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REVIEW

Sustainability of an economy from the water-energy-food nexus perspective

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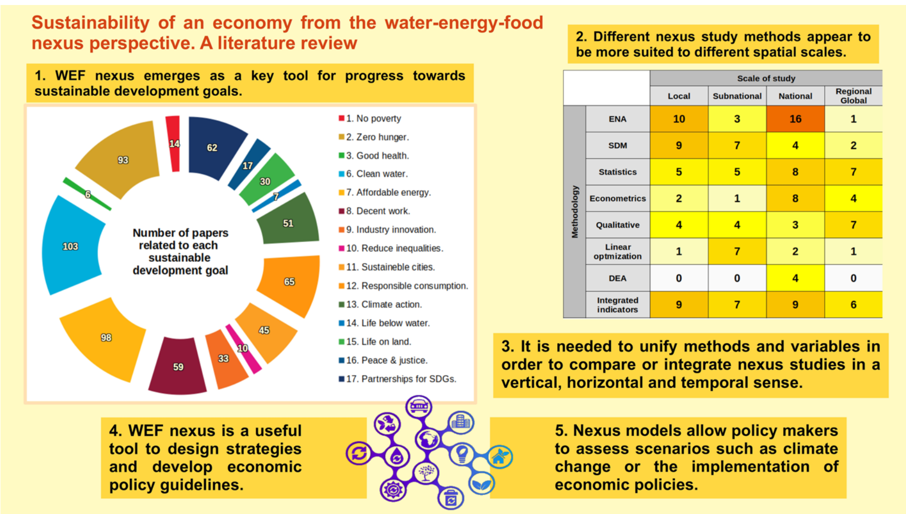
Abstract

In this paper we study the usefulness of the water-energy-food nexus in assessing the sustainability of an economy. All economic activity depends on its surrounding physical environment, and especially on the interconnection between these three essential resources. As a result, the nexus is a useful tool for detecting the economic risk of resource scarcity, optimising investments or resource use, and assessing the effects of economic policies or shocks such as climate change. The nexus approach is also useful for guiding policies towards achieving the United Nations Sustainable Development Goals (SDGs). We show that both the objective of each study and the scale on which it is conducted are factors worth considering when choosing the most suitable research methodology. We detected important challenges relating to the heterogeneity of the methods, scales and variables used, and therefore necessary measures nare suggested in order to homogenise the studies for their comparability and/or integration, both horizontally and vertically, or over time.

Graphical abstract



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Keywords Climate change · Energy · Environment · Food · Methods · Nexus · Scale · Security · Sustainable development goals · Water

1 Introduction

Economic activity takes place within a physical frame characterised by environmental conditions which limit its capacity to provide resources and absorb waste. Certain "environmental services", such as water, biomass and clean air provision, are related to human well-being and economic activity performance in a very complex way. The limits of an economy's physical environment are expressed via the appearance of resource stress, excessive external dependence or an excess of waste emissions beyond the capacity of environmental metabolism.

Current projections show that the world's population will grow to 9 billion by 2050, with energy demand increasing by 80% and food demand by 60%. Demand for water will increase proportionally, as agriculture currently consumes 70% of drinking water (EU, 2019). The existing trends of population growth, economic development, international trade, urbanisation, cultural and technological changes, and climate change only exacerbate these trends (Schulterbrandt Gragg et al., 2018). All of which leads to economic risk in the long run.

The water-energy-food nexus (WEFnX) framework emerges from the close interlinkage of these three basic resources as a way to analyse the performance of an economy, examining its sustainability from a triple perspective: economically, environmentally and socially (Hoff, 2011). The WEFnX offers a first approach to the interdependence between economic activity and the use of environmental resources, revealing the synergies and trade-offs that exist between them. The effects of mutual dependence and feedback in the complex relationships of the WEFnX ought to be studied using specific methods (Endo et al., 2015) to bring out the long-term effects of the use of some resources on each other, and on the environment.

Study into the allocation of scarce resources in productive activity is at the centre of economic science. As a result, numerous studies have been carried out to analyse, from the WEFnX perspective, the economies of various geographical areas, from regional to local, or at project level. The results of these studies allow academic fields to offer economic policy guidelines that are useful for moving towards more sustainable production and consumption patterns (Brouwer et al., 2018; Kulat et al., 2019).

The objective of this literature review is to analyse the aims, methods and scales of the nexus framework when used specifically to diagnose the sustainability of an economy and the risks for its future viability, with particular interest in the relationship between the nexus and the sustainable development goals (SDGs), as well as in investigations oriented to establishing strategies to overcome risks derived from nexus management and adapting to changing scenarios, such as climate change or the growing demand of resources.

Our work provides empirical evidence of heterogeneity in nexus studies, where previous work (Albrecht et al., 2018; Newell et al., 2019; Simpson & Jewitt, 2019; C. Zhang et al., 2018b) has demonstrated how diversity affects the frameworks, methods and scales. Our analysis shows that, aside from these factors, the variables used in the studies are completely different. This dispersion makes it difficult both to compare and to integrate these studies across scales or times, even in cases where the framework, method and scale are similar. Secondly, our analysis of the relationship between the nexus studies and the targets set out in the SDGs identifies the strengths of the nexus framework as an instrument for evaluating and guiding policies aimed at meeting certain SDGs or some of their specific targets. Finally, although there is no single valid method for nexus research, our review aims to provide guidance on which research methods are most valid for each scale of study. This work is divided into six sections. In the first section, we offer a brief explanation of the method and framework employed. In the second section, we differentiate nexus studies according to the ultimate purposes to which the research is oriented. In the third section we critically review the methods of nexus studies in relation to the purpose of the study and their respective limitations. Then, in two brief sections, we analyse the importance of participatory methods and the relationship between research methodologies and the geographical scale studied, respectively. Finally, a section on conclusions leads us to examine the usefulness of the nexus framework as a guide for orienting economic policies.

2 Framework and methodology

The conceptual framework of the nexus delimits the boundaries of the study, both in terms of spatial scope (scale) and the pillars and sub-systems covered. Strictly speaking, the nexus research framework focuses on the interdependence between the water, energy and food sectors and occasionally includes the use of other resources such as land or minerals (McGrane et al., 2019). More broadly, as examined in this review, the nexus framework encompasses both these relationships (the core of the nexus) and the interrelationships with the economic, social and environmental systems in which it is embedded (Fig. 1).

