



# Quantifying Nature-Based Solutions within the Water-Energy-Food-Ecosystems Nexus: an intensity-based WEFE assessment of an agroecological vineyard in Northern Spain

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## Abstract

This study develops a quantitative framework to assess how Nature-Based Solutions (NbS), implemented through agroecological practices, perform within the Water–Energy–Food–Ecosystems (WEFE) Nexus. While NbS are widely recognized for their environmental benefits, few studies provide operational tools to quantify their cross-sectoral trade-offs at the farm level. To address this gap, an intensity-based WEFE assessment and a composite WEFE Nexus Index were applied to a rainfed vineyard in Northern Spain and compared with prevailing conventional practices. The analysis integrates water, energy, carbon, and productivity indicators to reveal nexus interactions rather than sectoral footprints. Results show that the transition to agroecological practices reduces energy demand by 72% and carbon emissions by 57%, demonstrating pronounced water–energy–carbon interdependencies within the WEFE Nexus framework. However, lower yields introduce food–resource trade-offs, highlighting the need to balance environmental efficiency with productivity. These interactions are captured through the WEFE Nexus Index, which provides a systemic performance indicator. The findings demonstrate that agroecological NbS can significantly reduce resource dependency while maintaining viable production, offering both environmental and economic resilience. The study provides a practical methodology for integrating NbS into WEFE Nexus planning and policy at the farm scale.

**Keywords** Nature-Based Solutions · WEFE Nexus · Agroecological practices · Resource efficiency · Water-Energy-Food-Ecosystems Index

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## 1 Introduction

The integrated management of resource can be addressed and managed in multiple ways and with different approaches through technical and governance solutions. Over recent decades, Ecosystem-based Approaches (EbA) have received increasing attention as effective strategies for ecosystem management. Within this context, the concept of Nature-Based Solutions (NbS) has emerged as a focal point, gaining significant traction. The International Union for Conservation of Nature (IUCN) defines NbS as “actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (IUCN, 2020). Nature based solutions have the potential to provide multifaceted benefits for the Water-Energy-Food-Ecosystems (WEFE) Nexus, such as improving water availability, enhancing energy efficiency,

supporting agricultural productivity, and conserving ecosystems. For example, the restoration of wetlands can regulate water flows, reduce flood risks, enhance biodiversity, and store carbon, thus addressing multiple components of the WEFE Nexus simultaneously (Panagopoulos and Dimitriou 2020). In agricultural contexts, agroecological practices are increasingly recognized as a form of Nature-Based Solutions. According to the IUCN definition, NbS include actions that protect, sustainably manage, and restore ecosystems while addressing societal challenges. Agroecology aligns with this definition by enhancing soil organic matter, promoting biodiversity, reducing chemical inputs, and optimizing the use of natural water cycles. These practices restore ecological functions within farmland and rely on ecosystem processes rather than external inputs, thereby qualifying as operational NbS within agricultural systems.

Despite these benefits, significant gaps persist in understanding and evaluating the role of NbS within the WEFE Nexus framework. One of the main challenges lies in the absence of comprehensive quantitative methodologies for systematically assessing the effectiveness and scalability of NbS. Quantitative assessments remain limited, highlighting a significant research gap. While some studies provide metrics for specific components such as water retention in agroforestry systems or flood reduction in sponge city initiatives comprehensive evaluations that quantify the interconnected benefits and trade-offs across the entire Nexus are sparse. Most research focuses on qualitative descriptions or isolated impacts, leaving gaps in understanding the systemic interplay among water, energy, food, and ecosystem services. In addition, few studies incorporate long-term data, economic valuation, or comparative analyses between NbS and conventional grey infrastructure. Addressing this gap requires the development of integrated models and standardized metrics to holistically quantify NbS outcomes, enabling more robust and evidence-based decision-making for sustainable WEFE Nexus governance.

