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An approach to cluster the research field of the food-energy-water nexus to determine modeling capabilities at different levels using text mining and cluster analysis

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ABSTRACT

The global demand for resources such as energy, land, or water is constantly increasing. It is therefore not surprising that research on the Food-Energy-Water (FEW) nexus has become a scientific as well as a general focus in recent years. A significant increase in publications since 2015 can be observed, and it can be expected that this trend will continue. A multilevel (macro, meso, and micro) perspective is essential, as the FEW nexus has cross-sectoral interdependencies. Several review studies on the FEW nexus can be found in the literature, in general, it can be concluded that the FEW nexus is a multi-disciplinary and complex topic. The studies examined identify essential fields of action for research, policy, and society. However, questions such as what are the main research fields at each level? Is it possible to divide the research into specific clusters? and do the clusters correlate with the levels, and what are the methods of modeling used in the clusters and levels? are still not fully discussed in the literature. An extensive literature review was conducted to get insight into the existing research areas. Especially in such fields as the FEW nexus, the amount of literature can get huge, and a human could get lost analyzing the literature manually. For that, we created word clouds and performed a cluster- and network-analysis to support the selection of most relevant papers for a detailed reading. In 2021, the most publications were published, with 173 publications, which corresponds to a share of 26.6 %. There has been a significant increase since 2015, and it can be expected that this trend will continue in the coming years. Most of the first authors come from the USA (25.4 %), followed by China with 22.4 %. From the word cloud and the top 20 words, which appear in the title and abstract, it can be deduced that the topic water is the most represented. However, the terms system, resource, model, study, change, development, and management also appear to be very important, which indicates the importance of a holistic approach to the topic. In total 9 clusters could be identified at the different levels. It can be seen that three clusters form well. For the others, a rather diffuse picture can be observed. In order to find out which topics are hidden behind the individual clusters, 6 publications from each cluster were subjected to a more detailed examination. With these steps, a number of 54 publications were identified for detailed consideration. The modeling approaches that are currently being applied in research can be classified into domain-specific tools (e. g. global water models, crop models or global climate models) and into more general tools to perform for example a life cycle analysis, spatial analysis using geographic information system, or system dynamics for a general understanding of the links between the domains. With the domain-specific tools, detailed research questions can be addressed to answer questions for a specific domain. However, these tools have the disadvantage that especially the links between the sectors food, energy, and water are not fully considered. Many implementations that are made today are at lowest level (micro) relate to bounded spatial areas and are derived from macro and meso level goals.

Introduction

The global demand for resources such as energy, land, or water is constantly increasing. Guided by internationally accepted objectives of reducing anthropogenic emission of greenhouse gases (GHG), the United Nations (UN) and its member bodies are now participating in ambitious climate action goals targeting clean energy and sustainable food and water supplies. With the Bonn Conference in 2011, Food-Energy-Water (FEW) nexus topics moved into the scientific and non-scientific focus [1]. In January 2015, the agenda for sustainable development was ratified, with the aim to make significant shifts towards sustainable path-

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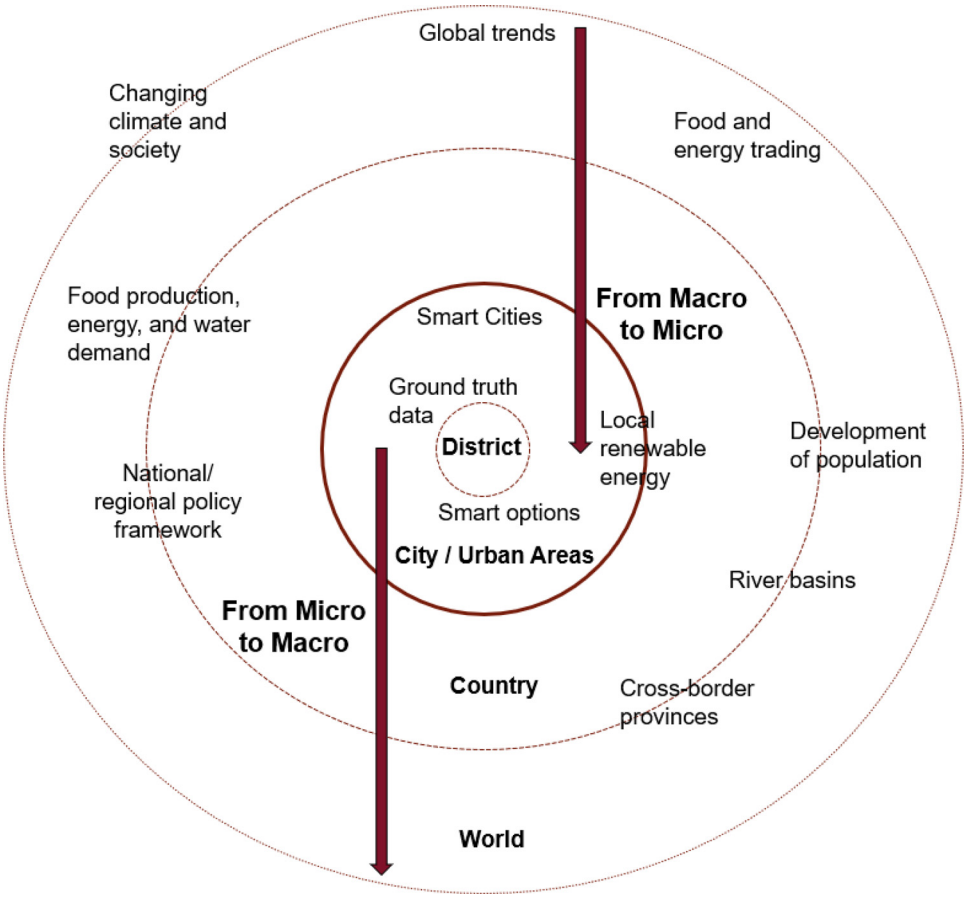