Within this conceptual framework, one basic issue is the reconciliation of environmental and economic requirements with an intergenerational equity perspective (Martinet & Doyen, 2007). Approaches that address the pillars of the nexus in an integrated way not only improve resource management efficiency but also economic efficiency (Yi et al., 2020). Given the direct link between the sustainability of the nexus and the sustainability of the economic system that depends on it, one of the main challenges in political decision-making is being able to jointly balance WEF and sustainability, as poor resource management leads to negative environmental consequences, in addition to having negative social and economic consequences (Bai & Sarkis, 2022). The challenge is developing policies that guarantee a sustainable use of resources, in a way that is accessible to the whole of society and within the appropriate level of environmental protection (Simpson & Jewitt, 2019).

To carry out this literature review, a systematic search was conducted according to the recommendations included in the PRISMA statement (Page et al., 2021). We looked for papers that employed the WEFnX framework to analyse a particular geographic area with an economic focus, centrally or laterally, on the analysis. The search in the WOS and SCOPUS databases yielded a total of 734 papers. The study of the abstracts, using our specific criteria, led to a selection of 141 articles; 106 case studies and 35 literature reviews or theoretical analyses of the nexus framework applied to a territorial domain. Without being exhaustive, the sample is of substantial scope to give an overview of the use of the WEFnX framework as a research approach for the interaction between economy and environment (Fig. 2). We provide a more detailed explanation of our systematic search in appendix I.

To establish a relationship with the SDGs of the nexus evaluation cases, the 106 case studies were reviewed in detail, taking into account their link with the 169 targets of the SDG framework. We established this relationship based on the following criteria:

- Firstly, research that explicitly included the SDGs in its framework.
- Secondly, articles that used indicators related to any of the SDG targets as a study variable for the nexus analysis. For example, access to drinking water (target 6.1.) or the proportion of green areas in urban spaces (target 11.7.)
- Thirdly, articles that evaluate the impact of nexus management on any of the 169 targets (in the discussion of their results).
- Lastly, works that include public policy recommendations directly related to the SDGs or their targets in their conclusions, such as investment in resilient infrastructure (target 9.A.) or participatory governance systems (target 16.7.)

3 The objectives of the nexus studies

Essentially, WEFnX is a tool used for carrying out an appropriate intersectoral analysis. We have identified four specific purposes for using the nexus framework. Firstly, as a tool to identify risks in terms of food, water or energy security. Secondly, as a guide to optimise resources or investments. Thirdly, as a means to make estimates of the performance of the nexus itself in future scenarios. And, finally, as a tool to provide analyses, criteria and strategies to advance towards meeting the SDGs.

3.1 Nexus security

In the context of WEFnX, security–there being enough availability, accessibility and sustainability for the use of these three essential resources–can be conceived as a unitary problem, since all the actors involved share a common interest in achieving security of the supply through efficient use of the resources (Tan et al., 2020). Nexus security is a very common approach in studies selected at a state, regional or city level. Nevertheless, comparative analyses of these studies must be done with the utmost care because they use different methodologies and types of data to approximate these three resource characteristics, as detailed below.

Within this framework, some studies (Putra et al., 2020; Sánchez-Zarco et al., 2020; Yuan et al., 2021) analyse the security of the three pillars of the nexus separately. This reveals the hidden heterogeneity of studied regions with an apparently similar degree of development (Mahlknecht et al., 2020), or shows the divergent trends of the security of one of the pillars in relation to the others. On the contrary, for a joint assessment of the nexus' security, other authors employ aggregated indexes based on the availability, accessibility and sustainability of the three pillars (Feng et al., 2020; Mohammadpour et al., 2019). An alternative way of measuring the degree of risk or security of the nexus resources is to use a ratio between aggregate demand and the quantity available for each resource (Chen et al., 2020b), with international trade emerging as a solution to resource scarcity.

Other approaches to assessing nexus security employ the study of statistical trends and variability in water resource availability for energy and food provision (Siderius et al., 2021), as well as the foreseeable deviation of resource availability from planned needs (Chen et al., 2020b). In addition, studying the matrix of synergies and conflicts in the provision of resources analyses the risk of exceeding the capacity of the global environment (Karabulut et al., 2018).

3.2 Resource optimisation

The improvement in efficient use of scarce resources and the search for intersectoral benefits is consubstantial to the nexus approach (Ringler et al., 2013), especially in the case of resources where consumption is linked to others and the identification of the synergies and trade-offs involved is of interest (Endo et al., 2015). For optimal use of the synergies that appear when using different resources, movement away from silo thinking, better information, dissemination of efficient technologies, and reduction of certain market-distorting subsidies is necessary (Bieber et al., 2018).

Studies focused on the optimisation of water as a resource deserve special attention because of its central role in the nexus. Water can be the main limiting factor both in the generation of energy and in food production (Perrone & Hornberger, 2016) and is a key factor when optimising production of these resources (Jalilov et al., 2018; Namany et al., 2019). The management of water as a scarce resource can be employed to optimise food production (Chamas et al., 2021) and the benefits of agricultural activity (Liu et al., 2020; Yu et al., 2020), or to analyse, from this perspective, the effects of biofuel production or potential changes in alimentary diets (Damerau et al., 2016).

From an economic point of view, the nexus is also employed to minimise both operational and capital costs when optimising the investments required to meet a given level of resource demand (Núñez-López et al., 2021; Ringler et al., 2013; Saif et al., 2020).

Finally, the nexus framework is also used to achieve joint minimisation of the greenhouse gas emissions and the cost of satisfying the resource needs of an economy (Tabatabaie & Murthy, 2021; Zhang & Vesselinov, 2017).

3.3 Scenario assessment

The nexus framework facilitates the building of models able to encompass the relationships between its three pillars and the socio-economic environment. Some investigations implement these models to infer the impact that the change of any of the variables will have over the complete model, and particularly on the nexus pillars. These models become tools for guiding economic policy decision-making. (Chamas et al., 2021).

Firstly, we find studies that assess the impact of the disruption of a factor external to policy makers, such as the disruption of international prices (Saif et al., 2020) or the reduction of an essential resource for the nexus, such as available arable land (Chamas et al., 2021) or water (Ding et al., 2019; Saif et al., 2020). Within this group we also find studies that assess the impact of climate change on the nexus performance. These works use forecasts by the Intergovernmental Panel on Climate Change (Mercure et al., 2019; Wicaksono & Kang, 2019) to generate future scenarios on which to apply the nexus model and to assess the consequences. For example, to estimate the efficacy of urban green infrastructure (Gondhalekar & Ramsauer, 2017); to evaluate the future performance of hydraulic infrastructures (Jalilov et al., 2018); mitigation strategies for climate change effects (Martinez et al., 2018); or the increased vulnerability of the territory due to the expected change in rainfall patterns (Siderius et al., 2021).