While several studies have examined the potential of NbS to address WEFE Nexus challenges (Wickenberg et al. 2021; Kauark-Fontes et al. 2023), a lack to consider the governance and policy aspects that hinder the implementation of NbS. The integration of NbS into existing governance systems requires cross-sectoral coordination, participatory decision-making, and adaptive governance mechanisms (Zingraff-Hamed et al. 2021). However, fragmented institutional frameworks, inadequate policy alignment, and limited stakeholder engagement often hinder the adoption and sustainability of NbS interventions.

In recent years, the integration of WEFE Nexus frameworks into environmental and agricultural research has expanded significantly. Rhouma et al. (2024) provide a comprehensive bibliometric review showing how WEFE-related

publications have evolved from theoretical frameworks to applied research, emphasizing systems thinking, governance integration, and cross-sectoral planning. Similarly, Daher et al. (2022) and Lee et al. (2023) show that WEFE Nexus approaches are being applied to address compound shocks in food systems and industrial resource flows. These studies reinforce the need for quantitative and cross-sectoral tools to evaluate trade-offs and synergies, particularly in contexts involving water scarcity, energy use, and food system transformation.

Despite growing recognition of both NbS and the WEFE Nexus, few studies operationalize how NbS can be quantitatively assessed within this framework at the farm level. Most research remains either conceptual or sector-specific, lacking tools to measure cross-sectoral trade-offs in real agricultural systems. This gap motivates the present study. Based on this context, the objectives of this study are to conduct a systematic review of NbS and examine their relevance to the WEFE Nexus, to quantify the water, energy, carbon, and ecosystem-related footprints of a vineyard in Northern Spain using farm-level data, and to apply and evaluate a WEFE Nexus Index in order to assess sustainability performance and resource trade-offs between conventional and agroecological vineyard practices.

## 2 Materials and methods

This study follows a structured methodological sequence designed to connect literature insights with quantitative farm-level assessment. First, a targeted literature review was conducted to identify existing gaps in the integration of Nature-Based Solutions within the WEFE Nexus. Second, a vineyard case study was selected to operationalize NbS through agroecological practices. Third, sectoral footprints (water, energy, carbon, and productivity) were calculated using established methods. Fourth, these indicators were integrated using an intensity-based framework to reveal nexus trade-offs and synergies. Finally, the normalized indicators were aggregated into a composite WEFE Nexus Index to evaluate systemic performance. This sequence ensures that the review, calculations, and index are not independent components but parts of a coherent analytical framework.

### 2.1 Review analysis

A structured literature review was conducted to examine the contribution of Nature-Based Solutions within the Water–Energy–Food–Ecosystems (WEFE) Nexus framework. A systematic search was performed in the Web of Science and Scopus databases covering the period 1997–2024. The primary search string included: (“nature-based solution\*” OR

“NbS”) AND water AND energy AND food AND ecosystems\* AND nexus. Additional related terms such as constructed wetlands, agroecological practices, hydroponics, and aquaponics were also included to broaden the scope of relevant NbS interventions.

The initial search yielded 312 publications. After screening titles and abstracts for relevance to both NbS and at least two WEFE components, 74 articles were retained for full-text review. Following further assessment based on explicit discussion or quantification of interactions between NbS and WEFE elements, 38 studies were selected for final analysis. Although a formal PRISMA protocol was not applied, a structured screening process was followed to ensure transparency and relevance.

To identify dominant research themes and thematic relationships, a co-occurrence network of author keywords was generated using VOSviewer (version 1.6.X). Author keywords extracted from the selected publications were analyzed using the full counting method. A minimum occurrence threshold was applied to reduce noise and improve visualization clarity. The network was constructed based on association strength normalization, clustering keywords according to co-occurrence frequency and link strength. This approach enabled identification of major thematic clusters linking NbS with water, energy, food, ecosystem services, governance, and sustainability dimensions.

