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To cite this article: Beatrice Sambo *et al* 2024 *Environ. Res. Lett.* **19** 121003

IOP Publishing Environ. Res. Lett. 19 (2024) 121003 https://doi.org/10.1088/1748-9326/ad96cf

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OPEN ACCESS

RECEIVED
18 January 2024

REVISED
11 November 2024

ACCEPTED FOR PUBLICATION
25 November 2024

PUBLISHED
6 December 2024

PERSPECTIVE

Looking at the Water-Energy-Food nexus through the lens of Ecosystem Services: a new perspective

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Keywords: WEFE nexus, Ecosystem Services, climate change, complex science methods

1. Introduction

Global demand for Water, Energy, and Food (WEF) has risen significantly in recent decades, a trend that is expected to continue. The interconnected nature of WEF systems, along with global change drivers, highlights the need for an integrated resource management approach known as 'nexus thinking.' This approach emphasizes the synergies and trade-offs among WEF policies to achieve sustainable outcomes. Water is essential for food production and energy generation; energy is required for water extraction, treatment, and distribution; and food production needs both water and energy. Ecosystems play a crucial role in this nexus by providing Ecosystem Services (ESs)—contributions of ecosystems to human well-being, such as provisioning (e.g. food, water), regulating (e.g. climate), and cultural services (e.g. recreational) (Burkhard and Maes 2017). ESs arise from interactions between the biosphere and anthroposphere, offering an operational perspective for their sustainable integration (Fürst *et al* 2017). Despite the recognized importance of ESs in WEF nexus discussions (Liu *et al* 2017, Hülsmann *et al* 2019), their integration into current nexus frameworks is limited. ESs are often underrepresented, and their role and mode of integration vary significantly (Fürst *et al* 2017). In literature, ESs are often considered as an additional node with equal importance to WEF, but closely intertwined with them through two main types of interrelationships. In some studies, ESs are treated as endpoints to assess the environmental impacts of WEF policies by examining how anthropogenic activities affect ESs (Ravar *et al* 2020). In others, ESs are seen as external drivers that influence WEF sectors through ecosystem conservation or nature-based adaptation (Muthee *et al* 2021). This conceptualization, however, overlooks the fact that while ecosystems can exist independently of the WEF sectors, WEF sectors are inherently dependent on and limited by ecosystems for their functioning. ESs conceptualize this dependency and interrelationships, making them not a separate component but rather an enabling feature of every nexus system. Accordingly, this perspective paper argues that a truly integrated nexus approach necessitates placing ESs at the center of the WEF nexus framework. It begins by defining ESs and discussing their role within this nexus. Subsequently, it illustrates how implementing nexus thinking could be enhanced and operationalized by incorporating an ESs-based perspective. Finally, it provides recommendations for future steps to foster this integration.

2. ESs in the center of the Water-Energy-Food (WEF) nexus

ESs arise at the interface between ecological and social systems (Ostrom 2009). They represent the ultimate spot of interactions among multiple nexus sectors. On one hand, WEF sectors are the recipient of the services provided by ecosystems. On the other, WEF sectors are drivers of landscapes transformation, impacting on ecosystems process and functions altering or inhibiting the capacity to deliver their services. In line with this framing, we argue that ESs should be incorporated in the center of any nexus framework as implicit features mediating other nexus links rather