Fig. 1. Illustration of the macro, meso and micro level as spatially resolved levels and mapping of some topics to the levels (own illustration)

ways for human habitation [2]. As part of that agenda, 17 goals and 169 targets were defined. The goals include a wide range of economic, social, and environmental objectives, while from the 169 targets, approximately 45 directly relate to food, energy and water and its nexus.

Therefore, governments worldwide have taken ground-breaking decisions to reduce emissions and thus limit the global temperature increase to a maximum of 1.5°C. Europe wants to become the first climate-neutral continent by 2050, as expressed with its Green Deal strategy [3]. Canada has introduced the Canadian Net-Zero Emissions Accountability Act to achieve a net-zero emissions economy by 2050 [4]. At the international level, the United Nations (UN) Sustainable Development Goals (SDGs) and the Paris Agreement [5] are the guiding frameworks.

On the one hand, it is essential to sign international agreements on climate protection, such as the Paris Agreement. However, this raises questions: ***What consequences have the agreements on local systems in cities, urban or rural areas? What are the possibilities to act locally? What is the impact of single measures, and what are the interrelations between the food, energy, and water sectors?***

The shift of population to cities provides challenges when considering the delivery of food, energy, and water to the urban population. The power delivery is shifting towards renewables and electrification (appliances using electricity rather than gas or liquid fuel). On the water topic, measures include water conservation and reuse, sustainable wastewater treatment, or sustainable irrigation in agriculture. On the food side, measures must be taken to reduce the environmental and climate impact of food production, distribution, processing, consumption, and waste recovery. Promising new concepts like urban farming (e. g. vertical farming, hydroponics, or aquaponics) or efficient greenhouses with integrated renewable energy sources must be explored further.

Since decisions on national or international levels directly impact the local level of cities, urban or rural areas, it is essential to consider the scale of decision making. A multilevel (micro, meso, and macro) perspective is essential, as the FEW nexus has cross-sectoral interdependencies [6]. The definition and research topics of each level are currently the subject of research. Chen and Chen [7] define the three levels as follows: The micro-level (microsystem) is the most direct environment in which the resources such as water, energy, and food are located and are the innermost layer. The meso-level connects the water, energy, and food microsystems. The macro-level is the external environment. It includes the social environment, the economic environment, and the natural environment.

Another way to describe the levels is outlined in the AWESOME project [8], where the macro-level represents the global perspective, where trends related to climate change and society must be considered. The meso-level can be considered as the country, or inter-country level (like river basins) where factors and scenarios related to the development of population, food production, energy, and water demand are crucial and guide the national and regional policy framework. At the lowest, the micro-level, the effectiveness of alternative options can be analyzed in detail and compared with ground truth. The definition of the levels from the AWESOME project can be interpreted as spatially resolved, as illustrated in Fig. 1.

At the beginning of this review paper, a broader view on the FEW nexus is taken, for which a systematic analysis of the existing literature was carried out. The databases Web of Science (WoS) and Scopus (SC) were searched for relevant literature using different search terms. The search terms should appear in the title, abstract, or in the keywords.

Material and methods

Several review studies on the FEW nexus can be found in the scientific literature. The identified studies have different scopes. In the fol-

lowing, a summary of the most relevant studies is presented. Further, it will be shown why it was important for this work to conduct our own review of the existing literature.

The review paper from Bazilian et al. [9] was already published in 2011, in the same year when the Bonn Conference took place. With 617 citations, it is currently the most cited. Descriptive elements such as rapidly growing global demand, resource constraints, global impacts, highly regulated markets, or varying regional availability and variations in supply and demand for energy, water, and food are described. In addition, five examples from the energy perspective (1. energy access and deforestation, 2. biofuels (and unconventional oil and gas) production, 3. irrigation and food security, 4. hydropower, and 5. desalination) were discussed. Three promising areas for further exploration are outlined (1) framing the issue around strong political 'motivators', (2) building institutional capacity to understand and act on the complex interactions, and (3) developing and applying modeling tools that can support integrated decision-making.

The review done by Guerra et al. [10] aimed to identify recommendations for public policy, research and development, and practices toward better understanding the importance of the nexus in the context of sustainable development. For this purpose, one case study from Europe, Asia, Africa, America, and Oceania is analyzed and discussed. In this review, a mapping of research activities done by different authors, recommendations, benefits, and the SDGs is undertaken. Recommendations based on the literature analyzed are (1) improve management of natural resources, (2) increase engagement of multiple stakeholders, (3) develop probabilistic and stochastic models to collect reliable data to assist decision-making, (4) increase investment in research and development, and (5) increase interconnection and policy coordination among economic sectors.