## 2.2 Case study: quantitative assessment of the WEFE Nexus of agroecology practices

### 2.2.1 Case study

The case study is located in Sant Pere de Ribes (Fig. 1), a municipality in the northern part of Spain, within the province of Barcelona. This study is based on a single farm, which was selected due to the availability of reliable field data and its adoption of agroecological practices, making it a suitable case for exploring the application of the WEFE Nexus framework at the local scale. The farm spans an area of 25 hectares and is primarily dedicated to cultivating wine grapes, highlighting the region’s strong viticultural heritage. Sant Pere de Ribes, located in the Mediterranean region, serves as an ideal case study for this intensity-based analysis. The region is renowned for its fertile soils and favourable climatic conditions, characterized by hot, dry summers and mild, wet winters. These conditions support both rainfed and irrigated vineyards, making the region a focal point for exploring the resource dynamics of conventional and agroecological farming practices. Grape cultivation is a cornerstone of the local agricultural economy, contributing significantly to employment, food systems, and winemaking industries. Conventional farming practices in the region rely heavily on irrigation, synthetic fertilizers, and mechanization, leading to high resource demands and environmental costs. In contrast, agroecological practices reduce blue water use and synthetic inputs, focusing on rainwater harvesting, organic fertilizers, and biodiversity-friendly methods to enhance sustainability. The comparison therefore reflects prevailing regional management alternatives



**Fig. 1** Location of the vineyard case study in Sant Pere de Ribes, Northern Spain, illustrating the Mediterranean rainfed viticultural context used for the WEFE Nexus assessment

(irrigated conventional versus rainfed agroecological vineyards) rather than an experimental attempt to equalize conditions, making the assessment relevant for real-world policy and farm decision-making.

The agroecological practices implemented in this vineyard are treated in this study as Nature-Based Solutions (NbS). While agroecological practices are framed here as a form of NbS at the farm scale, it is important to acknowledge that NbS encompass a wide spectrum of interventions, including wetland restoration, riparian buffers, and watershed-scale ecosystem management. The quantitative results presented in this study therefore reflect the performance of production-oriented NbS embedded within an agricultural system. Other forms of NbS, may exhibit different WEFE nexus interactions, trade-offs, and magnitudes of impact. However, the intensity-based assessment framework applied in this study is transferable and can be adapted to evaluate other NbS types, provided that relevant sectoral indicators are defined. In this case study, the NbS include rainfed farming, organic fertilization, biodiversity enhancement, and reduced mechanization, all of which rely on ecological processes rather than synthetic inputs. Framing agroecology as NbS allows the case study to serve as a practical example of how NbS can be quantitatively assessed within the WEFE nexus at the farm scale.

The transition to agroecological farming in Sant Pere de Ribes is driven by the need to optimize resource efficiency and minimize environmental impacts. Agroecological systems emphasize sustainable resource management, reducing reliance on blue water and chemical inputs while enhancing biodiversity, soil health, and climate resilience. These practices align with broader sustainability goals, offering a pathway to more efficient and environmentally friendly vineyard farming.

### 2.2.2 Data collection and source

Farm input data were collected through structured survey combined with on-site farm records and field observations. Fuel consumption data were obtained from machinery operation logs and annual fuel purchase records. Fertilizer and pesticide application rates were derived from farm management records specifying quantities applied per hectare. Electricity consumption for irrigation in the conventional scenario was estimated based on pump power ratings (kW), irrigation duration (hours), and seasonal irrigation schedules. Productivity data which represent the food component of the WEFE Nexus were obtained from official harvest records for the corresponding agricultural season. All data used in the analysis refer to the same production year to ensure internal consistency in footprint calculations.

### 2.2.3 Footprint calculations

The importance of footprint metrics extends across several dimensions. From an efficiency perspective, these coefficients reveal how effectively resources are utilized in production processes. Lower intensity values often indicate more efficient practices, highlighting opportunities to optimize resource use. Furthermore, footprints illuminate the strength of intersectoral linkages, with high values suggesting that a disruption in one sector could propagate and significantly affect others. This understanding is particularly critical for managing systemic vulnerabilities. These metrics provide a lens to evaluate environmental impacts, identifying sectors with high resource demands or emissions and prioritizing interventions to reduce their footprint.