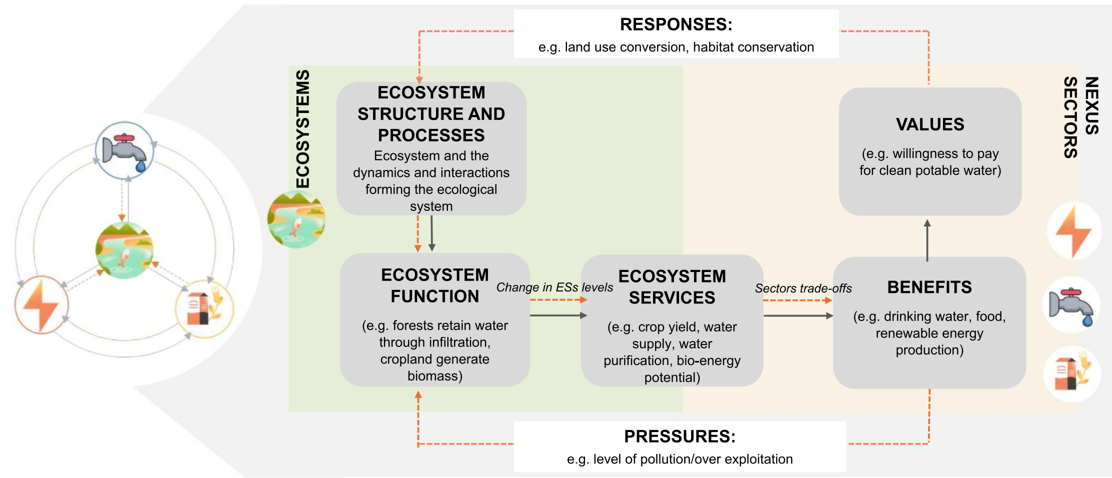

Figure 1. Integrating the Ecosystem Services cascade model in the WEF nexus framework. Adapted from Sperotto 2023.

than an additional node (figure 1). The role of ESs as a function to facilitate synergies and trade-off between multiple sectors become explicit when integrating the ESs cascade model (Haines-Young and Potschin 2018) into the WEF nexus framework (figure 1).

Ecosystems are characterized by ***biophysical structures and processes***, such as habitat types and the dynamics and interactions forming the ecological systems. These structures and processes underpin ***ecosystem functions***, which are essential for delivering ***ecosystem services***, that are valued for the direct ***benefits*** sustaining different nexus sectors. Different sectors value the same set of ESs in different ways. Such values drive the demand and actual use towards specific services rather than the others. The increase in the demand of a specific ESs however inevitably acts as driver of change in the system, either exerting ***pressures*** on ecosystems (e.g. overexploitation, pollutions) or putting in place ***responses*** (e.g. land use conversion) aimed at maximizing the supply of the desired service. Both of these mechanisms altering biophysical structures and processes can reduce or inhibit the capacity of ecosystem to provide either the same ESs or other types. In this latter case we speak about trade-offs among multiple ESs (i.e. when the increase in provisioning of one ESs reduces that of another one), which ultimately describe conflicts among nexus sectors.

Wetlands, for instance, purify water and recharge aquifers, supporting agricultural irrigation and yield and reducing the need for energy-intensive water treatment showcasing direct benefit for both food and energy sector. However, the increasing demand of such services from the food sector can induce over-extraction of water for irrigation purposes and deforestation for extending crop areas; With reduced water levels and vegetation cover, water purification services provided by wetland are in turn curtailed, resulting in important trade-offs across other services and users (i.e. water and energy sectors).

3. Benefits of the adoption of an ESs-based perspective

The adoption of an ESs perspective can significantly enhance the achievement of multiple nexus objectives (Carmona-Moreno *et al* 2019) by recognizing and leveraging the benefits that ESs provide (table 1).

The goal of nexus thinking is to develop integrated policies that enhance the sustainability of WEF security by focusing on system-wide efficiency rather than individual components. Understanding the interdependence of resources across space and time is crucial for identifying such solutions. Adopting an ES perspective within the WEF nexus allows for the spatial and temporal quantification of interactions among sectors. This approach reveals how resources flow and interact, capturing time-lag effects and distributional mechanisms. By mapping ES flows, critical areas of intersectoral synergies and trade-offs can be identified and optimized (Sušnik *et al* 2021). The ES perspective also promotes rational and inclusive dialogue and decision-making. It provides a common framework for stakeholders to understand the benefits ecosystems provide within nexus systems, making these services visible and quantifiable. This encourages stakeholder participation, highlights the shared benefits of efficient resource use, and enhances transparency and informed discussions (Purwanto *et al* 2019, Shi *et al* 2022). Involving local communities, industries, and conservation organizations ensures that policies reflect the interests of all affected sectors,

Table 1. Benefits of adopting an ESs perspective to nexus assessment.