The review done by Bardazzi and Bosello [11] analyzes how the Water-Energy-Food nexus is treated in Computable General Equilibrium (CGE) models. Furthermore, the design, importance, and possible ways to improve CGEs are discussed. CGE models are seen as potentially useful for a nexus analysis as they have (1) the ability to capture input-output linkages between sectors and countries, (2) are effective in representing impacts of technical changes or policy interventions, and (3) have the ability to account for macro-economic feedbacks. Three main links between the WEF nexus and CGE modeling are found (1) water-energy, (2) energy-food, and (3) water-food. The authors concluded that most CGEs struggle to represent the competing water uses across sectors, mainly in the energy sector. Johnson et al. [12] analyzed global models for the Water-Energy-Land (WEL) nexus, the aim was to identify challenges and opportunities for global models integrating resource management decisions across WEL systems. Critical areas for model improvement are presented. The main models analyzed are Global gridded crop models (GGCs) to quantify the implications of climate change for crop, Global Hydrological Models (GHMs) with which the evolution of water availability over time can be studied, Agro-Economic Models to explore the interactions between water and land, Energy-Economic Models, Hydro-Economic Models, and Global Integrated Nexus Solution Frameworks to bridge the gap across all three resources by the coupling and extending existing global models.

Newell et al. [13] conducted a quantitative review of the academic literature on the FEW Nexus using the search string 'food AND energy AND water AND systems'. This resulted in a data set of 1399 publications. The analysis of the bibliometric data revealed six distinct research communities, one of them focusing on the urban FEW nexus. The clustering and visualization were done by using Bibexcel to create a co-citation network and Gephi as a visualization tool. An evaluation matrix was developed to highlight respective methodological, topical, and conceptual attributes of the FEW nexus research using four criteria: (1) FEW 'trigger'; (2) nexus modeling approach; (3) study scale; and (4) governance. The review highlighted a deficit in terms of theorizing and analyzing the socio-economic dimensions of the nexus, the direct and indirect consumptions of cities influencing the global FEW scale. Further, specific modeling tools, qualitative approaches, and co-production strategies are presented to go beyond aggregate black-box measurements of a city's metabolism, to capture the relationships among nexus components, and to understand multiscale processes.

From the above review studies, it can be concluded that the FEW nexus is a multi-disciplinary and complex topic. Therefore, each sector cannot be discussed as an independent sector. There is a need for integrated policies and inter-sectoral and international cooperation [10]. Robust analytical tools, conceptual models, appropriate and validated algorithms, and robust datasets that can provide information on future energy, water, and food use are needed [9]. Methods to assess geospatial datasets derived from open access and remotely sensed data sources and database management schemes could help to address the analytical challenges [12]. The studies examined identify essential fields of action for research, policy, and society. However, questions such as what are the main research fields at each level (macro, meso, and micro), is it possible to divide the FEW nexus research into specific clusters like it is done in the smart cities research [14], and do the clusters correlate with

Table 1
Methodology of the literature review

Step	Phase 1: Search strategy
1.1	Selection of databases with bibliometric data: Web of Science (WoS) and Scopus (SC)
1.2	Selection of Query Wording (QW), boolean operators, and time period
1.3	Selection of software: Citavi, RapidMiner, Excel, Python, and Gephi
	Phase 2: Data collection, data cleaning, and setup of the software workflow
2.1	Import of the data sets from WoS and SC into the reference management system Citavi (https://www.citavi.com/)
2.2	Removing duplicates and combining the two data sets into a comprehensive one
2.3	Prepare the data sets for the text mining analysis with RapidMiner (https://rapidminer.com/)
2.4	Analyze RapidMiner output with a Python script and prepare data for the final network analysis with Gephi (https://gephi.org/) and run Gephi network analysis
	Phase 3: Data analysis
3.1	Defining topics of interest such as most frequently used words (word clouds), development of publications over time, country of the first author, numbers of citations, and levels
3.2	Extending the data set in the reference management system Citavi by the relevant information to answer questions from step 3.1
3.3	Run RapidMiner workflow to create Word Clouds and to identify the appropriate number of clusters
3.4	Run complete workflow to find most relevant papers for the reading phase
	Phase 4: Reading phase
4.1	Definition of the method for the reading phase, questions like which level (macro, meso, micro) is the publication addressing, which topic is the publication focusing most (food, energy, water) and what are the modeling approaches used in the publication.
4.2	Reading of the selected papers
	Phase 5: Conclusion and directions for future research
5.1	Summary of major findings and gaps
5.2	Summary of the leading open question(s) in the reviewed papers

Table 2
Results of the bibliometric search

No		WoS	SC
	Query Wording (QW) for WoS and SC search		
1	food AND water AND energy AND nexus AND (modelling OR modeling)	559	271
2	Remove duplicates	181	
3	Complete data set	649	

the levels and what are the methods of modeling used in the clusters and levels are still not fully discussed in the literature.

