The nexus social-ecological system framework (NexSESF): A conceptual and empirical examination of transdisciplinary food-water-energy nexus

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ABSTRACT

Over the past decade, debates on the governance of food, water, and energy resources (FWE nexus) have increased, provoking new insights into social importance in ecological balance. Policymakers, management professionals, and scholars of the FWE nexus call for new approaches that address ranges of social and ecological impacts of uncoordinated sectoral planning. From a theoretical perspective, social-ecological systems (SES) science offers a balanced approach for improved FWE nexus through consolidating knowledge from a wide range of disciplines and providing the opportunity to adapt to the changing environment. However, although increasingly employed, it has been complicated to empirically monitor and evaluate the dynamic social-ecological nexus systems. A framework for translating SES theory into FWE nexus practice is needed. This paper develops an integrated assessment framework of the social-ecological nexus systems governance and presents results from its application to a Dutch smart-eco city. An integrative multi-level analysis scheme is used to analyze intra- and inter-relationships, quantify social and ecological impacts of uncoordinated FWE management, and visualize FWE supply-chain risks posed to cities by the dynamic humans and nature interactions. The evidence-based approach of this study proved advantages of the proposed framework in (i) revealing connections of natural resources and the cultural, regulating, and supporting services of nexus systems, and (ii) making practical recommendations for improved socio-ecologically-balanced nexus interventions. The results can support policymakers and management professionals of the FWE nexus to organize their analytical, diagnostic, and prescriptive capabilities to make development decisions on urban resilience and ecological balance.

1. Introduction

It is widely acknowledged that the integrated food, water, and energy sectors management (FWE nexus) arises at the intersection of complicated social and natural systems (Berkes et al., 2003). Interests disputes, the cross-scale nature of nexus actions, and widespread social and ecological uncertainties demand new strategies. The best of FWE nexus strategies should be turned toward social and ecological uncertainties demand new strategies. The best of FWE nexus strategies should be turned toward social and ecological integration, aiming for an innovative governance approach that accommodates diverse views. Adaptive and transdisciplinary-based forms of governance have drawn attention to this need, yet much emphasis has been directed at the role of science and overcoming the information gap. Translating principles of the integrative social-ecological governance into FWE nexus strategies and practices has remained a challenge.

A newly emerging, integrative, and transdisciplinary approach that holds promise for adaptive FWE nexus governance is Social-Ecological Systems (SESs) (Maass, 2017). An SESs approach to FWE nexus governance frames linkages between humans and nature as part of a complex system with multi-scale dependencies and interactions. This approach provides insights into the multi-dimensional patterns and processes characterizing FWE nexus systems.

In practical application, questions arise on how the SESs approach helps identify systems-level responses to FWE nexus? A comprehensive framework and also empirical approaches are lacking in the literature to support such a nexus responsive concern. This paper addresses this concern by balancing the two thoughts of materialistic flows of the FWE resources and social flows into a social-ecological analysis. It does so by further conceptualizing the social-ecological interconnections between FWE resources flows. Specifically, this paper offers a conceptual framework that helps define and identify interconnections of the social and ecological flows shaping connections between the sectors of FWE and the actors facilitating these connections. Moreover, this study applies an evidence-based approach via analyzing real-world data from a...
Dutch smart-eco city in order to prove the usability of the proposed framework. In the urban context, this paper argues that it is in particular social interventions that lead the way towards more cross-sectorial provisioning of food, water, and energy.

The paper is structured as follows. Section 2 provides background information into the literature on FWE nexus, emphasizing social and ecological interconnections. Section 3 offers a conceptualization of an FWE nexus approach from the integrative social-ecological systems perspective for improved nexus strategies. To build this approach, we bring together different strands of the literature, including material flows analysis, environmental impacts, and the network society. Section 4, furthermore, illustrates these arguments through the employment of an example on FWE nexus in the Netherlands. The real-world examination sets the stage to support integrating thematic perspectives of FWE nexus, social-ecological balance, transdisciplinarity, and adaptive governance in a multi-level analysis presented in a tabular form (Section 5). Results of this study are meant to support policymakers, management professionals, and scholars of FWE nexus to organize their analytical, diagnostic, and prescriptive capabilities so that urban interventions can be made on social-ecological balance. Section 6 concludes by reflecting on future developments of integrative nexus strategies.

2. A shifting paradigm for FWE nexus

The FWE nexus has emerged as a concept to improve the sustainable use and supply of natural resources. It stands for cross-sectorial policy-making within FWE provisioning domains to overcome trade-offs and stimulate synergies in sustainable development. A key issue that it recently seeks to overcome is working in disciplinary isolation. Indeed, when it comes to resources governance, policymakers have continued to formulate policies in silos that do not guarantee coincident attainment of FWE security and social sustainability (Bhuduri et al., 2015). It needs to go further into a more socially driven vision that focuses on the role of institutional arrangements, networks, and social meanings in shaping urban provisioning of FWE resources (Covarrubias, 2019).