WEF nexus key principles	Contribution of an ESs-based perspective
Understand the interdependence of resources within a system across space and time	• Permit to spatially-temporally map ecosystem contributions revealing resource linkages and dependencies; • Accounts for spatial and temporal variation under changing conditions; • Identifies time lag effects and distributional mechanisms in resource use
Promote rational and inclusive dialogue and decision-making processes for the efficient use of resources	• Provides a common framework for stakeholders to understand ecosystem benefits and impacts; • Facilitate informed discussions by making resources flow visible and quantifiable; • Encourages stakeholder participation by highlighting the shared benefits of efficient resource use.
Identify integrated solutions to optimise trade-offs and maximise synergies across sectors	• Identifies sectoral trade-offs and synergies; • Inform integrated policies balancing competing sectoral demands; • Supports adaptive management strategies
Ensure policy coordination across sectors and stakeholders	• Aligns policy goals exploiting multiple benefits of ecosystem services; • Permit to account to multiple values and sectoral demands; • Promotes coordinated actions by highlighting mutual dependencies and benefits among stakeholders.
Value the natural capital of land, water, energy sources and ecosystems	• Highlights the long-term benefits of conserving natural capital for sustained resource availability; • Assigning value to ecosystem services permit their integration into cost-benefit analyses; • Encourages investments in nature-based solutions

fostering consensus-building and increasing the legitimacy and effectiveness of adopted policies (Sušnik *et al* 2021).

Moreover, the ES perspective fosters coherence between sectoral policies, such as the Water Framework Directive, Common Agricultural Policy, Climate Change Adaptation, and the Green Deal, by identifying trade-offs and synergies in ES provision. This alignment promotes cross-sectoral collaboration, encouraging coordinated actions and policies among stakeholders (Ravar *et al* 2020, van den Heuvel *et al* 2020). The approach also supports adaptive management strategies, enabling the measurement of policy outcomes on ES provision.

Adopting an ES perspective within the WEF nexus is crucial for recognizing and valuing natural capital in land, water, and energy sources. By assigning value to these services, the costs of ecosystem degradation and the benefits of conservation become clearer, integrating these considerations into cost-benefit analyses. Nature-based solutions, like wetlands restoration, afforestation are emphasized for their multifunctional benefits and sustainability, with incentives such as payments for ecosystem services further encouraging sustainable practices (Muthee *et al* 2021).

4. The step forward: recommendation for the operationalization of ESs within nexus assessment

Despite previous studies emphasizing the need to integrate ESs in WEF nexus assessments, their explicit inclusion in nexus modeling tools remains limited (Hülsmann *et al* 2019). Various methods traditionally applied in both nexus and ES assessments offer opportunities for this integration. Conceptual Models (CMs) and Causal Loop Diagrams provide valuable qualitative approaches to understand nexus behavior by identifying where ESs can be integrated, elucidating interlinkages and feedback mechanisms (van den Heuvel *et al* 2020, Muthee *et al* 2021). These tools can identify leverage points to enhance synergies between ES provisioning and critical nexus sectors. For example, improving forests conservation can create a positive feedback loop, benefiting water retention, soil quality, agricultural productivity, and bio-energy production. Such models help disentangle the complexity of the interactions between WEF sectors and ESs, identify feedback loops, and establish causal relationships without extensive data collection or complex modeling (Purwanto *et al* 2019). However, their reliance on qualitative data limits their ability to quantify feedbacks, preventing a full understanding of the dynamics at play (Ravar *et al* 2020).