Review process

An extensive literature review was conducted on the Web of Science (WoS) and Scopus (SC) databases to get insight into the existing research areas. The goal was to obtain a comprehensive literature review for this research area consisting of journal articles, books, and conferences papers from a range of sources and to identify main clusters in the research field. The method of the literature study is divided into 5 phases, and is based on the method presented in [15]. Table 1 shows the methodology and the five phases and Table 2 the numbers of papers found in the two databases. In phase 1, the search strategy is defined. This includes the identification of relevant databases, the definition of query words, boolean operators, and the time period. At the end of phase 1, appropriate software tools are identified to carry out an extensive literature analysis. Phase 2 focuses on the data collection, data cleaning, and the setup of the software workflow. The goal of phase 2 and phase 3 is to have an automated text mining and data visualization workflow which supports the later detailed reading phase (phase 4) of the identified literature. Especially in such fields as the FEW nexus, the amount of literature can get huge, and a human could get lost analyzing the literature manually. For that, methods like creating word clouds, cluster- and network-analysis can help to support the reading phase. Finally, in phase 5, conclusions and directions for future research are derived. Fig. 2 shows a summary of the methodological steps and data created stets in the different phases.

For text-mining, RapidMiner Studio 9.10 with text processing and R-Script extensions was used. More detailed information on the implemented text-mining process in RapidMiner can be found in Appendix A.

Table 3
Top 10 - country of first author, number of publications, and percentage

	Country ofFirst Author	Numberof Publications	Percentage
1	USA	164	25.4
2	China	145	22.4
3	England	47	7.3
4	Germany	27	4.2
5	Netherlands	20	3.1
6	Brazil	17	2.6
7	Australia	17	2.6
8	Spain	16	2.5
9	Qatar	15	2.3
10	Italy	15	2.3

Results

Publications over time, country of first author, and journals

Fig. 3 shows the temporal trend of publications from 1995 to 2022 (as of January 2022) of the 649 publications examined. In 2021, the most publications were published, with 173 publications, which corresponds to a share of 26.6 %. There has been a significant increase since 2015, and it can be expected that this trend will continue in the coming years. Especially as the need for a common view on the FEW nexus sectors becomes more and more prominent [13].

To get a deeper understanding of the topics discussed in the FEW nexus, it is also valuable to take a look at the countries of the first authors as well as the journals in which most of the publications take place. In Table 3, it can be seen that most of the first authors come from the USA (25.4 %), followed by China with 22.4 %. This means that almost half (47.8 %) of all publications come from these two countries. England, Germany, and the Netherlands together account for about 14.6 %. The top three journals are Elsevier's Journal of Cleaner Production and Science of the Total Environment and Water from MDPI, (see Appendix B). The rapid increase in publications and publishing in multi-disciplinary journals shows the complexity of FEW nexus research at present.

