [1] = data exists for most developed & developing countries Medium [2] = data is hard to find for developing countries Low [3] = data is difficult to find; derivation needs other modeling tools
5. Number of data inputs (by user)	Parameters are defined as the input data requirements for scenario development and analysis. The average number of data inputs by the user for the tools being assessed is 15.	Low [1]: 0–15 Medium [2]: 16–32 High [3]: 33+
6. Subject matter expertise	Based on developer reports, tool description, and target audience.	Low [1]: expertise not needed Medium [2]: needs understanding of general subject matter High [3]: expertise and high skill needed
7. Training intensity (for use of tool)	From an organizational perspective, time for training comes with opportunity costs, such as potential investment in teaching resources and time away from other project tasks. Training can include self-directed, online tutorial modules or in-person instructional classes. Time required to effectively learn and apply a tool varies as a factor of the user's background, making time needed dependent upon the defined measures. Training times are derived from the model documentations.	Low [1]: 1 day Medium [2]: 2–3 days High [3]: 1 week
8. User-defined scenarios	Some tools have pre-set scenarios that can be selected and included in the modeling assessment to capture different externalities, such as population growth and climate change projections. Other tools have user-defined scenarios that give the user greater flexibility, but may require more data and time to define the scenarios independently. Thus, user-defined scenarios add to complexity.	[Yes - 1] [No/N-A - 0]

potential impacts and risks from climate and geophysical hazards, inform dialogue, consultation and planning processes at the project or program level, recognize need for detailed assessment during project preparation and planning processes, and identify other resources and tools to complement assessments (World Bank, 2014a,b,c).

3.2. Complexity index

The *complexity index* uses an aggregate of qualitative and quantitative measures to capture complexity and suitability for different applications of nexus tools that exist in the literature. Complexity is subjectively dependent upon data availability, accessibility, user background, objectives, and time constraints. As discussed in the literature review, usability is a key component of overall tool complexity. Thus, the complexity index stems from the *system usability scale* (*SUS*) (Brooke, 1996, 2013), which looks at the usability of products from the user perspective, then builds upon the *SUS* to include measures that can capture more complexity characteristics with respect to nexus tools. Measures to define tool complexity were chosen based on discussions in the literature that challenge nexus modeling approaches (Kaddoura and El Khatib, 2017; Byers, 2015; Daher and Mohtar, 2015; Leck et al., 2015; Bazilian et al., 2011). To allow straightforward and fair comparison, the measures are kept broad and simple. While the components of nexus tools may be complex from the user perspective, they are not so from the developer's perspective. This section describes the scoring criteria and methodology used to develop the complexity index for a given nexus tool.

The complexity index uses a scale of 5–16, in which the higher index value correlates to a higher user-complexity tool. Note that negative answers (i.e. 'no' or 'low' may correlate to lower scores, implying lower relative complexity). Criteria are derived from existing tool comparison charts (UNECE, 2015; IRENA, 2015; FAO, 2014; Kaddoura and El Khatib, 2017) and selected based on researcher defined shortcomings or challenges of existing tools in literature. Table 2 is a rubric of the scoring criteria and includes qualitative and quantitative definitions and justifications for each criterion. The complexity index is used to develop relationships between the type, purpose, and characteristics of nexus tools in the form of simple data visualization as reflected in scatter plot charts. Through the visual mapping process, decision-makers can more easily identify tools relevant to their interests and desired level of complexity. The *Appendix* section describes the scoring for each of the sampled nexus modeling tools and offers a justification for the score based on the judgement of the authors.

3.3. Mapping tool complexity

As noted by (Mannschatz et al., 2016), none of the cited authors' or organizations' data on nexus tools follow a 'uniform terminology' for tool categorization. This makes it difficult to convert and compile existing work into one platform. Common categories used to classify nexus tools, such as 'quantitative' and 'qualitative' as seen in Dai et al.