However, such a social-ecological perspective is often ignored when analyzing interconnections among the FWE resources in cities (Covarrubias, 2019). Only a few studies have addressed the FWE resources governance from a more balanced social-ecological perspective (see Pahl-Wostl et al., 2013; Schiller et al., 2014; Scott et al., 2011).

At a societal level, Grant et al. (2002) presented a sociological approach, namely quantified theory of Luhmann, to couple societal aspects of natural resources management with material flow models. They quantified the impacts of societal constraints on environmentally relevant human actions. Quantitative representation of the social system in framing ecological problems is an advantage to nexus studies; however, it is rather a simplistic model that lacks the feedback of human action on social structure and the strength of the different social components on ecological decision-making.

At the level of organization, Binder (2007) introduced a structural agent analysis approach based on Giddens structuration theory that provides the understanding of social structures restricting or enabling strategies for managing ecological flows. This approach analyses the dynamics of social structure, including culture, studies interferences among agent groups (i.e., local communities, scholars, management professionals, and industries), and examines the different time scales of changes in social structure and ecological flows. However, in practice, this approach encounters some methodological issues regarding the weighting and operationalization procedures of factors.

At an individual level, psychological approaches such as surveys and experiments for explaining social agents’ behavior affecting material flows in ecosystems and interventions for changing such behavior are mostly used. Hansmann et al. (2005); Jean et al. (2018) analyzed how game simulations of environmental and economic impacts of resources (e.g., water or food) consumption patterns influenced participants’ subsequent behavior towards the use of the resources in an environmentally friendly manner. These approaches provide information about factors influencing human behavior towards natural resources consumption, although they are data and time intensive.

On closer inspection of how such approaches address the social dynamics of nexus systems, the result mainly reflects that the social dimension is not adequately conceptualized. Although those approaches provide a step forward in proposing methodologies for social-ecological analysis and perspectives, what is missing is an approach that understands the social significance of different nexus systems interactions and how they get configured through FWE resources governance. Recently, de Grenade et al. (2016); Maass (2017) introduced the social-ecological systems (SESS) theory to support encompassing the novel paradigm in FWE nexus although the gap yet exists in a lucid exposition of the SESS theory to nexus strategies. Therefore, this research posits the SESS theory as a suitable analytical perspective for emphasizing that the nexus is about the connectivity of resources flows and their embedded social relationships around FWE.

3. The nexus social-ecological system framework (NexSESF)

This study used social-ecological systems theory as a base to address the FWE nexus from a more balanced social-ecological perspective. The SESS theory conceptualizes the uncertain and dynamic human-environmental systems and develops a systematic process for continuously improving management policies and practices by evaluating alternative scenarios about the systems being managed and learning from operational plans outcomes (Petrosillo et al., 2015). A central aspect in dealing with nexus SESSs is that they are characterized by cross-scale interactions, both spatial and temporal, and the same applies to their governance since decisions made on one location at a time can affect people at the same or another time living elsewhere. In this perspective, humans are considered as agents acting within nexus SESSs rather than external drivers of natural systems, so that site-based, bottom-up, and transdisciplinary approaches are at the core of the nexus SESSs research for sustainability.

To make the SESS theory fully operational for FWE nexus research, a right choice of social-ecological system frameworks, differing significantly in their goals and applicability, needs to be made to guide a more sustainable nexus SESSs management. There are several existing frameworks for analyzing social-ecological systems that reflect the variety of research fields, and that can be applied according to the problem to be studied and how the social-ecological system is conceptualized (see Binder et al., 2013). Our comparison of the frameworks’ contextual and structural criteria concerning the goal of integrative FWE resources governance guides our research for selecting an adequate framework for nexus systems understanding (Table 1).

Among the frameworks studied, SESS (Social-Ecological Systems Framework) (see Appendix: Fig. A. 1) is the one that best serves our purpose of understanding nexus systems’ dynamics and interactions. SESS treats the social and ecological systems in almost equal depth and provides a frame for developing different degrees of specificity in analyzing the potential sustainable development of a social-ecological system. In SESS, the social system is conceptualized as resource users (actors) and the governance structure that affects the actors’ actions, and the ecological system is conceptualized from an anthropocentric viewpoint as resource systems and corresponding resource units (Binder et al., 2013). Research revealed that longer-term sustainability of an SES depends on rules matching the resources systems, resource units, and actors’ attributes. SESS contributes strongly in this regard. It helps to better understand the governance challenges that arise in nexus SESSs and understand which governance arrangements effectively preserve the systems. The governance structure by defining rules as well as monitoring mechanisms and characterizing the kind of interdependence between users together set the condition under which action situations occur (Hinkel et al., 2015).