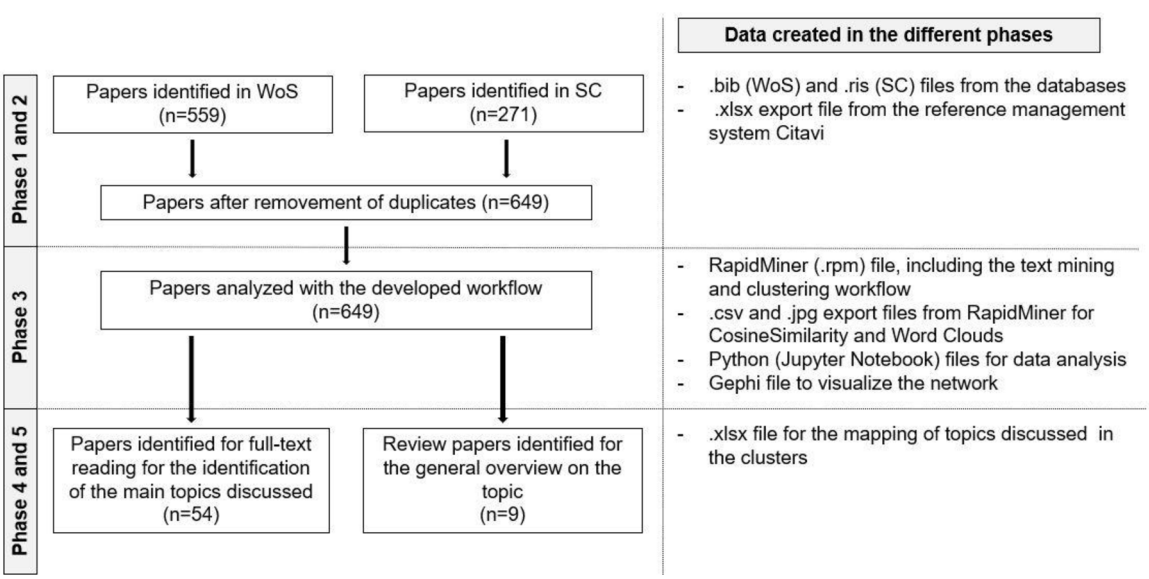

Fig. 2. Methodological steps and data created in the different phases

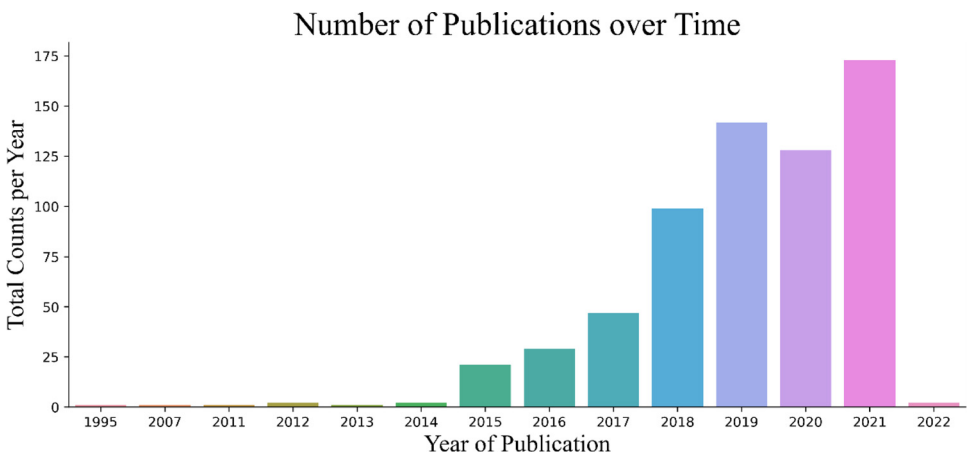

Fig. 3. Number of publications over time in the food-energy-water nexus

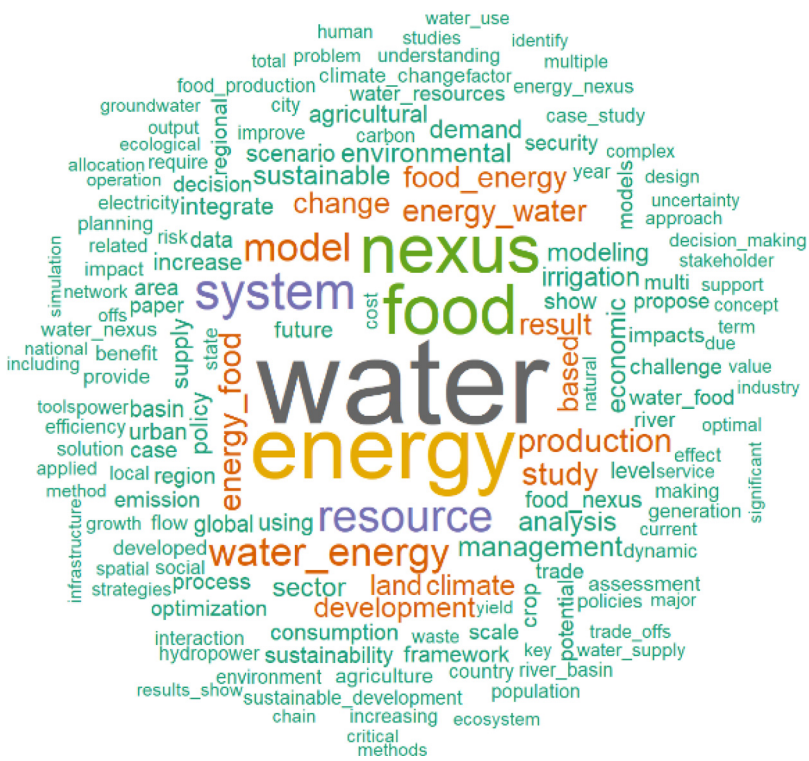

Fig. 4. Word cloud of the complete data set of 649 papers, minimum frequency of occurring words = 100

Word cloud-analysis

Fig. 4 shows the created word cloud for words which occurred minimum 100 times, based on the title and abstract as input. The term wef was excluded from the analysis as it stands for the abbreviation water-energy-food, and it appeared in most of the publications. So the abbreviation wef does not help much in classifying the main topics and would only cause confusion. Water occurred 3551 times and is the most used word in the title and abstracts of the publication, followed by energy and food. The term nexus is on the fourth place with 1829 occurrences. Many publications focus on specific areas of the nexus, and the topics of food, energy, and water are not always equally weighted. From the word cloud and the top 20 words analysis (see table in Appendix B) it can be deduced that in the FEW nexus the topic water is the most represented. However, the terms system, resource, model, study, change, development, and management also appear to be very important, which indicates the importance of a holistic approach to the topic. Words such as crop or river that might indicate a specific topic appear on 46th place with 272 mentions and 62nd place with 233 mentions, respectively.

Cluster- and network-analysis

In addition to the development of publications over time, the country of the first authors, and the word cloud, it is also worthwhile to analyze the highly connected (high degree, which is representing the number of edges a node has) and most cited papers in a cluster. Also in this case, the title and the abstract serve as input parameters. For the cluster analysis x-means, with k-means clustering algorithm, and cosine similarity is used. Fig. 5 shows the network graph generated in Gephi, the cluster analysis was set to nine clusters. In the figure, it can be seen that three clusters (clusters 5, 6, and 8) form well. For the others, a rather diffuse picture can be seen. The center of cluster 0 has proximity to cluster 6, but with distributed publications that are also found in the vicinity of other clusters, the largest distance is to cluster 8. Clusters 1, 3, and 5 are located in near to cluster 8, the most distributed cluster in the network graph is cluster 4. In order to find out which topics are hidden behind