In the second group we find a substantial number of studies oriented to assessing scenarios where the characteristics depend on the alternatives adopted in political and economic decisions. As a result, it is possible to compare the results of a classic development strategy versus another characterised by sustainable development integrated policies (Fan et al., 2019; Niva et al., 2020). Or to estimate the outcome of strategies for mitigating the effects of climate change and improving the sustainability of water use (Martinez et al., 2018) and changes in water management (Ding et al., 2019). This includes combining tariff policies for different uses (Tan et al., 2020), altering the water available for irrigation (Chen & Chen, 2020; Wu et al., 2021) or introducing uses for treated water (Chen et al., 2020a). Regarding energy, we find scenarios that address the impact of the introduction of renewable technologies and improvements in efficiency (Brouwer et al., 2018; Hardy et al., 2012; Wu et al., 2021), as well as the introduction of systems of carbon capture (Brouwer et al., 2018; Hardy et al., 2012) or different alternatives for the energetic mix (Govindan et al., 2018). Finally, centred around the evaluation of the food pillar, we have scenarios that study the effects of changes in the composition and diversity of diet (Chamas et al., 2021), as well as in the crop structure (Chen & Chen, 2020).

Another use for scenario building is for evaluating investments such as reservoir systems (Jalilov et al., 2018; Wicaksono & Kang, 2019), different wastewater separation technologies (Villarroel Walker et al., 2014) or those needed for implementing different combinations of water management systems (Kulat et al., 2019).

3.4 Sustainable development goals

Integrated resource management, which forms the core of WEFnX, plays a crucial role in the SDGs (Fan et al., 2019; Saladini et al., 2018). The SDGs allude to security, sustainability and accessibility in the provision of nexus resources. Moreover, the nexus is connected to all of the SDGs directly or indirectly (Liu et al., 2018). Consequently, an improvement in the management of the nexus means a stronger likelihood of the SDGs being achieved (Cansino-Loeza et al., 2020). Thus, the analytical framework of the nexus is useful for measuring how improved resource management leads to progression in achieving the SDGs (Nhamo et al., 2020b). Conversely, the SDGs are a framework for assessing the impact of WEFnX-related measures (Saladini et al., 2018).

Given this close relationship, increasing socio-economic pressure on nexus resources is a negative factor in moving towards the SDGs (Arthur et al., 2019), and therefore approaches aimed at improving nexus resource management and security are essential for achievement of the SDGs (Arthur et al., 2019; Cansino-Loeza et al., 2020; Mpandeli et al., 2018; Rasul & Sharm, 2016). Proper nexus management alleviates resource scarcity or degradation, which is a step towards the SDGs. At the same time, the scope of the SDGs has a positive impact on the three pillars of the nexus, bringing us closer to a situation of balance in the use of its resources (Malagó et al., 2021).

The analysis of an economy from the WEFnX perspective is useful for identifying synergies and trade-offs that affect the SDG (Putra et al., 2020) given the interdependence of the key resources involved in the nexus. This can make it easier to advance in some objectives in an indirect way, through the improvement of others (Storey et al., 2017). On the contrary, identification of trade-offs allows us to draw up strategies to avoid the advance in an objective occurring at the expense of the deterioration of another (Terrapon-Pfaff et al., 2018).

The interdependence of nexus resources is similar to the interconnectedness of the development goals. Cross-sectoral integration is a challenge for both frameworks (Liu et al., 2018). Interconnectedness can mean that, when approached from a purely sectoral analysis, some development goals are difficult to achieve due to interference or imbalances induced by policies implemented to advance others (Mpandeli et al., 2018). Given the close relationship between WEFnX and SDGs, the integrated resource management approach of the nexus–which allows us to identify synergies and trade-offs between its pillars–is a useful tool for combatting silo thinking and for applying a multi-criteria method to the evaluation of SDG-oriented policies (EU, 2019).

The nexus approach is indispensable when making decisions in resource management for the attainment of the SDGs (Arthur et al., 2019). On this same note, Liu et al. (2018) highlight that improvement in the SDGs has a significantly positive impact on all three pillars of the nexus, because of the interlinks between them. The SDG performance indicator systems can be used as a tool to assess the urban nexus (Yuan et al., 2021) or the degree of security of the nexus and its possible evolution (Cansino-Loeza et al., 2020).

The nexus has a direct impact on SDGs 2, 6 and 7, relating to food, water and energy security, respectively (Saladini et al., 2018; Simpson & Jewitt, 2019). In a more indirect form, the nexus also has a bearing on goals 11 and 12, sustainable cities and sustainable production and consumption, respectively (Storey et al., 2017). Nevertheless, analysis of the works taken into consideration links to most of the goals and a large set of the sustainable development targets (Table 1). Assessing the degree of approximation to meeting the