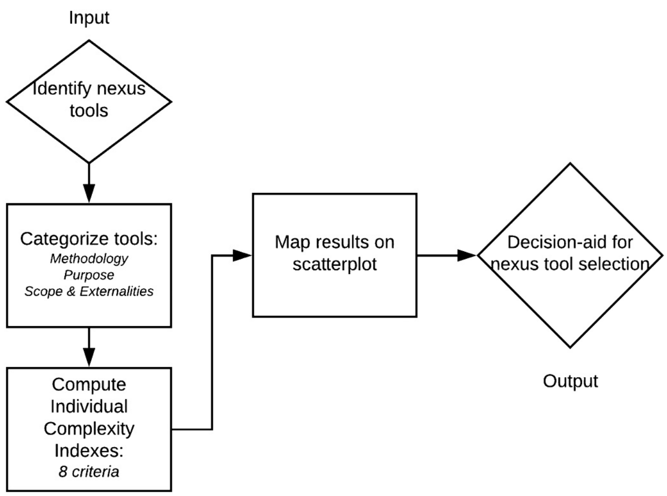

Fig. 2. Building and visualizing tool complexity relationships.

(2017) and Endo et al. (2015), are too vague and not conducive for comparing tool capabilities. To create consistency in model and tool classification and categorization, 'tool methodologies' and 'purposes' were modified from the *UN SDG Acceleration Toolkit*, an online system developed by the UN that uses a filtering mechanism to identify tools relevant to the seventeen Sustainable Development Goals.

Fig. 2 is a flowchart representing the nexus tool complexity mapping methodology. It begins with the identification of the array of tools to be filtered through the mapping process. The available tools are then categorized according to methodology type, purpose, nexus scope, and externalities. Next, complexity indexes are computed for each tool based on the eight criteria presented in Table 5. In scatterplot formations, tool categories (*methodology*, *purpose*, *scope* (IRENA, 2015) and *externalities*) act as the independent variables on the x-axis, while the *complexity index scores* appear on the y-axis as the dependent variables. The results of the categorization and scoring processes are mapped into scatterplot displays to be used as a decision-aid tools for nexus tool selection.

3.3.1. Tool categories

Tool *scope* defines the primary nexus interlinkages (water-energy, water-food, energy-food, water-energy-food), while *externalities* are component interactions significant to WEF nexus studies. Thus, the externalities considered are *climate change* and *socioeconomics*. Climate change, population, and economic growth are commonly cited externalities driving changes in w-e-f systems. Therefore, capturing their interactions and impact on resource systems can bring added value to modeling nexus systems. *Socioeconomics* is a category used, broadly, in tools that consider population growth and or economic factors as inputs and or outputs of scenarios. These relationships can be leveraged to visualize and identify tools with similar scope and at varying levels of complexity. The tool methodology outlined in Table 3 categorizes tools by the primary characteristic(s) of their modeling approach. These are modified from UN SDG Acceleration Toolkit classification categories (UNDG, 2016).

The *tool purpose* (Table 4) measure more specifically captures the general output of the specified tool. These measures are drawn from the following categories used by the UN SDG Accelerator Toolkit: diagnostics, guidelines, computer models and programs, monitoring indicators and indices, financing instruments and funds, technology access protocols, training programs, communication plans, capacity building, knowledge management platforms, econometric models, scenario builders, forecasting and back-casting methodologies, and narrative (storytelling) guidelines (Villeneuve et al., 2017). The following methodology categories were selected for the tool comparison analysis.

Table 3
Tool methodology.

Tool methodology	Description
Integration	Analyzes interconnections, synergies, trade-offs and bottlenecks between WEF sectors (i.e. dynamic simulation tools, indicators & assessment, static interlinkage analysis).
Last-mile	Supports meeting certain targets and unlocking bottlenecks for all segments of society: community-based planning, multi-stakeholder engagement tools, data revolution tools, fragility assessment, vulnerability assessment.
Risk-informed planning	Disaster risk reduction, economic forecasting, reducing risk of environmental degradation, epidemic and pandemic analysis, risk-foresight-and scenario tools, financing resilience.