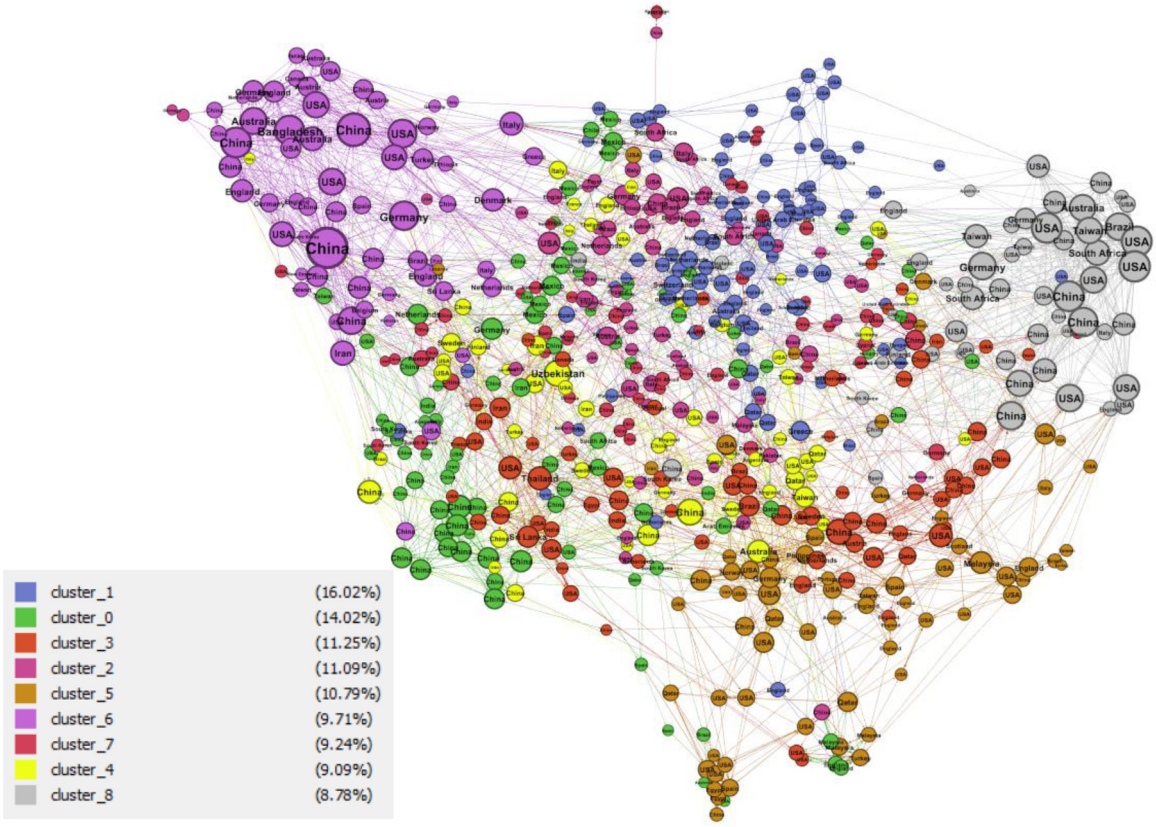

Fig. 5. Network graph of the publications, for the nine clusters and country of first author

the individual clusters, 6 publications from each cluster (top degree and most cited) were subjected to a more detailed examination. With these steps, a number of 54 publications were identified for detailed consideration (see Appendix C).

The following is a summary and the main topics discussed in the clusters, the levels addressed and main modeling approaches of each cluster is given,

Cluster 0 – Development of simulation models, optimization methods, and simulation tools

In this cluster, an exact level (macro, meso, micro) cannot be assigned here. Examples can be found on all three levels, up to the modeling of energy production plants [16], the trade-offs between the conflicting objectives of hydropower and irrigation [17], water allocation for electricity generation [18], for the regional agricultural water resources management [18]. The nearness to cluster 6 shows that there is high proximity to the research field of river and watershed issues, as also discussed in [17,19]. The research here considers the areas of food, energy, and water equally weighted. In the six papers studied, the development of simulation models and optimization methods stands out.

Cluster 1 - Risks and security, water scarcity, water competition mechanism, simulation, and modeling tools

Cluster 1 focuses on the macro and meso levels. Water, especially the risks of water scarcity on food and energy, is central here [20]. Cross-level risks are investigated [21], water competition mechanism [22], as well as water security elements [23] are examined. The three papers with the highest degree in this cluster focus on the application of simulation and modeling tools [20–22]. Two of the most cited papers are theory papers and consider water security on a global scale [24,25]. In summary, water is the driving factor in the cluster, especially water security and the resulting governance mechanisms.

Cluster 2 – Ecosystem services, sustainable development goals, and scenario modeling

The discussion of ecosystem services and climate change scenarios on the meso level stands out in this cluster. Ecosystem services can include provisioning services (e. g. water provision at a distinct quality), regulating and maintenance services (e. g. buffering capacity for extreme events (floods and droughts) or nutrient recycling, enabling biomass production), and cultural services (e. g. touristic) [26,27]. Climate aspects and the Sustainable Development Goals (SDGs) [28] are criteria for the nexus modeling. No specific proximity to other clusters can be assigned to this cluster either, nor is there a real concentration point of several publications as is the case with other clusters. The main focus of the three papers with the highest degree is on food, agricultural landscape, biomass production, simulation of the flow river networks, integrated modeling and management of water resources, and water provision [26,27,29]. In summary, the food-water nexus is very prominent here.