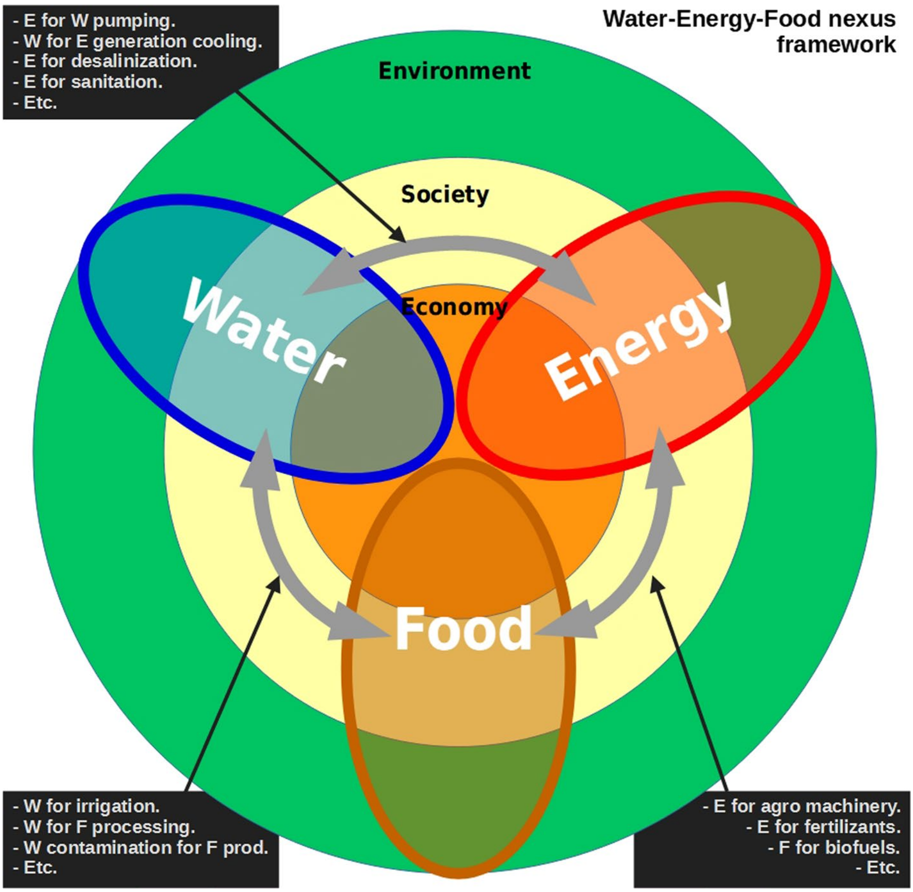

Fig. 1 WEF nexus Framework

Table 1 Number of selected articles related to sustainable development goals and targets

1	*End poverty in all its forms everywhere*	*14*
1.1	Eradication of extreme poverty	8
1.2	Reduction of relative poverty in all its dimensions	6
1.5	Resilience to environmental, economic and social disasters	2
2	*End hunger, achieve food security and improved nutrition and promote sustainable agriculture*	*93*
2.1	End hunger	70
2.2	End all forms of malnutrition	15
2.3	Doubling of small-scale agricultural productivity and income	13
2.4	Prácticas agrícolas sostenibles y resilientes	58
2.A	Increased investment in agriculture	38
2.B	Stability of world agricultural markets	2
2.C	Control of food price volatility	13
3	*Healthy lives and promote well-being for all at all ages*	*6*
6	*Ensure availability and sustainable management of water and sanitation for all*	*103*
6.1	Universal access to safe and affordable drinking water for all	82
6.2	Access to adequate sanitation and hygiene systems	20
6.3	Improve water quality. Reduce pollution and untreated wastewater	49
6.4	Increase water-use efficiency	71
6.5	Implement integrated water resources management	20
6.6	Protect and restore water-related ecosystems	16
6.B	Participation of local communities in water management	3
7	*Ensure access to affordable, reliable, sustainable and modern energy for all*	*98*
7.1	Universal access to affordable and modern energy services	76
7.2	Increase the share of renewable energy in the global energy mix	62
7.3	Double the global rate of improvement in energy efficiency	49
7.A	International cooperation to facilitate access to clean energy	3
7.B	Expand infrastructure and upgrade technology for developing countries	1
8	*Promote sustained, inclusive and sustainable economic growth, full employment and decent work for all*	*59*
8.1	Sustain per capita economic growth	41
8.2	Increase productivity through diversification, technological upgrading and innovation	18
8.4	Improve resource efficiency in consumption and production	23
8.5	Full and productive employment and decent work	10
8.9	Sustainable tourism	6
9	*Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation*	*33*
9.1	Develop quality, reliable, sustainable and resilient infrastructure	27
9.2	Promote inclusive and sustainable industrialization	3
9.4	Upgrade infrastructure and retrofit industries to make them sustainable	3
10	*Reduce inequality within and among countries*	*10*
10.1	Income growth of the bottom 40 per cent of the population	7
11	*Make cities and human settlements inclusive, safe, resilient and sustainable*	*45*
11.1	Access for all to adequate and affordable housing and services	2
11.2	Ensure access to public transport	2
11.3	Enhance inclusive and sustainable urbanisation	11
11.4	Protect and safeguard the world's cultural and natural heritage	4

Table 1 (continued)

11.5	Reduction of disaster deaths and reduction of vulnerability	10
11.6	Reduce the adverse per capita environmental impact of cities	19
11.7	Universal access to green public spaces	8
11.A	Support positive links between urban, peri-urban and rural areas	18
11.B	Integrated plans for Disaster Risk Reduction	11
11.C	Support least developed countries in building sustainable and resilient buildings	1
12	*Ensure sustainable consumption and production patterns*	*65*
12.2	Sustainable management and efficient use of natural resources	13
12.3	Halve per capita global food waste and reduce food losses	7
12.4	Reduce chemicals and waste release to air, water and soil	53
12.5	Reduce waste generation: prevention, recycling and reuse	16
12.8	Information and awareness for sustainable development	4
12.C	Rationalise inefficient fossil-fuel subsidies	4
13	*Urgent action to combat climate change and its impacts*	*51*
13.1	Strengthen resilience and adaptive capacity to climate-related hazards	48
13.2	Integrate climate change measures into national policies	12
13.3	Improve education, awareness and institutional capacity on climate change	4
13.B	Raising capacity for climate change management in least developed countries	2
14	*Conserve and sustainably use the oceans, seas and marine resources for sustainable development*	*7*
14.1	Prevent and significantly reduce marine pollution	5
14.2	Protect marine and coastal ecosystems	3
15	*Protect, restore and promote sustainable use of terrestrial ecosystems*	*30*
15.1	Conservation and sustainable use of terrestrial and freshwater ecosystems	27
15.2	Sustainable management of all types of forests	5
15.3	Combat desertification, restore degraded land and soil	6
15.4	Conservation of mountain ecosystems, including their biodiversity	2
15.5	Reduce the degradation of natural habitats, halt the loss of biodiversity	7
16	*Promote peaceful and inclusive societies for sustainable development*	*17*
16.6	Develop effective, accountable and transparent institutions	2
16.7	Ensure responsive, inclusive, participatory and representative decision-making	17
17	*Global partnership for sustainable development*	*62*
17.5	Investment promotion regimes for least developed countries	5
17.6	Enhance international cooperation and access to science, technology and innovation	7
17.7	Promote of environmentally sound technologies	6
17.9	International support for implementing SDG	10
17.10	Promote a universal, rules-based multilateral trading system	9
17.13	Enhance global macroeconomic stability	4
17.17	Effective public, public–private and civil society partnership	16
17.18	Increase the availability of high-quality and reliable data	14
17.19	Develop measurements of progress on sustainable development beyond GDP	5

SDGs is relevant regardless of the degree of development of each nation as, according to current trends, no country will be in a position to meet the goals by 2030 (Simpson & Jewitt, 2019). Furthermore, the nexus approach allows us to identify synergies between goals;

diminish antagonistic effects between goals, uncover unintended consequences of measures aimed at improving a goal, and improve planning and decision-making (J. Liu et al., 2018). Appendix II provides detailed information on the relationship between each of the articles analysed and the 17 SDGs and their consequent 169 concrete targets.