**2.2.3.1 Crop water use and water footprint** The crop water use (CWU) was calculated using the following formula where CWR is Crop Water Requirement and  $P_{eff}$  is the effective rain. CWR and  $P_{eff}$  were calculated using CROPWAT software.

$$Crop\ water\ Use = 10 \times \sum_{d=1}^n \min(CWR, P_{eff}) \quad (1)$$

The water footprint is obtained by dividing the CWU by the yield.

- CWR is the crop water requirement on day  $d$  (mm/day),
- $P_{eff}$  is the effective rainfall on day  $d$  (mm/day),
- $d$  represents the day within the growing period,
- $n$  is the total number of days in the growing season,
- $\min(CWR, P_{eff})$  represents the minimum value between crop water requirement and effective rainfall for each day, reflecting that actual crop water use under rainfed conditions cannot exceed either rainfall or crop demand, and,
- 10 is a unit conversion factor used to convert water depth (mm) into volumetric units ( $m^3/ha$ ), since 1 mm of water over 1 hectare corresponds to  $10\ m^3$ .

The daily values of CWR and effective rainfall were obtained using FAO CROPWAT 8.0 based on local climatic, crop, and soil parameters.

**2.2.3.2 Carbon footprint** The calculation of carbon footprint was quantified using the following equation according to Ghiglieno et al. (2023). The methodology from Ghiglieno et al. (2023) was selected due to its specificity to vineyard systems and alignment with IPCC guidelines for emission factors, making it suitable for farm-scale analysis where detailed life-cycle data may not be available. This approach

is widely used in viticulture studies and offers a transparent and replicable basis for calculating emissions from fuel use, fertilizers, and pesticides. While more complex LCA models exist, their application requires extensive data and system boundaries that are beyond the scope and scale of this study.

$$CF = \sum (Pdi \cdot EFi) \quad (2)$$

where Pdi represents the quantity of each input used in vineyard operations (fuel, fertilizers, pesticides, electricity) and EFi is the corresponding emission factor obtained from Table 1 and referenced sources.

The specific factors are those report in Table 1. This table presents the greenhouse gas emission factors used to estimate the carbon footprint for vineyard operations, as reported by Tomaz et al. (2025). These factors are widely accepted for farm-level GHG accounting in Mediterranean viticulture. Fuel use (e.g., for tractors) contributes significantly to CO<sub>2</sub> emissions, while electricity used primarily for irrigation in conventional systems adds further emissions, especially when sourced from fossil-based grids. Fertilizers, particularly nitrogen-based ones, are major sources of both direct and indirect N<sub>2</sub>O emissions, which have high global warming potential. Pesticide categories (herbicides, fungicides, insecticides) are included due to their upstream manufacturing emissions and application-related energy use. These components were selected because they capture the main emission sources in vineyard management and align with IPCC Tier 1 methodologies, allowing for