Cluster 3 - Greenhouse gase emissions, embodied land use, food trade, virtual water, water supply chains

Noticeable in this cluster are the topics of land-use and land-use change in relationship to GHG emission flows and emission fluxes and the modeling of international import/export of agricultural products [30]. Quantifying embodied energy and GHG emissions from irrigation through virtual water transfers in the food trade, embodied energy from irrigation water in domestic food transfers [31], and crop yield responses to water and energy and groundwater irrigation systems [32]. Further, agricultural land and freshwater use embodied in worldwide supply chains embodied land/freshwater intensity of goods or services [33]. Water and energy as importing and exporting functions of major economic sectors and considering agriculture and food processing sec-

tors as virtual water suppliers [34]. For out of the six papers focus on the macro level.

Cluster 4 – Crop and food production system, energy input, and energy production

The analysis of the selected papers in this cluster shows that the subjects of crop cultivation is highly present. [35] and [36] analyzed the effects of climate change and land degradation on crop production, water scarcity, or drought-tolerant crops, the influence of soil fertility levels, and irrigation water shortage on crops, crop intensification, land use, and on-farm energy-use [36] are frequently discussed. Furthermore, topics such as the assessment of the environmental impact of food production systems (e. g. fertilizer production and livestock management), including the modeling of the energy subsystem under consideration of photovoltaics or the water subsystem [37], the demand for food and bioethanol from both domestic and international markets [38] or agriculture as land and water user in river basins [39,40] are subjects in the cluster. This cluster has strong connections with clusters 0, 2 and 6. Further, it is noticeable that the considered use cases in the publications are on the macro and meso level.

Cluster 5 - Bioenergy production, biomass productivity, water-reuse, forest systems, aquaculture, productivity increase

Two of the publications examined in this cluster were review publications, Lee et al. [41] examined low-carbon emissions mitigation strategies for the energy sector, waste management, and environmental management system, and Giampietro [42] focused on the definitions and interpretations of the term circular bioeconomy by comparing the concepts of circular economy and bioeconomy. The papers with the highest degree in the network graph, analyzed how aquaculture systems can be combined with forest plantations to enhance ecosystem services through fertilization, increase water-reuse and biomass productivity, and regulate clean water by land applying pond waters to forest soils [43]. Furthermore, the implications of large-scale bioenergy production on the future energy mix, climate change mitigation, and the pressure on land and water resources were studied [44]. Lastly, the impact of surface sediments in aquatic ecosystems to control the distribution of microbial biomass and activity and microbial activity was addressed [45].

Cluster 6 - River basins, transboundary, hydropower production, dam impacts, hydro-agro-ecological impacts, hydro-economic models

All publications examined in this cluster addressed the impact of river basins and dam constructions on the surrounding ecosystems (e. g. water availability, riverine ecosystem health, fisheries). Do et al. [46] analyzed trade-offs between hydropower and irrigation, hydropower and fisheries, and irrigation and fisheries. Further trade-offs among different countries and sectors at different spatial scales were investigated, and how the rivers connecting multiple sectors and the management of hydropower in synergy with other sectors and stakeholders up and downstream were discussed [46–48]. Some authors also highlighted the impact of large dams constructions on transboundary rivers and how these constructions can lead to conflicts in water use for hydropower, food production, ecosystem conservation, the consequences for riparian countries, and impact on irrigated agriculture [48,49]. The importance of modeling the seasonal flow of water and sediment transport [50] as well as short-term (daily scale) [51] to optimize reservoir operations, to improve hydropower output and the raise the final reservoir storage. A characteristic feature of this cluster is that the focus of the analyses is on river basins and what influences they have on states and ecosystems. The research focuses on the macro and meso levels.

Cluster 7 - Regional resource management, population growth, gross domestic product, consumption and end-use

In this cluster, a transition from the meso to the micro level can be seen. Not only in the spatial resolution (regional and city scale) of the areas considered in the publications, but also in the data used for the analysis. For example, the nexus relationships and trends in cities and regions are considered by identifying regional consumption of resources such as water, energy and food. Input factors such as the gross domestic product (GDP), water supply and water demand, food consumption per capita, family size, income, energy consumption for water heating, greywater and food waste production and labor force [52–55] are considered in the studies. Evaluation indexes to compare the state of the FEW nexus of different regions were developed and used to compare regions [52,54,56].

Cluster 8 – Cities and urban agglomeration, water and energy networks, direct and embodied energy, energy-water, urban sustainability, sustainable planning

Cluster 8 is the most granular cluster. The research in this cluster focuses on cities and urban agglomeration areas. Two out of the six papers reviewed are broader review papers [57] and [58], both publications address the FEW nexus at the urban level, including the driving factors of urban growth and the comparison of methods to model the nexus. It is also noticeable that the topic of energy and the technologies for energy conversion is much more present here than in other clusters. Chen and Chen [59] and et al. [60] highlight the importance of the energy–water nexus and water-energy nexus for cities. The depth of detail in this cluster stands out, as the individual systems (food water energy) are broken down into several sub-sub-systems (e. g. agriculture, manufacture, electricity and gas supply, water supply, construction, transport and services) [59]. Bieber et. al. [61] analyzed the FEW nexus from the energy perspective and how the implementation of suitable electric power and water services supports urban growth. Urban systems programs (e. g. planning, policies, regulations, capital investment, and adaptive management), stakeholder engagement in combination with global trends for city development were highlighted by [61]. This cluster can be clearly assigned to the micro-level.