However, Venghaus and Dieken (2019), after comparing the degree of implementation of the SDGs and different nexus indexes for a sample of 40 countries, found strong inconsistencies that are difficult to justify. They therefore conclude that static, high-aggregate nexus indexes should be interpreted carefully, particularly when used as a criterion for decision-making, because "their capacity to represent the complexity of the interdependent food, energy and water systems is limited."

4 The nexus study methods

One of the main characteristics of research conducted under the WEFnX approach, which makes it difficult to compare studies with a view to drawing general conclusions, is the wide variety of methodologies and frameworks employed. This is due to several factors, but notably the plurality of scientific fields from which such studies are approached, ranging from environmental management to economic or social sciences (Albrecht et al., 2018). The different interpretations that are given to the concepts involved in the nexus, together with the relative novelty of this framework and the diversity of elements that are considered central in each study, also contribute to the multiplicity of methodologies used (Zhang et al., 2018a). The proper transversal character of the nexus and the complexity of the systems studied mean that "research assumption, goals, scales and data availability are important in determining which approach should be used for the investigation," (Fan et al., 2019). As a result, we must assume that there is no single methodology that is valid for all research. (Endo et al., 2015).

In response to this plurality, successive works have proposed different classifications of the methods used in nexus research, either in literature reviews (Newell et al., 2019), those particularly focused on methodological aspects (Albrecht et al., 2018; Endo et al., 2015; Zhang et al., 2018a) or as part of the theoretical underpinning of more particular studies (Fan et al., 2019; Li et al., 2019; Yuan et al., 2021).

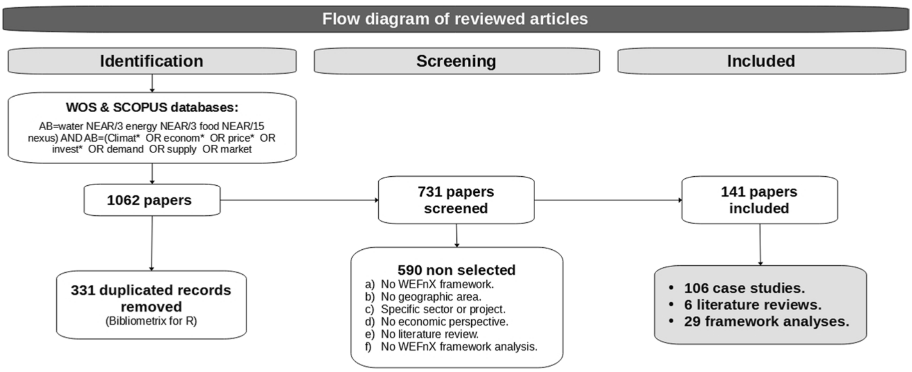

Fig. 2 Method for systematic literature review

In light of the studies included in our selection, we propose the following classification of nexus study methods. Appendix II provides detailed information on the method employed by the articles analysed. However, it should also be noted that most studies employ several methodologies simultaneously, which helps to improve the robustness of their results (Albrecht et al., 2018).

4.1 Ecological network analysis (ENA)

These studies are based on the quantification of material fluxes related to the system metabolism, a single network in which the economic and environmental elements are integrated (Fan et al., 2019). Even when ENA is capable of describing the system performance, its main limitation is that it is essentially a static method, with a low capacity for depicting the dynamic evolution of the system. This is because of its assumption of a state of equilibrium between network inputs and outputs (Zhang et al., 2018a). More commonly employed techniques using this method–usually together–are the material flow analysis (MFA), the life cycle analysis (LCA) and the input–output analysis (IOA).

MFA is based on a systematic examination of the transfer of resources and wastes between system components, ensuring the integrity of the mass and energy involved (Chen et al., 2020a). The MFA's ability to record flows and stocks in socio-technical and socio-economic systems (Newell et al., 2019) is employed under the nexus framework to identify key processes in improving resource management efficiency.

LCA is oriented towards the assessment of all the environmental impacts of the necessary inputs and outputs in a process, the production of a good or a whole system throughout its entire lifespan (Al-Ansari et al., 2015). The calculation reveals hidden

Table 2 Scales and methods of the nexus studies

		Scale of study			
		Local	Subnational	National	Regional Global
Methodology	ENA	10	3	16	1
	SDM	9	7	4	2
	Statistics	5	5	8	7
	Econometrics	2	1	8	4
	Qualitative	4	4	3	7
	Linear optimization	1	7	2	1
	DEA	0	0	4	0
	Integrated indicators	9	7	9	6

environmental impacts (Chen et al., 2020a). Ecological footprint calculations are included in this group–the water footprint, essentially–and are used in various studies. The application of LCA can detect the existence of a rebound effect of improved water use efficiency, which, when fully accounted for, instead of reducing pressure on water supplies, increases it (Willaarts et al., 2020).

IOA represents the links between sectors of an economic system in matrix form, related by the inputs and outputs of supplies and wastes along the production chain (Mekonnen et al., 2019). Applied to the nexus, this technique allows for the modelling of the final direct and indirect impacts of the three pillars along the interlinked chains of consumption and production (Fan et al., 2019). This method reveals that consumption in the intermediate stages is more determinant than in the final stages for improving nexus efficiency (Feng et al., 2019). Some authors (Liu et al., 2017, 2021; Owen et al., 2018) use an extended version of IOA from a regional perspective to include sectorial links, as well as interregional and international links. This allows us to identify the critical points of the chain regarding the use of resources, from both a sectoral and geographical perspective.

4.2 System dynamics model (SDM)

SDM is applied to the study of the nexus, assuming that its behaviour, like that of any system, is determined by its structure (Fan et al., 2019). The analysis of components and processes makes it possible to identify causal relationships and feedback loops, quantify them and, finally, build a dynamic model capable of simulating the behaviour of the system (Zhang et al., 2018a), extrapolating the results of its operation under changing management conditions (Khan et al., 2017).