Concerning FWE nexus principles and SESS fundamentals, we
introduce NexSESF (Nexus Social-Ecological Systems Framework) for nexus research to grasp the significance of a socio-ecological view on FWE systems (Fig. 1). Conceptually, the development of NexSESF is supported by adapting a generic data organizing structure for characterizing the intertwined nature of SES within FWE production systems. The scope of characterization includes food, water, energy supply and waste treatment as well as social and technological interacting components significant for nexus policies and practices. At the abstract level, an FWE system comprises several interrelated components each in turn encompasses one or more processes of transforming or generating flows and possibly changing states of components. NexSESF characterizes an FWE system with four different types of components:

- **Ecological components** address food, water, and energy related ecosystems, including forest, wetlands, and heathlands. These components include ecological processes which although affect the availability of basic FWE resources, can, in turn, provide ecosystem services by means of raw material flows such as biomass for energy production.

- **Social components** refer to the socio-economic structure encompassing social practices, networks, and power dynamics that go along through FWE material flows. These components focus on the role of policies, institutional arrangements, and social meanings in shaping urban provisioning of resources (Covarrubias, 2019). Incorporating social and material flows emphasizes that the FWE nexus policies and practices should rely on the connectivity of FWE resources flows and their embedded social relationships.

- **Technological components** are principally human-made facilities that provide services and products through FWE material flows. These components focus on the role of technological interventions in a particular situation of an SES.

- **Action-oriented frameworks** act upon or intervene in a particular situation of an SES.

### Table 1

A comparison of existing frameworks for analyzing social-ecological systems and a guide for selecting the adequate framework for evaluating and improving FWE nexus SESs performance.

<table>
<thead>
<tr>
<th>Framework</th>
<th>Social scale</th>
<th>Spatial scale</th>
<th>Interaction type</th>
<th>Dynamics</th>
<th>Degree of equal S and E representation</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPSIR Driver, Pressure, State, Impact, Response</td>
<td>Decision-makers</td>
<td>Any scale</td>
<td>E → S</td>
<td>Not conceptualized</td>
<td>Anthropocentric</td>
<td>S &gt; E</td>
</tr>
<tr>
<td>ESA Earth Systems Analysis</td>
<td>Society</td>
<td>Global scale</td>
<td>S → E</td>
<td>Not conceptualized</td>
<td>Eocentric</td>
<td>E &gt; S</td>
</tr>
<tr>
<td>ES Ecosystem Services</td>
<td>Society</td>
<td>Any scale; favors regional, national scale</td>
<td>S → E</td>
<td>Not conceptualized</td>
<td>Eocentric</td>
<td>E &gt; S</td>
</tr>
<tr>
<td>HES Human Environment Systems Framework</td>
<td>Includes all hierarchical levels</td>
<td>Any scale; favors regional, national scale</td>
<td>S ↔ E</td>
<td>Short- and long-term feedback loops between S and E</td>
<td>Anthropocentric</td>
<td>S &gt; E</td>
</tr>
<tr>
<td>MEF Material and Energy Flow Analysis</td>
<td>Society</td>
<td>Any scale; favors regional, national scale</td>
<td>S → E</td>
<td>Not conceptualized</td>
<td>Eocentric</td>
<td>E &gt; S</td>
</tr>
<tr>
<td>MTF Management and Transition Framework</td>
<td>Includes all hierarchical levels</td>
<td>Any scale; favors regional, national scale</td>
<td>S ↔ E</td>
<td>Single, double, and triple loop learning of S as a reaction to changes in E</td>
<td>Anthropocentric</td>
<td>S &gt; E</td>
</tr>
<tr>
<td>SES Socio-Ecological Systems Framework</td>
<td>Includes all hierarchical levels</td>
<td>Local and regional scale</td>
<td>S ↔ E</td>
<td>Feedback between the resource conditions and the rules determining the consumption rates of the resource</td>
<td>Anthropocentric</td>
<td>S ≈ E</td>
</tr>
<tr>
<td>SLA Sustainable Livelihood Approach</td>
<td>Local stakeholders</td>
<td>Local and regional scale</td>
<td>E ↔ S</td>
<td>Not conceptualized</td>
<td>Anthropocentric</td>
<td>S &gt; E</td>
</tr>
<tr>
<td>TNS The Natural Step</td>
<td>Businesses or regions</td>
<td>Business and regions</td>
<td>S → E</td>
<td>Not conceptualized</td>
<td>Eocentric</td>
<td>E &gt; S</td>
</tr>
<tr>
<td>TVUL Turners Vulnerability Framework</td>
<td>Local communities</td>
<td>Local scale</td>
<td>E → S</td>
<td>Not conceptualized</td>
<td>Anthropocentric</td>
<td>S &gt; E</td>
</tr>
</tbody>
</table>