Discussion

Main problem(s) researchers are currently trying to solve

Many implementations that are made today are at lowest level (micro) relate to bounded spatial areas and are derived from goals that the macro and meso levels (UNO SDG´s, Germans EEG, etc.) induce in the form of changes in legislation or socio-technical framework conditions. For example, the question of agriculture (food domain) cannot be discussed in isolation from dam projects (water domain) and the regenerative energy supply (energy domain) intended with them. The FEW nexus offers the scientific methods to better model and understand the interaction of the domains by means of simulations and to plan the potential of regional development projects more sustainably. The methods used are cross-domain, are combined from the Nexus context (system dynamics or input/output analyses), and thus determine the need for domain-specific data. The present research aims to make the interdependency and indexicality of the target/domain/method and data spaces transparent.

Limitations in the current state of the art, approaches, and conflicts

Table 5 gives an overview of the main topics, the levels, and the main modeling approaches in the clusters. The modeling approaches that are currently being applied in research can be classified into domain-specific tools (e. g. global water models) and into more general tools to perform LCA analysis, GIS, or System Dynamics (SD). With the domain-specific tools, detailed research questions can be addressed to answer questions for a specific domain. However, these tools have the disadvantage that especially the links between the sectors food, energy, and water are not fully considered. Tools such as LCA, GIS, or SD are flexible in their use but have the disadvantage that they need to be fed with data that is often not available.

Table 4
Overview of the main topics discussed in the clusters

Cluster Nr.	Main topics discussed in the clusters
0	Development of simulation models, optimization methods, and simulation tools
1	Risks and security, water scarcity and water competition mechanism, simulation and modeling tools
2	Ecosystem services, sustainable development goals, and scenario modeling
3	Greenhouse gase emissions, embodied land use, food trade, virtual water, water supply chains
4	Crop and food production system, energy input, and energy production
5	Bioenergy production, biomass productivity, water-reuse with forest systems, aquaculture, productivity increase
6	River basins, transboundary, hydropower production, dam impacts, hydro-agro-ecological impacts, hydro-economic models
7	Regional resource management, population growth, GDP, consumption, end-use
8	Cities and urban agglomeration, water and energy networks, direct and embodied energy, energy-water, urban sustainability, sustainable planning

Table 5
Overview of the levels addressed, and the main modeling approaches in the clusters

Cluster Nr.	Level	Main modeling approaches
0	Macro, Meso and Micro	Multi-stage stochastic programming, hydronomeas tool, Water–energy–food (WEF) Nexus Tool 2.0, pareto optimization, parameterization-simulation-optimization, global sensitivity analysis
1	Macro and Meso	System Dynamics, global water models (H08, PCR-GLOBWB, and WaterGAP)
2	Macro and Meso	Global Climate Models (CNRM-CM5, HadGEM2-ES, and CanESM2), Aquatic ecosystem models (AEMs)
3	Mainly Macro	Input-output models, aquacrop modeling, crop yields simulation
4	Macro and Meso	CropSyst model, life cycle assessment
5	Mainly Micro	Biomass productivity, carbon storage, and nitrogen storage
6	Meso	Hydro-economic model, Soil and Water Assessment Tool (SWAT), hydrological streamflow
7	Meso and Micro	System Dynamics, input–output models
8	Micro	Urban growth models, input–output models, agent-based modeling, System Dynamics

Conclusion and outlook for future work

The review highlights different approaches for modeling and simulating the FEW nexus. The methods described in Cluster 8 in particular have the potential to drive GHG reduction more integrated and thus faster than before.

Essential research questions that arise from the described FEW-Nexus perspective are:

- What are the relevant target systems and indicators to describe the FEW-Nexus and what methods are there to calculate the indicators? (target systems)
- Which methods and tools must/could be combined in order to capture the FEW nexus on the individual levels and their connection? (method integration)
- Which relevant datasets are needed to model the FEW-Nexus and which public data sources can be used as input for simulation models? (data models/sources)

To answer the research questions, a step-by-step analysis of the nexus dimension of the three domains (food, energy and water) in an empirical, spatial planning problem, such as the urban food supply, is required. Starting at the level of regional food production, distribution and disposal, the water and energy requirements involved can be calculated, modeled and cross-domain scenarios can be simulated under the targets of the SDGs. The insights gained from this (spatial, temporal and logical dependencies) could potentially flow into a tool for area partnerships for low-CO2 and resource-saving spatial planning (Table 4).

Highlights for Review (initial submission)

- Extensive literature review was conducted on the Web of Science (WoS) and Scopus (SC) databases to get insight into the existing research areas.
- From the above review studies, it can be concluded that the FEW nexus is a multi-disciplinary and complex topic. Therefore, each sector cannot be discussed as an independent sector.
- Robust analytical tools, conceptual models, appropriate and validated algorithms, and robust datasets that can provide information on future energy, water, and food use are needed.
- Review highlights different approaches for modeling and simulating the FEW nexus.
- The insights gained from this could potentially flow into a tool for area partnerships for low-CO2 and resource-saving spatial planning.

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Declaration of interests

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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nexus.2022.100101.

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