4. Results

Table 5 summarizes the results of the scoring and tool categorizations. This data was then transferred into scatterplot tools in order to draw relationships and trends. The results of the complexity analysis reveal that the most commonly applied nexus assessment tools are "integration tools" that analyze various scenarios to simulate nexus relationships. Higher complexity index scores for some of the evaluated tools (MuSIASEM, CLEWS, WEAP-LEAP) can be attributed to usability factors (i.e. open access, web-interface, training intensity, data accessibility). For example, MuSIASEM and CLEWS are detailed, open-access frameworks for modeling nexus system interactions. The benefit of the framework approach is that it can be specifically tailored to a location and/or problem. The tradeoffs of the approach include the necessity for more granular data and the need for highly-skilled analysts to ensure proper application of the framework in real-life application. The integrated WEAP-LEAP model requires intermediate expertise of both modeling software packages and an understanding of the nexus systems for both robust scenario development and model simulation. Tools with lower complexity index scores (Climate and Disaster Risk Screening Tool, WEF Nexus Rapid Appraisal Tool) may be more applicable as capacity building and educational tools, particularly in the initial stages of policy development or project planning.

The resulting scatterplots of the data presented in Table 5 are displayed in the following subsections and include detailed explanations of the findings for each. Colored points on the scatterplot graphs represent individual nexus tools. Because some of the nexus tools fall into more than one category, their corresponding color points will appear multiple times on the plot. A legend is provided with each plot that identifies the colors with the respective nexus tool name.

Table 4
'Tool purposes' modified from classification categories of the SDG Acceleration Toolkit (UNDG, 2016); descriptions provided by authors.

Tool purpose	Description
Diagnostics	Tools used generally for the detection of nexus hotspots
Guidelines	Tool provides policy direction, suggests approaches for the user
Scenario-builders, forecasting, and back-casting	Tools allow users to develop or select from pre-arranged nexus scenarios that either rely on forecasting methods (future values are extrapolated from historical trends and data) or back-casting (develop scenarios based on future targets and goals)
Capacity building	Tools focused on stakeholder engagement and building awareness of specific issues
Indicators and indices sets	Tools and models that use indicators and/or indexes to describe the nexus system (Endo et al., 2015).

Table 5
Categorization and complexity scoring results.

Nexus Tool	Complexity index	Tool purpose	Tool methodology	Tool scope	Externalities
WEF Nexus Rapid Appraisal	8	Indicators and indices sets; capacity building	Integration tool	W-E-F	Socioeconomics, climate change
World Bank Climate and Disaster Risk Screening Tools	6	Diagnostics	Risk-informed planning	W-E-F	Climate change
iSDG Planning Model	9	Scenario-builders, forecasting & back-casting	Integration	W-E-F	Socioeconomics
Foreseer	10	Scenario-builders, forecasting & back-casting	Integration; risk informed planning	W-E	Climate change; socioeconomics
WEF Nexus Tool 2.0	11	Scenario-builders, forecasting & back-casting	Integration tools	W-E-F	
MuSIASEM	15	Scenario-builders, forecasting & back-casting	Integration tool	W-E-F	Socioeconomics
CLEWS	15.5	Diagnostics; monitoring indicators and indices, scenario builders, forecasting and back-casting	Integration tools; last-mile; risk-informed planning	W-E-F	Climate change
WEAP-LEAP Integrated Model	16	Scenario-builders, forecasting & back-casting	Integration	W-E	