**Note:** The table presents key criteria of the several existing frameworks for analyzing social (in this table referred as S) and ecological (in this table referred as E) systems in different ways. These frameworks reflect the variety of research fields and can be applied according to the problem to be studied and the way in which social-ecological systems are conceptualized. This research made a comparison of the SES related frameworks based on a number of criteria namely: social scale (i.e., social system hierarchal levels), spatial scale (i.e., spatial scale of the ecological system, at which the framework can be applied), interaction type (i.e., the way interactions between S and E are conceptualized; S → E presents how human actions and resource needs affect the ecological system, E → S describe the influences of the ecological systems on the social systems, S ↔ E addresses the reciprocity between social and ecological systems), dynamics (i.e., the way in which SES change over time), degree of equal S and E representation (i.e., the extent to which S and E are treated equally with respect to analytical depth), and orientation (i.e., perspective of the framework; analysis-oriented frameworks provides a general language for formulating and approaching different research questions, and action-oriented frameworks act upon of intervening in a particular situation of an SES).

Source: Adapted from Binder et al. (2013).
support processes for converting raw materials from ecological components into product flows; the treatment of waste and water; and the storage of resources. Such components interact well with each other through flows of FWE resources.

**Demand components** represent those components of the system that can receive flows that either process them to generate new flows or act as terminating points for flows, such as discharge or local consumption. These components may be of a social, ecological, or technological nature, but not fulfilling a function, merely representing a demand (Martínez-Hernández et al., 2017).

NexSESF couples the different components of an FWE system through direct input and output material and services flows among resources, indirect effects such as alteration of biogeophysical conditions or effects on stability and quality of ecosystem services, or indirect socio-economic impacts on the natural systems such as changes in resources availability conditions.

### 3.1. NexSESF operationalization and employment

Employment of NexSESF into a real-world FWE nexus locale is achieved by operationalizing the underlying drivers of the nexus components and adopting an unsupervised learning algorithm, Principal Component Analysis (PCA), for quantifying the interrelated drivers. The structure of NexSESF operationalization is presented in Table 2. We turned concepts of the nexus system components depicted by NexSESF into measurable variables and indicators. Variables comprise predictability of the ecological system dynamics; resource units’ flexibility, dependency, stability, efficiency, and accessibility; social network structure; operational rules; economic development; social project; operational processes; and social and ecological performance measures. To quantitatively measure the variables, we defined several indicators for each, presented in Table 2. The selection of indicators was based on multiple criteria: confirming international standards, considering biophysical limits, being limited in numbers (i.e., quantifying nexus drivers as numbers, even those of qualitative description), and considering data availability.

The defined indicators represent a trend tracking the measurable changes in an FWE nexus system over time. Indicators need to draw upon a large set of data, possibly varying in scale, to quantify the latent or underlying relationships among components of an FWE nexus system and the key drivers of such relationships. Several challenges are associated with using large datasets for nexus research, including integrating data varying in scale, tricky process of converting large datasets into valuable insights, and complexity of managing data exploration and visualization. The employment of NexSESF which relies on a significant number of indicators and a large set of data requires a method that can overcome the challenges of working with high-dimensional datasets.

PCA, as one of the most widely used exploratory methods for data analysis, simplifies the complexities of high-dimensional data while retaining trends and patterns. Although dimensionality reduction normally comes at the expense of accuracy, the resulting simplicity is well worth it since smaller datasets are easier to explore and visualize. PCA transforms the data into fewer dimensions called principal components (PCs), which act as best summaries of the dataset features (Lever et al., 2017). PCs are new uncorrelated variables constructed as a linear combination of the initial variables so that most of the information within the data is compressed into the first PCs. Geometrically speaking, PCs represent the directions of maximum variance in the data, having the first PC capturing the highest possible variance. The relationship between variance and information here is that the larger the variance carried by a line, the larger the distribution of the data points along it, and the larger the data distribution along a line, the more the information it covers.

This research took advantage of the PCA method to recognize central dynamics of FWE nexus changes, in a real-world context, over time. We used Python programming language and the Scikit-learn machine learning library to perform PCA analysis.
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In this section, we present a case study to demonstrate the application of NexSESF, by the following steps:

(1) Introducing the FWE nexus setting of the case study, including the objectives and the specific system components studied for the selected locale (Section 4.1); and

(2) Presenting application results of the NexSESF on a system with synergistic relations (Section 4.2).