SDM is often used to model water management systems characterised by supply sources, treatment processes, transport and the different consumption entities. The system will also be subject to certain physical limits and allocation rules (Guan et al., 2020). The results allow some authors to simulate and assess diverse water management policies (Chen & Chen, 2020; Tan et al., 2020). At other times, the purpose of the model is to optimise water use for both food and energy production (Hu et al., 2019; Kulat et al., 2019; Naderi et al., 2021; Wu et al., 2021).

A variation of SDM is constituted by models based on agents, where the behaviour of entities participating in nexus management is simulated. These actors take part in interacting with each other and with the environment according to their capabilities and interests (Izquierdo et al., 2008). These models show the effects of competition for resources between agents and sectors (Ding et al., 2019).

4.3 Statistical analysis

Statistical analysis is usually based on official published information, to interpret a geographical area and/or the relationships between the use of resources over time, and the impact of socio-economic or environmental variables. These methods are particularly useful for understanding the key factors that dominate the evolution of the nexus, although they are unable to provide information on the internal mechanism of their interactions (Zhang et al., 2018a). Twenty-five of the studies analysed mostly employ statistical methods, including the use of cluster techniques, to identify, within the region of study, subregions with common characteristics in the nexus management. (Han et al., 2020; Li et al., 2016; Ma et al., 2021; Mahjabin et al., 2020).

4.4 Econometrics

Econometrics is generally used in studies that aim to quantify the sensitivity of resource intensity. The sensitivity can be studied between resource use in the face of changes in elements such as the sectoral distribution of the production model, or for changes in external factors such as population density or land use. Regarding the nexus, econometric techniques lead to the construction of models in which the relationships between the resources or relevant economic variables are expressed as mathematical relations based on economic theories (Zhang et al., 2018a). This, in turn, allows us to test the validity of policies in terms of the causal relationships inferred (Yuan et al., 2021).

Simple linear correlation is employed to relate nexus with external factors such as the degree of urbanisation (Taniguchi et al., 2018), while multiple regression models–with random and temporal effects over panel data sets–are used to study the factors that have an impact on poverty (Ozturk, 2017) and characterise the spatiotemporal distribution of a nexus security index (Feng et al., 2020), or to assess the environmental Kuznets curve, connecting greenhouse gas emissions with the nexus pillars (Zaman et al., 2017). Simultaneous equation models are employed to reflect the mutual dependency between nexus resources, in the same way as models used to estimate the trading frontier between nexus resources (Perrone & Hornberger, 2016). Finally, Putra et al. (2020) carried out a nonparametric correlation analysis among 36 indexes in order to identify synergies and trade-offs between nexus pillars.

4.5 Qualitative studies

These methodologies are generally employed to depict the nexus of the region of interest by means of primary research techniques (Endo et al., 2015). For example, interviews with experts (Dalla Fontana & Boas, 2019), semi-structured interviews (Covarrubias et al., 2019), integration in the Delphi method (Smajgl et al., 2016) or elaboration of nexus interaction maps through participatory methods (Martinez et al., 2018). But qualitative interpretations are also made based on the synthesis of previous studies, together with statistical analysis techniques. This makes it possible, for example, to demonstrate the exposure to risks arising from the effects of climate change on the nexus in Africa (Chirisa & Bandauko, 2015; Conway et al., 2015); to assess the pressure for water exerted from the energy sector (Karatayev et al., 2017); or the conflict between the use of water for energy or food (Kattelus et al., 2014; Mayor et al., 2015). It is also used to assess the financial and environmental impacts of different technological alternatives on alleviating water scarcity confronting supply augmentation and demand reduction strategies (Saif et al., 2014). A total of 13 of the studies analysed can be considered mainly qualitative.

4.6 Linear optimisation (LO)

A significant number of the selected works are focused on optimisation that, as mentioned previously, constitutes one of the most common purposes of the use of the WEFnX framework. The employed optimisation techniques encompass linear programming: simple (Damerau et al., 2016; Zhang & Vesselinov, 2017) or multi-objective (Tabatabaie & Murthy, 2021), mixed integer linear programming (Núñez-López et al., 2021; Saif et al., 2020), multi-level interval fuzzy programming (Yu et al., 2020), interval two-stage stochastic programming (Liu et al., 2020), multi-objective stochastic programming (Namany et al., 2019) or production frontier optimisation (Perrone & Hornberger, 2016).

4.7 Data envelopment analysis (DEA)

This nonparametric technique used for estimating the relative efficiency of a set of decision units (Charnes et al., 1978) is used in the nexus context. Water, energy and food resources are used as inputs, together with other factors of economic or environmental interest, such as investment, GDP, waste generation or labour force, considered to be inputs or outputs (Chen et al., 2019; Han et al., 2020; Li et al., 2016; Sun et al., 2021). Malmquist efficiency indexes allow for the measuring of relative efficiency from the perspective of nexus relationships in a group of entities within a territorial domain, as well as its temporal evolution. In addition, the efficiency index decomposition is used to assess the pure technical and scale efficiencies. Finally, the results can be completed using cluster techniques to analyse their regional grouping (Sun et al., 2021).

4.8 Integrated indicators

Using this methodology, researchers seek to represent the state and performance of the nexus through a small number of magnitudes in a standardised format (Yuan et al., 2021). The use of indicators is very useful from a policy orientation point of view as it presents information from a complex system in a condensed and comprehensible way, albeit at the expense of simplifying reality. Arthur et al. (2019) distinguish between material flow, efficiency and environmental impact indicators, highlighting their usefulness for policy makers and, in particular, in relation to the implementation of the UN's SDGs. For this reason, Flammini et al. (2014) carried out a detailed study of the indicators available to assess the different interactions between nexus components in relation to these goals.

The relative simplicity of the indicator method allows for synthetic assessments with practical purposes. This is the case for indicators such as The *Nexus City Index* (Schlör et al., 2018) based on UN indicators, or the *Nexus Rapid Appraisal system* (Smajgl et al., 2016) when prioritising development strategies in regions with great climate and development differences. Indicators are used as a measure to characterise the degree of security of the nexus. This assessment can be done by considering the security of the three pillars, using their respective indicators as a basis (Cansino-Loeza et al., 2020; Djehdian et al., 2019; Mahlknecht et al., 2020; Sánchez-Zarco et al., 2020). Or by the construction of integrated indicators that synthesise in a single scalar the capacity of a territory to continue supplying resources in an accessible, sustainable and sufficient form. (Hua et al., 2020; Huang et al., 2020; Mohammadpour et al., 2019; Venghaus & Dieken, 2019).