**Table 1** Greenhouse gas emission factors used to estimate carbon footprint for vineyard activities

Emission Source	Unit	GHG Emissions/Unit
Fuel	kg CO <sub>2</sub> e L <sup>-1</sup>	3.12
Electricity for irrigation	kg CO <sub>2</sub> e kWh <sup>-1</sup>	0.34
N <sub>2</sub> O direct emissions <sup>a</sup>	kg N <sub>2</sub> O\u2013N (kg N) <sup>-1</sup>	0.01
N <sub>2</sub> O indirect emissions <sup>a</sup>	kg N <sub>2</sub> O\u2013N (kg N) <sup>-1</sup>	0.01
N fertilizer <sup>b</sup>	kg CO <sub>2</sub> e kg <sup>-1</sup>	2.78
P <sub>2</sub> O <sub>5</sub> fertilizer <sup>b</sup>	kg CO <sub>2</sub> e kg <sup>-1</sup>	0.12
K <sub>2</sub> O fertilizer <sup>b</sup>	kg CO <sub>2</sub> e kg <sup>-1</sup>	0.41
Herbicides <sup>c</sup>	kg CO <sub>2</sub> e kg <sup>-1</sup>	4.70
Fungicides <sup>c</sup>	kg CO <sub>2</sub> e kg <sup>-1</sup>	5.18
Insecticides <sup>c</sup>	kg CO <sub>2</sub> e kg <sup>-1</sup>	4.93

Adapted from Tomaz et al. (2025); the values cover key inputs such as fuel, electricity, fertilizers, and pesticides based on standard European agricultural practices

<sup>a</sup>Default value for dry cropland in the Tier 1 approach of IPCC

<sup>b</sup>Default value for the European region

<sup>c</sup>Aggregated value for production and post-production of each pesticide type

comparability and consistency with other farm-level studies. A brief explanation of each emission category and its relevance to vineyard carbon accounting is now included to provide better context.

**2.2.3.3 Energy footprint** The energy footprint was calculated following the methodology of Fabiani et al. (2020) which quantifies the total energy inputs required for agricultural production. This includes energy associated with fuel consumption for field operations, mechanization, and, in the conventional scenario, electricity used for irrigation pumping. Energy inputs were converted into megajoules (MJ) per ton of grape production to enable comparison between scenarios and integration into the WEFEX Nexus assessment. This indicator reflects the dependency of the production system on external energy inputs and is particularly relevant for identifying water–energy linkages in irrigated systems.

$$\text{The energy productivity} = \frac{\text{Total energy } (E_i)}{\text{Yield } (kg)} \quad (3)$$

where E<sub>i</sub> represents the energy associated with each agricultural input or operation (fuel use, mechanization, irrigation electricity), converted into MJ per ton of grape production.

## 2.2.4 Calculation of a WEFEX Index

Since the indicators have different units, so at first, the indicators should be normalized, for which the Equation proposed by Juwana et al. (2012) was used. The normalization approach proposed by Juwana et al. (2012) was selected due to its simplicity and adaptability to cases where only single-point data or a limited range is available. It is particularly useful for small-scale, farm-level assessments where standardization of units is essential to compute an integrated index. We considered multi-criteria decision-making tools (e.g., AHP or TOPSIS), but they require stakeholder-derived weights and preferences, which were not feasible in this exploratory, data-driven study. This normalisation was carried out depending on whether the indicator contributes negatively or positively. For the normalization of the indicators that contribute positively we apply this formula:

$$X_i = \frac{x_i - \text{Min}(x_i)}{\text{Max}(x_i) - \text{Min}(x_i)} \quad (4)$$

Where X<sub>i</sub> is each indicator's normalized value, x<sub>i</sub> is each indicator's actual value, Max (x<sub>i</sub>) is the indicator's maximum value and Min (x<sub>i</sub>) is the indicator's minimum value.

For the normalization of the indicators that contribute negatively we apply this formula:

$$X_i = \frac{Max(x_i) - x_i}{Max(x_i) - Min(x_i)} \quad (5)$$

Where  $X_i$  is each indicator's normalized value,  $x_i$  is each indicator's actual value,  $Max(x_i)$  is the indicator's maximum value and  $Min(x_i)$  is the indicator's minimum value.

Since we have data for only one farm with single values for the footprints, we opted to use  $Min(x_i)$  as the lowest acceptable or ideal value (representing best performance) and  $Max(x_i)$  as the highest acceptable or worst-case performance range, based on values reported in the published literature.