4.1. Characterization of the case study

NexSESF was employed to analyze a nexus system comprising components considered for the Eindhoven smart-eco city in the Netherlands as part of a restructuring urban development plan. The plan considers a vision of integrated blue, green, and grey infrastructure that fully satisfies the food, water, and energy needs of the corresponding population (Hawxwell et al., 2018). To meet such needs, Eindhoven has integrated several social, ecological, and technological systems components and incorporated many nature-based features into re-development plans of the city. Developing gas-free districts, increasing permeable surfaces, creating greener areas, controlling stormwater, and encouraging citizens in local food production are examples of Eindhoven’s SES incorporation activities. In addition, citizens have been challenged to discuss ecological problems of their living area and organize the exchanges with policymakers, management professionals, and scholars that provide solutions to the problem posed.

Here, the principal objective is to examine the various components of the local FWE systems and their interdependencies on the level of demand satisfaction in Eindhoven. The spatial scope of the study included the FWE systems available to the city, including residential, industrial, and ecosystem areas. The temporal scope is of 15 years from 2004 to 2018, which is a scale suitable to observe changes in ecological components due to the impact by social and technological components.

The local nexus system under study comprises multiple components of the food, water, energy nexus subsystems along with the main social and technological parameters required for evaluation.

4.1.1. Food subsystem component

The potential production of fresh vegetables, grains, fruit, meat, and dairy for local demand was considered in the Eindhoven food subsystem. Water, energy, and fertilizer requirements are compiled from the trend of resources consumption over time. The food components produce biomass as residues for which a waste processing is of need. The food subsystem also plays a role of assimilating excess nutrients available in the local system.

4.1.2. Water subsystem component

It includes wastewater treatment plant as a technological component and some aquifers set off to the city as ecological components in Eindhoven which also significantly absorb CO₂ and excess nutrients but may be under threat from the current environmental and management conditions.

4.1.3. Energy subsystem component

It includes combined heat and power plants and roof-mounted solar panels on the houses as technological components. Heathlands are ecological components that provide biomass as an ecosystem service in Eindhoven for local demand was considered in the Eindhoven food subsystem. Water, energy, and fertilizer requirements are compiled from the trend of resources consumption over time. The food components produce biomass as residues for which a waste processing is of need. The food subsystem also plays a role of assimilating excess nutrients available in the local system.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Variable</th>
<th>Indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>External drivers</td>
<td>Economic development</td>
<td>GDP (% annual change), average income per private household (x 1000 euros).</td>
</tr>
<tr>
<td>SES interactions effects and outcomes</td>
<td>Demographic trend</td>
<td>Population growth rate (%).</td>
</tr>
<tr>
<td></td>
<td>Deliberation processes</td>
<td>Social cohesion measured based on citizens’ attitudes relative to social relations.</td>
</tr>
<tr>
<td>Social measures</td>
<td>Percentage of population overweight (%), drinking water quality in terms of total nutrients emission to water by private households (1000 inhabitant equivalents), annual volume of effluent wastewater discharged from urban wastewater treatment plants (1000 m³), total capacity of urban wastewater treatment plants (1000 inhabitant equivalents).</td>
<td></td>
</tr>
<tr>
<td>Ecological measures</td>
<td>Annual carbon dioxide (CO₂) emission by different sectors of private households, energy, agriculture, and waste and water treatment (million kg). Contribution of the use of different renewable energy types (i.e., solar energy, wind power, hydropower) in avoidance of CO₂ emission (in % of the total annual CO₂ emission), annual amount of household’s residual waste (kg per inhabitant), installed capacity of solar panels on agriculture (kW), the amount of soil mineral excretion, including nitrogen, phosphate, and potassium, per hectare of cultivated land (kg/ha).</td>
<td></td>
</tr>
</tbody>
</table>

Note: This table presents the operationalization of variables depicting different social, ecological, technological, and demand components of an FWE nexus system, their dynamics, and interactions. The dependent variable of this study is the performance of integrative nexus systems governance, while the independent variables consist of economic and demographic development; predictability of the ecological system dynamics; resource units’ flexibility, dependency, stability, efficiency, and accessibility; social network structure; operational rules; deliberation processes; and performance measures from both social and ecological perspectives. In the ‘indicators’ column, the parentheses represent units for the quantification of the indicators. See Appendix: Table A.1 for a detailed presentation of the indicators and their quantification measures for the case study of this paper.