a. Tool complexity index scores vs. tool purpose

Fig. 3 portrays the relationship between the computed complexity index (y-axis) and tool purpose (x-axis). The mapping of the nexus tools using these variables highlights the lack of capacity building and guideline tools, which demonstrates the gap between decision-making and research in the WEF nexus. Not only does the analysis reflect that the majority of accessible nexus-tools are scenario development tools that use forecasting or back-casting methods, but also that they span medium to high complexity levels. The variation of complexity index scores within the diagnostics category exemplifies a situation in which tools have similar methodologies but differ in the level of detail that is achieved by the tool output. For example, the WEF Nexus Rapid Appraisal Tool requires minimal data inputs from the user because the background data is provided by the tool developer. On the other hand, the CLEWs framework is more labor-intensive and requires higher technical skill and background knowledge of nexus systems. While the Rapid Appraisal tool aims to communicate, at a high-level, the potential impacts of pre-specified policy interventions from a w-e-f nexus perspective, CLEWs is designed to provide prospective users with a framework to conduct a detailed, contextual analysis of user-specified WEF nexus system interactions. For example, a decision-maker may opt for the lower-complexity WEF Nexus Rapid Appraisal Tool if seeking a snapshot of the current state of their country's W-E-F resource systems and their performance under relevant policy changes. As a result, a decision-maker might use the data provided by this tool to select the type of water, energy, and/or food policies/projects, then use the CLEWs model to build on further analysis. Lastly a notable observation of the scatterplot in Fig. 3 is that only one of the surveyed tools falls under both 'Guideline' and 'Capacity Building' purposes categories. These two categories were included as x-axis variables because they are valuable for decision-makers in understanding and facilitating dialogues on nexus issues and challenges. As discussed in the literature review, a gap between the policy-making community and the nexus research community persists. Fig. 3 illustrates this gap between the lack of capacity building and guideline components in the selected tools. It is possible for more complex tools to improve their usability and understanding of results by including these categories.

b. Tool complexity index scores vs. tool methodology

The results of the complexity index scores and their respective tool methodologies are plotted in Fig. 4. Points on this scatterplot are concentrated under the *Integration* category. The relationships evident in Fig. 4 also show a significant range of complexity levels between integration tools alone. The differing complexity levels may also indicate the varying levels of detail and depth the tool is able to provide.

c. Tool complexity index scores vs. tool scope & externalities

In comparing tool complexity with scope and externalities (Fig. 5), it is evident that most tools tend to capture aspects of all nexus

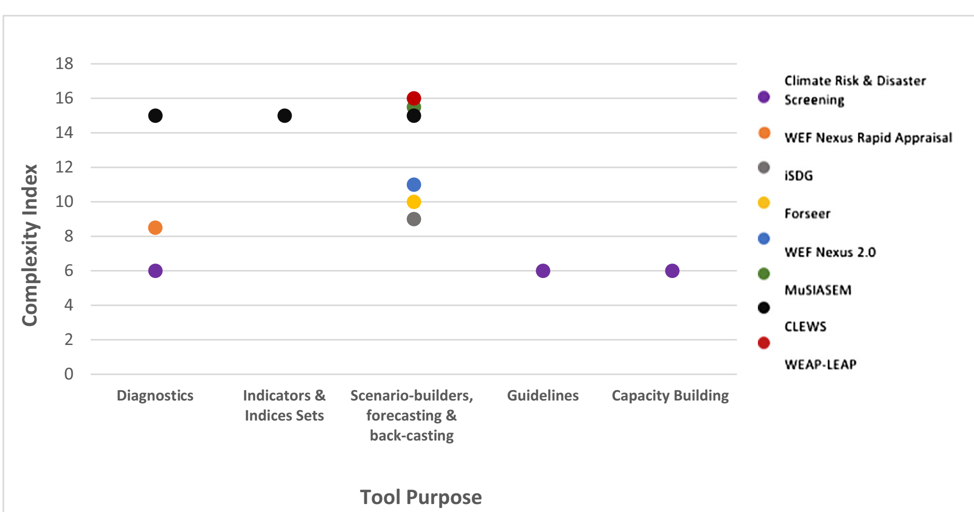

Fig. 3. Complexity vs. tool purpose.