Nexus dynamics can be effectively captured using indicators, which allow quantifying relationships providing a semi-quantitative approach that bridges the gap between qualitative CMs and more complex quantitative methods. Wang *et al* (2021) analyzed synergies and trade-offs change among sectors by means of a specific set of nexus-related ESs indicators (e.g. energy production, water demand, food supply). In addition, by employing statistical approaches such as temporal and spatial correlation analysis, researchers can identify whether synergies or trade-offs exist between pairs of ESs, providing valuable insights into the interconnected nature of the system. ESs indicators, such carbon storage, crop yield, food production, landscape aesthetic, can be utilized in statistical models, such as correlation and bundle analysis, which aims to identify areas where ESs with similar characteristics are present to detect spatial-temporal heterogeneity of ES and thus 'hot-spot' area for nexus sustainment (Xia *et al* 2023). This allows decision-makers to manage these regions in a coordinated manner, optimizing the balance between ESs and ensuring sustainable resource management enhancing policy coherence. Quantitative models like System Dynamics Models (SDMs) and Bayesian Networks (BNs) are employed in nexus assessments to translate qualitative insights into measurable outputs. BNs can model complex relationships between WEF sectors and ESs, providing probabilistic insights into risks, trade-offs, and synergies over time taking into consideration uncertainties in the evolution of the future. (Wang *et al* 2021) analyzed how synergies and trade-offs among ESs indicators change under 27 different scenarios combining both climate (i.e. change in precipitation) and socio-economic (i.e. per capita GDP growth rate, and population growth rate) changes throughout BN models. They predict how changes in one sector, such as water demand, might impact ESs like energy production or food provision over the long term. BNs also facilitate inclusive and transparent decision-making processes by allowing stakeholders to input their knowledge and data. However, BNs struggle with capturing feedback loops essential for understanding long-term impacts, a gap where SDMs are particularly useful. SDMs excel in capturing feedback loops, allowing for the testing of policy interventions and management strategies that optimize outcomes across multiple ESs, reducing trade-offs, and maximizing synergies (Sušnik *et al* 2021).

Additionally, spatial models like InVEST (Integrated Valuation of ESs and Trade-offs) are traditionally used in ES assessments to spatially map and quantify ES flows across nexus sectors. InVEST enables analysis of trade-offs, synergies, and impacts of management practices, making it a valuable tool for guiding sustainable policies (Shi *et al* 2022). Given the complexity of the WEF nexus and the necessity to integrate ESs, a multi-faceted approach combining multiple models, diverse data sources, and spatial-temporal scales is crucial. No single model can capture the full scope of this intricate system. Driven by societal demands and the convergence of big data, advanced computing power, and efficient algorithms, data-driven methods can transform the way we understand and manage complex systems including the nexus (Jonsson *et al* 2024; Willcock *et al* 2018). Integrative technologies like ARIES (Artificial Intelligence for ESs) (Villa *et al* 2014, Martínez-López *et al* 2019) represent promising tools that should be better explored to significantly enhance our ability to operationalize ESs within the WEF nexus, supporting the development of more sustainable and resilient policies.

To conclude, the inclusion of ecosystems within the nexus is gaining increasing attention, with ESs recognized not as an additional dimension but as an essential underlying feature that should be placed at the center of the nexus framework. Although few examples exist in the literature, these cases demonstrate enormous benefits of this paradigm shift in enhancing nexus coherence and understanding. Emergent tools such as SDM, BNs and AI offer promising pathways to further advance this critical integration and should be better explored for the operationalization of ESs into nexus assessment in future works.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgment

This publication was supported by the Horizon2020 Project 'Facilitating the next generation of effective and intelligent water-related policies utilising artificial intelligence and reinforcement learning to assess the water-energy-food-ecosystem (WEFE) nexus' (NEXOGENESIS - 101003881), by the European Union—NextGenerationEU, in the framework of the iNEST—Interconnected Nord-Est Innovation Ecosystem (iNEST ECS_00000043—CUP H43C22000540006) and by European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie 859 Grant Agreement No. 893103. The views and opinions expressed are solely those of the authors and do not necessarily reflect those of the European Union, nor can the European Union be held responsible for them.

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