Source: Adapted from Arthur et al. (2019); Giupponi and Gain (2017); International Organization of Standards (2018); King and Carbajales-Dale (2016); Leslie et al. (2015); Maass (2017); Ostrom (2009); Ozturk (2015); Saladini et al. (2018); Wang et al. (2017).
4.1.4. Demand component

Inhabitants are considered in this study as a demand component of the nexus system in Eindhoven which the overall production system should aim to serve by satisfying its food, water, and energy needs.

The interdependence of nexus components in Eindhoven was considered through an exchange of flows among food, water, and energy subsystems and the demand component. These specifications for Eindhoven were generated based on the information available from CBS (Centraal Bureau voor de Statistiek), an online statistical database in the Netherlands, and the Eindhoven city planning documents (see Appendix: Table A.1 for a descriptive summary of the compiled data for Eindhoven and how it is used to cover each indicator, and Table A.2 for the raw data). Due to the different nature of the resources in a nexus system that integrates heterogeneous components, it is desirable to adopt a unifying quantity. In this study, exergy, defined as the available energy of a resource to do useful work, is used (Adapted from Leung Pah Hang et al., 2016).

Fig. 2 depicts how the food, water, and energy subsystems’ components reflect the studied local nexus setting in a quantitative manner. The diagram demonstrates the FWE resources interdependence (in plot (a)) and their pairwise interaction on the level of demand satisfaction in Eindhoven, depicting 15 years of integrative environmental management from 2004 to 2018 (in plot (b)). It can be observed from Fig. 2a that in this integrated case of the nexus system, the water subsystem is more directly dependent in the system, especially on energy, as is presented in Fig. 2b. Although water and energy, in this case, are hardly dependent on direct input from the food subsystem, any changes in the food subsystem will affect the other two by changing water and energy utilization in the nexus.

4.2. Analyzing the FWE nexus in a synergistically integrated scheme

Employing NexSESF, the FWE nexus analysis was evolved into a synergistically integrated scheme intended to reveal central dynamics of the system components. The role of PCA here is to offer NexSESF an exploratory tool that discovers the extent of the influence different variables exert on an FWE nexus system and its variant components interactions.

In this study, NexSESF using PCA discovered key variables that significantly influence FWE nexus in Eindhoven, as shown in Fig. 3 and Table A.3. The plot axes show the value of each indicator in each of the corresponding component. The dots represent NexSESF indicators and their color stands for their values, the darker the color the greater the value (see Appendix: Table A.2 for the numerical data of this figure). Having PC1 as the x-axis and PC2 as the y-axis and the zero value at the intersection of the two components, indicators with the highest absolute X and Y value contribute more to the associated PC. The indicators with high values (darker dots on this plot) have more influence on defining underlying drivers of nexus interactions and changes (a detailed explanation of such indicators is presented in Fig. 4). In addition, the positive values stand for a positive correlation between the indicator and the FWE nexus improvement in Eindhoven. The same applies to the negative values which show a negative correlation of corresponding indicators with the improvement of FWE nexus processes in Eindhoven. The values of the ‘explained variance ratio’ are percentages of variance explained by each of the selected principal components. PC1 explains almost 48% of the data variance, PC2 explains about 23% of the data variance, and cumulatively, they explain almost 71% of the data in this analysis.

Fig. 2. Plots of (a) the FWE resources interdependence and (b) their pairwise interaction on the level of demand satisfaction in Eindhoven depicting 15 years of integrative environmental management from 2004 to 2018. This information is based on the visualization of the unified quantity of NexSESF indicators (in exergy) for Eindhoven. In plot (a), all sources of food, water, and energy that contribute, to any extent, to the production of one another are concerned. We overlayed the resources input-output relationships over the years. The value zero shows the equality of input and output flows for a resource. Darker areas in plot (a) illustrate the most dominant material and production flows across resources over time. For instance, the water subsystem which has a dominant value close to 0.4 over years, receives more input from the other two resource subsystems than its outputs toward them. The line chart (b) displays the magnitude of changes in pairwise food, water, and energy relationships over time. It shows the total values across an almost coordinated trend. The values presented in the chart demonstrate the extent to which each resource is dependent on one another. For instance, over the studied 15 years of resources management in Eindhoven, the demand of water subsystem for energy is significantly high compare with other FWE relationships.
Fig. 4. To minimize complexities and reflect clearly on visible trends in data, we focused on the first two principal components which contribute significantly (i.e., $\approx 71\%$) to explaining the variance of the data. In a two-dimensional graph, Fig. 3 shows the distribution of NexSESF indicators across the selected PCs. Having PC1 as the horizontal x-axis and PC2 as the vertical y-axis, indicators with the highest absolute X and Y values (i.e., darker dots in Fig. 3) contribute more to the associated PC, therefore, have more influence on exploring the FWE nexus in Eindhoven. In this case, whether the value of an indicator across each PC is positive or negative corresponds to how it influences the subject of the analysis. Indicators with positive values correlate positively with the FWE nexus in Eindhoven, and vice versa, there are negative correlations between the FWE nexus in Eindhoven and the indicators having negative values of the PCs.