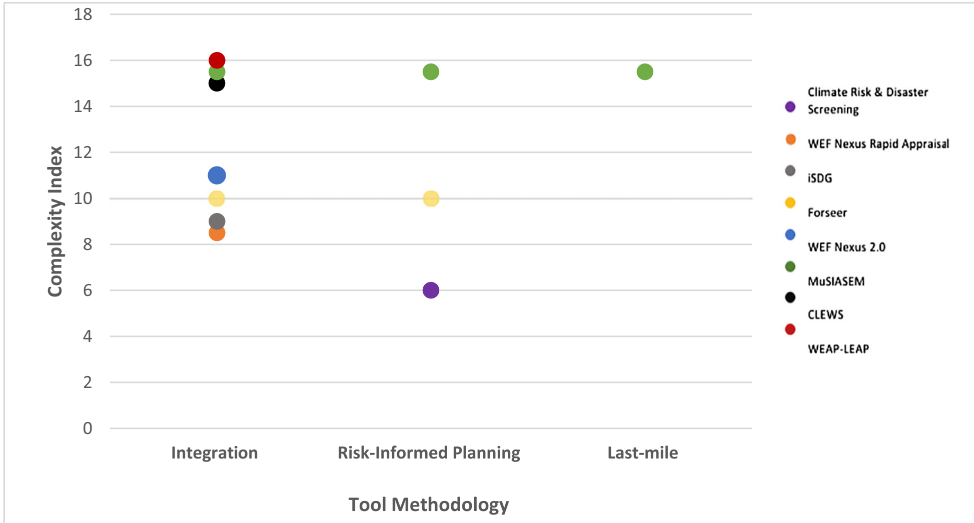

Fig. 4. Complexity vs. tool methodology.

components (water-energy-food). The WEF Nexus Rapid Appraisal Tool developed by FAO is shown to be the only tool that includes all nexus components and the socioeconomic and climate change externalities in its modeling process. Foreseer also includes socioeconomic and climate change factors in its scenario development, but Foreseer can only be applied to water-energy nexus relationships. The analysis lacks tools for the study of Energy-Food and Water-Food nexus components. Tools for these sub-nexi have been developed, but due to the constraints of methodology, they could not be included in the scope of this paper, which attempts to draw a relationship between tool complexity, nexus components, and externalities covered in the tool analysis. The assumption is that the more components and externalities a tool is able to cover, the higher its use-complexity. One drawback of using the nexus component relationship for the scope variable is that it does not specify 'resource entry points' (Salam et al., 2017) for the tool. For example, the WEF Nexus Tool 2.0 is classified as containing each water, energy, food resource interactions, but this classification does not show the tool's focus 'food self-sufficiency' with food as the resource entry-point.

4.1. Limitations

The objective of this paper was to demonstrate the application of the complexity index framework and tool mapping exercise using a small inventory of nexus tools. To overcome the limitation of a small sample size, more tools can be added to the evaluation, which in turn, will provide enhanced analysis and improved trend insights. The chart comparison is a prototype for visualizing the capabilities and purposes of tools in terms of their complexity. While scatterplots were employed in this study, alternative visuals and graphics could be used to improve the