When elaborating integrated indicators of nexus security or performance, the lack of investigation systematisation under this framework is revealed. Therefore, the majority of studies employ indicators that give equal importance or relative weight to the three pillars of the nexus, or the factors that make up the nexus assessment. Recently, other research (Nhamo et al., 2020a; Xu et al., 2019; Yi et al., 2020; Yuan et al., 2021; Zhang et al., 2019) has introduced the use of the hierarchical analytical process technique to establish different weights for the indicators of the nexus pillars and their components.

The diversity of methods, scales and objectives of the nexus studies (Endo et al., 2015), as well as the emerging character of this framework, means there is great heterogeneity on the considered factors and more still on the variables selected by each researcher. To all this we must add the difficulty of accessing data, which becomes a limiting factor for the investigation (Higgins & Abou Najm, 2020; McGrane et al., 2019; Opejin et al., 2020). This leads some authors to select the objects of study on the basis of available data (Ozturk, 2017; Venghaus & Dieken, 2019). Sometimes, countries offer a low level of available and accurate data on socio-economic or environmental variables. The resulting research is therefore hardly comparable (Markantonis et al., 2019).

As an expression of this heterogeneity, in a sample of 41 case studies used for this review, we found 201 different variables representing the nexus, with no two studies using the same set of variables. Sometimes different proxy variables are used for comparable factors, but very often the factors used in the particular framework are completely different (see Appendix III). In some cases, this heterogeneity may be justified by the very nature of the study (e.g., the use of resources in contexts of extreme poverty versus industrialised countries), however, in many other cases there seems to be no other explanation than the absence of methodological homogenisation, a shortcoming that needs to be addressed by establishing standardised frameworks and methodologies (Endo et al., 2017). Some homogenisation is desirable, to be able to conduct comparable studies across different nexus assessments and to establish uniform databases in terms of accuracy and temporal or spatial resolution (Markantonis et al., 2019).

5 Non-academic participation in nexus studies

The inclusion of non-academic actors in research allows for the understanding of changing systems, connections to decision-making at a political or economic level, and even the importance and credibility of the results (Wahl et al., 2021). This participatory process can be implemented as a preliminary qualitative phase to acquire high-level information on the functioning and interactions of a complex system (Tan et al., 2020).

Improved understanding of the nexus requires the explicit inclusion of all sectoral interdependencies. Only in this way will the effects of second and third order on its components be revealed (Smajgl et al., 2016). This knowledge can be obtained by involving various kinds of participants: The use of experts allows one to refine the system of indicators used and to establish the appropriate institutional and socio-economic framework (Kurian, 2017). The participation of the actors involved in nexus management can generate relevant information about the links between nexus pillars at an aggregate level, about the interests of the actors themselves or even non-public information (Flammini et al., 2014). Finally, the inclusion of end users provides information on the final impact of nexus management on actors such as small and medium-sized enterprises (Brouwer et al., 2018).

Participation can be used alongside structured or semi-structured surveys to implement indicator weighting systems in a hierarchical analysis process (Yuan et al., 2021; Zhang et al., 2019) This basic form of participation is also used to establish hierarchies based on the interrelationships between parameters affecting the nexus (Li et al., 2019).

At a deeper level, participation is used for the design of the nexus study framework. Combining qualitative participatory methods with quantitative methods that integrate statistical data may be the key to understanding complex nexus relationships (González-Rosell et al., 2020). Interviews and workshops are used to identify interrelationships that determine the structure of the nexus in any given field (Martinez et al., 2018). At a later stage, this information can be applied to form a system dynamics model (Brouwer et al., 2018; Tan et al., 2020).

Participation can also be conceived as the central element of the study, a qualitative technique for gaining knowledge about nexus on a reduced scale; to demonstrate the influence of social power relations over economic activity within the urban nexus (Covarrubias et al., 2019) or to show the utility of the nexus framework for designing policies based on the experience of diverse social actors (Treemore-Spears et al., 2016).

6 The scales of the nexus

The scale at which study of the nexus is undertaken is another aspect in which we find great diversity. The selection of the scale of each study may be based on different criteria, including the application area of a project, administrative boundaries, or delimitation of an ecological nature, such as a river or a mountain range (Newell et al., 2019). The overlap of these scales makes the study difficult, as different data for a territory are grouped with incompatible criteria (administrative divisions of economic data versus natural divisions of hydrological data, for example). This fragmentation also affects the governance of the nexus, with watershed scale being of great interest, especially for water management (Lawford et al., 2013). Studies on transboundary basins (Khan et al., 2017; Rasul, 2014) are paradigmatic cases of a scale established with ecological criteria that overlaps with a political division, making the study of nexus more complex.

McGrane et al. (2019) underline the importance of identifying the different scales at which the nexus is analysed, management measures implemented, or governance mechanisms found. These areas can range from domestic to global, to municipalities, states or regions. In particular, it is complex to integrate the actions of different actors from different spatial and temporal scales operating on the same nexus. This is an approach that has been poorly addressed in existing studies (Endo et al., 2015). Finally, availability and access to data appears to be a critical issue, with access becoming more difficult the smaller the scale of research.

Endo et al. (2017), after reviewing 37 projects under different nexus approaches, note that there is a lack, methodologically, in typifying the connection and establishing mutual influences among the nexus studied for areas of similar scale in a horizontal dimension. This is also the case in connecting, in a vertical dimension, nexus assessments from a local scale to national, regional or global scales. This vertical connection of the different nexus levels is of great relevance, given the different scales at which different factors operate. Thus, while resource management planning is usually local or sub-national, governance decisions are typically national or supranational, as in the case of the EU. On the other hand, climate change phenomena or resource flows, which also affect the nexus, operate on an international or global scale. This makes it necessary to take trans scalar interactions of an economic and ecological type into account in the study of the nexus. And not only in a spatial sense, but also in a temporal sense, extending from weeks to decades, depending on the impact of a project or climate change, for example (Schulterbrandt Gragg et al., 2018). This problem is addressed by King and Carbajales-Dale (2016), differentiating studies at project level–with time and scale delimitations determined by their own nature–from the analysis of nexuses of higher scales, whose boundaries must be fixed by the study itself.