While we acknowledge that relying on one farm limits the generalizability of findings, the objective here is not to provide statistically representative outcomes but to serve as a methodological demonstration of how footprint metrics and the WEFENI can be calculated and interpreted at the farm level. This approach allows for testing the framework's practicality, identifying trade-offs, and assessing synergies in a real-world agroecological setting. Future studies can build upon this framework by expanding to multi-farm or regional analyses to validate and scale up the results.

The calculation of the WEFENI was calculated according to following formula (Karamian et al. 2021)

$$WEFENI = \frac{\sum_{i=1}^n w_i X_i}{\sum_{i=1}^n w_i} \quad (6)$$

The weights have been assigned equally to each component of the WEFENI.

The WEFENI is a composite indicator designed to evaluate systemic performance across the four nexus dimensions: water, energy, food, and ecosystems. It integrates normalized values of the selected indicators (water footprint, energy footprint, carbon footprint, and productivity) into a single metric that captures trade-offs and synergies among these components. The index serves as an operational tool to translate sectoral footprints into a holistic nexus performance indicator, enabling comparison between management scenarios.

The WEFENI is a composite indicator that evaluates systemic performance across the four Nexus dimensions: water, energy, food, and ecosystems. In this study, the food component of the WEFENI is represented by vineyard productivity, expressed as tons of grapes per hectare. Productivity is used as a proxy for food output because it reflects the system's capacity to generate agricultural yield while interacting with water, energy, and ecosystem conditions. Using productivity as the food indicator allows explicit analysis of trade-offs between

environmental performance and agricultural output within the Nexus framework. It uses normalized values of key indicators (e.g., water and energy footprints, carbon emissions, productivity) to allow integration across different units. The index is designed to highlight trade-offs and synergies and can serve as a comparative tool for assessing sustainability performance under different management scenarios. To address these gaps.

## 2.2.5 Quantitative assessment of resources

The Integrated Water-Energy-Food-Ecosystems (WEFE) nexus has been explored through various analytical methodologies, including input-output models, system dynamics, and multilevel frameworks. While these approaches provide comprehensive insights into resource interdependencies, their complexity and extensive data requirements often limit their practicality for localized applications (Kaddoura and El Khatib 2017). To address these challenges, this study adopts a simplified intensity-based framework that builds on the concept of resource intensities, which has been effectively utilized in WEFE nexus modelling by Karnib and Alameh (2020) and Karnib et al. (2024). These studies demonstrated how intensity coefficients could be leveraged to quantify intersectoral linkages and assess resource use across the WEFE nexus in a more practical and streamlined manner.

The proposed intensity-based approach is expressed as:

$$X = A \cdot Y \quad (7)$$

where  $X$  represents the impact vector, which includes the total inputs required to meet the final demand for agricultural production.  $Y$  denotes the target outputs, such as the amount of grapes required for market, processing, or export.  $A$  captures the amount of input required per unit of output, where each intensity coefficient ( $a_i$ ) quantifies the specific input or resource dependency for producing one ton of agricultural output. The intensity coefficients are the footprints that have been calculated in Sect. 2.2.3. These coefficients are essential for understanding the efficiency of resource use and interdependencies across sectors. By translating resource flows into quantifiable metrics, they enable an integrated assessment of economic, environmental, and intersectoral dynamics within the WEFE nexus.

The intensity-based framework is applied to evaluate resource use and environmental impacts in vineyard farming, focusing on two scenarios: (i) a baseline scenario representing conventional farming practices and (ii) an agroecological scenario emphasizing sustainable methods. The baseline scenario is characterized by heavy reliance on irrigation (blue water), synthetic fertilizers, and mechanization,