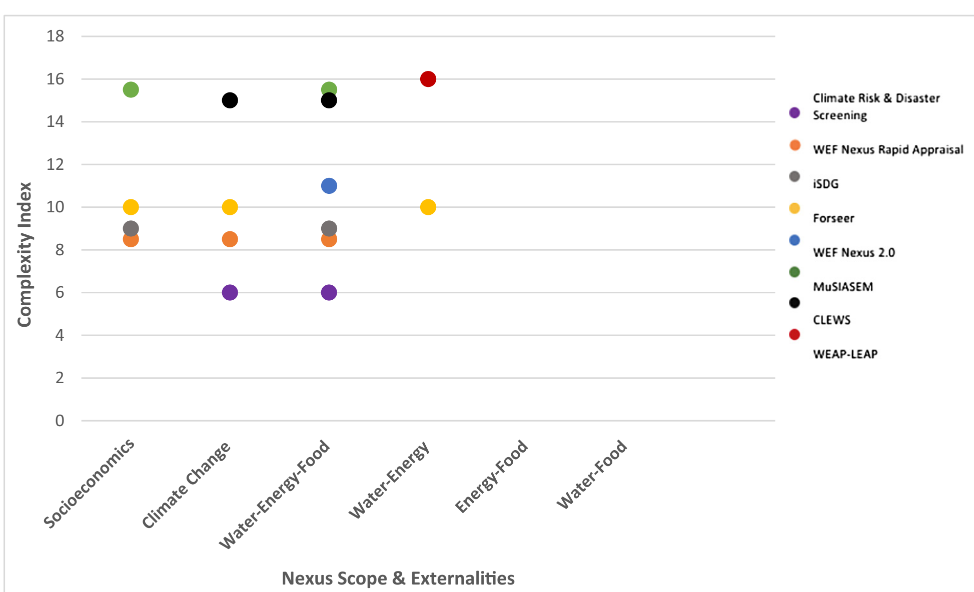

Fig. 5. Complexity vs. scope & externalities covered in the tool.

aesthetics and coherence of the visuals. As more tools are added to the inventory, a web-based platform with filtering mechanisms such as those offered by Mannschatz et al. (2016) could be employed to make the scoring and mapping processes more efficient. While the categories used (scope, purpose, methodology, externality) were selected to best capture the overall application and use of a tool, some tool attributes could not be included. *Tool scope* only captures the key nexus resource system interactions, and does not specify the primary focus or resource entry point: this could be a helpful determining factor for stakeholders.

5. Conclusion

This paper opens up a new discussion on the notion of simplicity and complexity among nexus assessment tools. A scoring system has been delineated to measure a tool's relative complexity through a set of prescribed attributes derived from the user-experience (UX) and systems engineering concepts. The mapping of tool complexity relative to different categories allows for a visual representation of tool applications as well as their relationships and trends with respect to other nexus tools. The resulting visuals are to be leveraged by the prospective user as guides for identifying the tool(s) best suited for specific assessment requirements.

The scoring and mapping exercises further highlight the varying roles of all nexus tools across the simplicity-complexity spectrum. While higher complexity tools generally allow for more detailed analysis and include more advanced features to accommodate scenario-development, it does so at the cost of narrowing analysis to certain sub-nexi (i.e. Water-Energy issues) in addition to increasing the need for more granular data and high-skilled users who have an understanding of the water-energy-food nexus. As a result, complex nexus tools require more institutional support to ensure the human and technical resources to operate a tool are available and accessible. Similarly, while 'simple' nexus tools do not generally require a specified skillset and data inputs that are less granular, the tradeoff of 'simplicity' is that the tool outputs capture nexus interactions and relationships at a high-level of understanding. 'Simple' tools thus play a useful role in identifying nexus "hotspots," a key component to the initial stages of any nexus assessment or application in new or existing policy.

Most available tools seek to quantify the inter-sectoral trade-offs across water, energy, food sectors, and include external factors such as climate change and population growth, however, risk assessment is often left out. 'Risk-informed planning' is shown to be a component of only three of the studied tools. Given the variable state of global climate and the socio-economic-political environment, evaluating risk helps stakeholders develop resilient, adaptive policies. Overall, the comparative study of the nexus tools produced results that concur with the concerns expressed in various literature sources on the nexus challenges about the knowledge gap between the field of policy/decision-making and that of research. Most of the tools studied here received medium-to-high complexity scores, while tools for preliminary assessment and capacity building purposes are lacking.

Further work is needed in the organization of accessible nexus tools and to ensure that the tools are accessible to stakeholders in the decision-making sectors. This can be achieved by integrating collaborative and participatory approaches to nexus tools. The disarray in structure, organization, and collaboration on nexus management tools became evident through the mapping process and the creation of the *complexity index*. Going forward, it is imperative that researchers and stakeholders in the WEF nexus community increase coordination and collaboration to avoid repetition in methodologies and tool development. This collective approach can result in building upon and strengthening existing tools.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.09.080.

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