From the data in Fig. 4, it is apparent that the FWE nexus governance in Eindhoven needs to count on adapting techno-ecological solutions to overcome society’s tendency for more resources. Technological advances in renewable energies such as solar panels, wind turbines, and thermal energy storage may support Eindhoven in balancing resources and reducing the CO$_2$ emission as a climate protective measure. Such developments have positive influences on the FWE nexus purpose of Eindhoven in preserving scarce natural resources. According to Fig. 4, there exist several drivers that influence the FWE nexus in Eindhoven negatively. From plot (a) in Fig. 4, the continuance in the supply of natural gas retards the success of nexus policies and plans in Eindhoven.

In addition to advanced technologies, some socio-economic aspects such as population growth and GDP (per capita) appear to correlate closely to food, water, and energy metrics in Eindhoven (Fig. 4b). Research expressed that areas with higher GDP generally withdraw more water, consume more food, and produce more energy (Susnik, 2018). It is also acknowledged that cities cannot interfere in such socio-economic aspects for FWE nexus improvement. Therefore, along with the previously mentioned techno-ecological actions, Eindhoven needs to focus on the possible indirect drivers of such socio-economic changes.

In addition to PCs emphasizing key direct nexus drivers, PCA, by calculating highly significant correlations among NexSESF indicators, determines indirect drivers of the FWE nexus success (see Appendix: Fig. A. 4). In Eindhoven, level of disciplinarity in socio-ecological projects and the motivation and attitudes of nexus actors have significant indirect influences on FWE nexus progress.

5. Verifying the role of NexSESF in FWE nexus strategies

This section verifies the role of NexSESF in FWE nexus improvement by incorporating several intimate connections between key practical concepts of NexSESF, current FWE nexus concerns, and the goal of social-ecological balance. At the end of this section, further developments of the integrative NexSESF conceptual model are discussed (Section 5.1).

Based on our empirical examination, the novel NexSESF framework presents a great reflection of systematic, transdisciplinary, adaptive, and monitoring mechanisms for FWE nexus concerns in practice. From a practical point of view, FWE nexus concerns how uncovering synergies, detecting detrimental trade-offs, unveiling unexpected consequences, and promoting integrated decision-making and governance. Table 3 illustrates the role of NexSESF, by means of its key practical concepts, in addressing such concerns over FWE nexus.

Systemic thinking entails considering FWE nexus as interrelated connections among multiple social, environmental, technological, and organizational scales, so that the synergistic effects and varying demands are identified (Wolfe et al., 2016). From our practical experience, NexSESF can support a systemic nexus thinking through (i) stressing variables that are most likely to change in response to systems dynamics (Fig. 4) and (ii) identifying synergistic effects and co-benefits that might otherwise be missed in complex production systems (Fig. 2). This perspective is particularly important in densely populated areas where benefits of more efficient resources consumption are high.
Table 3
A thematic perspective on the role of NexSESF, by means of its key practical concepts, in addressing FWE nexus concerns.

<table>
<thead>
<tr>
<th>FWE nexus concerns</th>
<th>Uncovering synergies</th>
<th>Detecting harmful trade-offs</th>
<th>Unveiling unexpected consequences</th>
<th>Promoting integrated governance</th>
<th>Relevance to regaining social-ecological balance</th>
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<tr>
<td>NexSESF practical concepts</td>
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<td>Stability</td>
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<td></td>
<td>Systemic thinking</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>Cost of extraction</td>
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<td></td>
<td>Transdisciplinarity</td>
<td>×</td>
<td></td>
<td></td>
<td>Robustness against over-exploitation of resources</td>
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<tr>
<td></td>
<td>Adaptive governance</td>
<td>×</td>
<td>×</td>
<td></td>
<td>Transparency</td>
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<td>Monitoring mechanism</td>
<td></td>
<td>×</td>
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<td>Willingness to collaborate</td>
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<td>Integrated management decisions</td>
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<td>Deterrence of free riders</td>
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<td>Adapted rules</td>
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</table>

Note: This table aims to verify the assessment of this study by incorporating several intimate connections between NexSESF, current FWE nexus concerns, and the goal of social-ecological balance. Systematic thinking, transdisciplinarity, adaptive governance, and monitoring mechanism are key concepts characterizing NexSESF from a practical point of view.