Artioli et al. (2017) highlight the implications of the analysis of the governance of the nexus on the scale at which the study is conducted. Thus, a macro-level approach, such as the global or continental scale, will be more closely related to the economic and ecological consequences of globalisation. On the contrary, an approach in a more specific spatial context, such as the local or provincial scale, is more conducive to considering the role of specific policies and actors affected by resource interdependence.

Of the 106 territorial studies of nexus analysed, the majority are national (32) and urban (29), followed by sub-national (17) and regional (14) country groupings, and basin level (9) (Table 2). Two studies have a global scope and two study a particular sector in an economy, while at the project level there is only one study. However, these delimitations are flexible as some regional studies consist of a set of studies at national level, while several urban studies generously cover an entire metropolitan area, approaching the sub-national level. Appendix II provides detailed information about the geographical scale of the articles analysed.

We can also observe a differentiation by the type of methodologies adopted depending on the scale at which the study is located. Thus, both statistical-based methodologies and their subsequent application through econometric techniques are concentrated more on studies at national or regional levels. Most likely, the availability of data from official sources is the limiting factor for applying these methodologies to smaller scales (Opejin et al., 2020). However, more complex methodologies such as SDM, which require the representation of all system interactions to a high level of detail, are more common in urban or most sub-national scale studies, because of the difficulty of carrying out the construction of these models on a higher scale. The high number of national ecological network studies is related to IO, based on national balance sheets typically being prepared at this scale, while urban studies use more specific ecological footprint data at a municipal level. Finally, the methodology based on integrated indicators is the most transversal to the scales of the nexus.

Among the country-level studies, a specific case is that which proposes an analysis of the nexus according to a framework that interprets the national economy as a network of economies of sub-national administrative scope, whose respective nexus can be evaluated separately. Following this approach, various studies have modelled the Chinese economy on its provinces (Han et al., 2020; Hua et al., 2020; Li et al., 2016; Sun et al., 2021) or the USA from its state-wide nexus, in a study focusing on virtual water consumption (Mahjabin et al., 2020).

On a smaller scale than a national one, geographic regions close to large cities appear in studies of quantification of material flows as their main territory for the supply of water, food and energy. It is in these areas that most of the extraction of resources for urban supply is concentrated (Arthur et al., 2019; Djehdian et al., 2019; Ramaswami et al., 2017; Schlör et al., 2018). For this reason, in a first approximation, the urban nexus can be linked to the nexus of these administrative territories of which the city is the centre (Niva et al., 2020) and which in turn make up the nexus network on a national scale (Amaral et al., 2021; Chini et al., 2017).

7 Conclusions and policy implications

The WEFnX demonstrates itself to be a useful approach for jointly assessing the sustainability of an economy. This approach allows us to overcome single-sector analysis, which is unable to detect cross-effects on resource consumption. Integrated assessment can identify positive links between resource use or specific policies and technologies (synergies), as well as negative interactions. These antagonistic links represent a conflict between the use of resources or cause the appearance of an external cost in the implementation of a policy or use of a technology, in the form of indirect consumption of other resources. Indirect or second-order effects remain hidden in sectoral or compartmentalised analyses. Equally, the framework allows for the evaluation of the degree of performance and efficiency of the system represented in the nexus, the security of access to resources or optimisation of its use.

We found a close link between the SDGs and the nexus studies, a valuable tool for evaluating the degree of development and the progress towards most of the goals and targets, as detected in the sample considered in this study. Similarly, the design of policies inspired by the synergies detected through the nexus studies are a potential source of progress towards SDG compliance.

The nexus framework offers a wide range of methodologies; each of which may be considered more appropriate depending on the objectives of the research, the scale at which the study is proposed and even the data available to the research team. This diversity, however, requires a certain harmonisation and homogenisation of both the methods and the variables used, so as to make progress in the comparability of the studies. Another desirable effect of homogenising methods and studies is the possibility of integrating them rigorously on both a horizontal and vertical scale, as well as in a chronological sense.

By their very nature, the studies seek to overcome silo mentality (Guan et al., 2020; Liu et al., 2018; Ringler et al., 2013) as their approach is transversal and based on interactions between different fields and managed by different actors. The use of techniques of participation of the actors involved in the nexus can provide both quantitative and qualitative information that enriches the studies and allows for a greater approximation to reality.

In an applied way, the nexus' ability to highlight certain critical points of an economic system makes it possible to use its conclusions to design strategies and develop economic policy guidelines such as investment planning (Chen et al., 2020b; Elbehri & Sadiddin, 2016; Mpandeli et al., 2018; Wang et al., 2021), urban design (Gondhalekar & Ramsauer, 2017; Toboso-Chavero et al., 2018), sectoral distribution of resource use (Nhamo et al., 2020b) and tariff policies (Bieber et al., 2018; Ding et al., 2019; Tan et al., 2020). Comparative analysis of the nexus allows for the establishment of regional economic policy guidelines within the same country (Han et al., 2020; Hua et al., 2020), while in other cases the results lead to recommendation of a greater degree of economic integration between countries in the same region (Jalilov et al., 2018; Mpandeli et al., 2018). Similarly, nexus analyses can serve as a basis for public policies to drive socio-economic changes, such as greater collaboration between institutions (Yuan et al., 2021) and improving innovation in the agricultural sector through incentives (Bieber et al., 2018; Wang et al., 2021). As well as changes to domestic wastewater management systems (Villarroel Walker et al., 2014), favouring changes in food consumption patterns (Damerau et al., 2016), or the development of free trade as an alternative way of optimising resource management (Elbehri & Sadiddin, 2016; Hardy et al., 2012).

Finally, the models constructed using the WEFnX framework allow for the characterisation of the environmental impact and economic performance of both future and alternative scenarios. This applies to the evaluation of economic policy alternatives or investments. The assessment of the implications for resource availability, and the performance of economic sectors in the face of different climate change scenarios is of particular interest and serves to guide adaptation and resilience policies. In our study, there is evidence of a relationship between the methods used and the scale of each study. Research using a larger sample and with a specific focus on this aspect could provide more meaningful conclusions. On the other hand, our study limits itself to showing the need to homogenise the variables used in nexus research. Future research aimed at proposing optimal sets of indicators for each methodology could be very useful. Finally, given the relationship between the nexus and the SDGs, with many works aimed at proposing guidelines for policy action, it would be of great interest to investigate to what extent such academic analyses have had an impact on decision-making in national agendas aimed at achieving the SDGs.

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