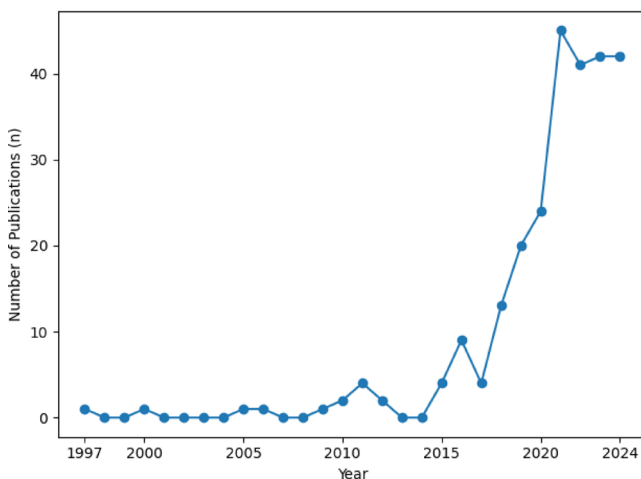
while the agroecological scenario prioritizes rainwater use (green water), organic fertilizers, reduced mechanization, and biodiversity-enhancing practices.

Data for this analysis were collected from a combination of on-site evaluations and farmer interviews. These inputs were integrated into the intensity-based framework to quantify resource use and environmental footprints for each scenario. The model allows for a systematic comparison of the two scenarios mentioned above, emphasizing the trade-offs and synergies inherent in transitioning to agroecological practices.

Within this framework, trade-offs are revealed through changes in the intensity coefficients (A). Each coefficient represents the amount of water, energy, or emissions required to produce one ton of grapes. When productivity (Y) decreases, these coefficients increase, indicating higher resource intensity per unit of output. Conversely, when irrigation is removed, the water coefficient decreases, which subsequently reduces the energy coefficient associated with pumping. This demonstrates how modifications in one sector propagate to others through the intensity matrix. Therefore, Eq. (7) is not only used for scaling resource use but also for identifying how changes in farming practices create trade-offs and synergies across water, energy, food, and ecosystem components.

### 3 Results

The literature review revealed that research on NbS within the WEFE nexus has rapidly expanded, but remains fragmented. Most studies emphasize ecosystem restoration, water regulation, or urban green infrastructure without quantitatively linking these actions to energy use, food



**Fig. 2** Temporal evolution of scientific publications linking Nature-Based Solutions and the WEFE Nexus from 1997 to 2024 based on Web of Science and Scopus databases

production, and farm-level decision making. In addition, many WEFE nexus studies rely on complex system models that are difficult to apply at local scales. These limitations indicate the need for simplified, operational tools capable of translating NbS principles into measurable nexus performance indicators. This study responds to this need by applying a practical intensity-based framework and a WEFE Nexus Index using farm data.

### 3.1 Results of literature review

#### 3.1.1 Publication trends on Nature-Based Solutions within the WEFE Nexus framework

The analysis of the publication trends related to Nature-Based Solutions (NbS) and their integration within the Water-Energy-Food-Ecosystems (WEFE) Nexus reveals a marked evolution in scholarly attention over the past two decades (Fig. 2). Between 1997 and 2015, the number of articles remained relatively low, with minimal annual fluctuations, suggesting limited recognition of this interdisciplinary topic during this period. This can be attributed to the predominance of sector-specific studies and the absence of frameworks that explicitly addressed the synergies and trade-offs among water, energy, food, and ecosystems.

A turning point is observed around 2016, with a gradual increase in publications, likely driven by global efforts to promote sustainable development, such as the adoption of the Paris Agreement and the Sustainable Development Goals (SDGs). This period marks the emergence of NbS as a transformative concept capable of addressing interconnected resource management challenges. The increasing attention aligns with broader adoption of integrative approaches like the WEFE Nexus, highlighting the growing academic and policy relevance of these frameworks.

The most notable growth occurred post-2019, with the number of publications exponentially increasing through 2022. This post-2019 surge aligns with a broader academic trend toward integrative and systems-based approaches, as confirmed by recent bibliometric analyses (Rhouma et al. 2024; Zhang et al. 2022). For instance, Zhang et al. (2022) conducted a comprehensive bibliometric review of WEFE Nexus literature and identified a sharp increase in interdisciplinary studies after 2020, particularly linking sustainability, climate adaptation, and policy instruments. The EU Green Deal, along with international initiatives promoting NbS, likely contributed to this acceleration. The peak in 2022 underscores the culmination of interdisciplinary research efforts and policy-driven studies emphasizing NbS as a pivotal tool for addressing nexus-related challenges.