Source: Frey (2017); Ghodsvali et al. (2019); Howarth and Monasterolo (2016); Ostrom (2009); Virapongse et al. (2016).

Transdisciplinarity frames FWE nexus as a process that starts with ‘what exists’, continuing with ‘what we can do’, moving towards ‘what we want to do’, and resulting in ‘what we need to do’. The empirical examination of an FWE nexus system using NexSESF in this paper shows that our proposed framework contributes greatly towards transdisciplinarity (see Table 2). It characterizes ecological structure (e.g., FWE demand profile) and socio-economic status (e.g., social network) of a nexus system to understand ‘what exists’. In addition, by studying ecological functions (e.g., resources stability, efficiency, and accessibility) and decision-making processes (e.g., operational rules, and attitudes of actors), NexSESF identifies capabilities of a system for a state of preservation and referring to ‘what we can do’ and ‘what we want to do’. Moreover, NexSESF stresses the potential for practical FWE nexus improvements by highlighting central drivers of social and ecological interactions that can respond to ‘what we need to do’. Accordingly, NexSESF can help detect and minimize detrimental trade-offs through identifying context-specific solutions adapted to the respective resource scarcities (e.g., the right choice of irrigation systems for drier regions).

Adaptive governance supports the great deal of nexus uncertainties originate from mismatches between characteristics of environmental sectors and the way corresponding organizations are governed. NexSESF couples social and ecological metabolisms of a nexus setting through characterizing interconnections between ecological structures and socio-economic processing and organizational decision-making. It can, accordingly, assist in considering unexpected consequences of solutions to environmental management.

Monitoring mechanism acts to position assessment, reflection, and learning in empirical FWE nexus contexts. NexSESF, by bringing together different actors involved in FWE management and considering uncertainties involved in social-ecological interactions, can promote coordination and policy coherence, and help keep track of the impacts generated by policies. It draws attention to key variables that structure the most complex interactions in nexus systems and support the understanding of future trajectories.

5.1. Future developments of the nexus integrative framework

Through examining NexSESF application results, useful information for decision-making can be derived for the nexus situation in a particular locale. This is helpful, especially because the nexus can manifest differently depending on the condition. As a framework mainly for studying integrative social-ecological nexus systems, NexSESF needs sufficient details of a locality to carry out meaningful assessments. As long as context-specific data is unavailable, the adoption of generic values for missing parameters could introduce inaccuracies to NexSESF outputs. Therefore, engagement with nexus scholars and local communities to develop context-specific datasets is crucial for successfully applying such a framework.

Although arguably less critical at local scales, NexSESF currently does not explain spatial variations of ecosystem components and will benefit from adding spatially explicit assessment capabilities. Moreover, the framework could be enhanced in aligning the FWE nexus studies at different resolutions. Given the multi-scale nature of FWE nexus challenges, it would be helpful to connect a framework that focuses on detailed assessment at a local level, such as NexSESF, with tools that address other levels.

6. Concluding remarks

Addressing the need for integrated frameworks to understand and assess the food-water-energy nexus from a social-ecological perspective, this research presented a new analytical framework, namely NexSESF. A novel aspect of the framework involves analyzing social and ecological systems and demand components to capture temporal dynamics while incorporating specific technological components for food, water, and energy supply. The framework can explore interactions and dynamics of social structure, including the role of factors such as deliberation culture and level of disciplinarity in analysis. This provides a cross-level approach allowing the study of interferences among agent groups involving in processes of resources production, processing, and distribution. To achieve more efficient resource consumption and a better balance between demand and supply within a local system, the framework helps explore potential synergies between different technological components. These aspects allow nexus scholars to incorporate details and gain holistic insights into not only the interdependencies but also the dynamics in the social and techno-ecological system and the opportunities of better managing the FWE nexus. NexSESF allowed synergistic assessment of a local nexus system in a Dutch smart-eco city. It was found that the synergistic assessment through a combination of clarifications on social responsibility, ecological balance, technological progress, and political participation suggested potential amendments to nexus practices.

NexSESF is particularly useful in exploring potential improvement options for specific optimization strategies within a wider context of a local nexus system. As a framework mainly for studying integrative social-ecological nexus systems, NexSESF needs sufficient details of a locality to be able to carry out meaningful assessments. Engagement with nexus scholars and local communities to develop context-specific datasets is crucial for successfully applying such a framework.
CRediT authorship contribution statement

Maryam Ghodsvalli: Conceptualization, Methodology, Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. Gamze Dane: Writing – review & editing. Bauke de Vries: Writing – review & editing, Supervision.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.01.010.

References