Interestingly, a slight decline in publications is observed in 2023 and 2024, which may indicate a shift from theoretical



planning. The blue cluster, centred on “water,” underscores the critical role of NbS in water management. Keywords like “water supply,” “water conservation,” and “water quality” point to the importance of NbS in addressing water-related challenges, such as scarcity, pollution, and flooding. This cluster reflects the growing recognition of NbS as a sustainable approach to improving water security in a changing climate. Another prominent area is the red cluster, which focuses on the integration of NbS within food and energy systems. Keywords such as “agriculture,” “energy,” and “food security” highlight research on NbS solutions for improving resource efficiency, enhancing food production, and supporting energy transitions. This cluster aligns with the broader Water-Energy-Food-Ecosystems (WEFE) Nexus framework, which seeks to address the interdependencies between these critical sectors.

The yellow cluster reflects the ecological dimensions of NbS, with keywords such as “biodiversity,” “resilience,” and “ecosystem services.” These terms emphasize the role of NbS in conserving biodiversity, enhancing ecosystem health, and increasing societal resilience to climate change impacts. This cluster underscores NbS’s potential to deliver co-benefits across ecological, social, and economic dimensions.

In addition to these core themes, emerging keywords such as “governance,” “policy,” and “decision making” point to the increasing attention being paid to institutional and policy frameworks for scaling NbS implementation.

Keywords like “optimization” and “model” reflect the adoption of innovative tools and methodologies to evaluate the effectiveness and scalability of NbS interventions.

This keyword analysis highlights the multidimensional and interconnected nature of NbS research. The strong linkages between sustainability, water, energy, food security, and ecosystem services underscore the integrative potential of NbS to address global challenges. However, the increasing prominence of governance and policy-related keywords signals the need for more research on the enabling conditions required to scale NbS effectively. This analysis demonstrates the critical role of NbS in advancing sustainability and resilience across diverse systems and sectors.

### 3.1.3 Case studies of integration of Nature Based Solution in the WEFE Nexus

The case studies reported in Table 2 highlight the transformative potential of Nature-Based Solutions (NbS) in addressing interconnected challenges within the WEFE Nexus. Across diverse geographic and socio-ecological contexts, NbS have demonstrated their ability to improve water quality and availability, enhance agricultural productivity, conserve biodiversity, and promote energy efficiency. For instance, wetland restoration in Greece and mangrove reforestation in Vietnam have not only improved water regulation and ecosystem health but also bolstered food security and climate resilience. Similarly, urban green

**Table 2** Examples of Nature Based Solutions and their link to the WEFE Nexus

Case Study Location	NbS Implemented	Link to WEFE Nexus	References
Nima River sub-basin, Colombia	Forest landscape restoration (afforestation and reforestation)	Increased water retention (+2.9%) (Water); improved water quality (−4.7% nitrogen pollution) (Ecosystem); and slight trade-offs in food provisioning (−0.8%).	Restrepo et al. (2024)
Koiliaris River Basin, Greece	Terraces, riparian forest, and agroecological practices	Terraces reduced sediment loads by 95%, riparian forests by 93%, and combined NbS by 97% (Water); agroecological practices enhanced soil health, biomass production, and nutrient sequestration (Food & Ecosystem).	Maragkaki et al. (2024)
Foglia River Basin, Marche Region, Italy	Agro-environmental actions including wooded buffer strips and contour ploughing	Improved water regulation and supply (Water); significant erosion protection (Ecosystems); enhanced nitrogen adsorption and reduction of soil loss by 61% (Food & Ecosystems).	Morri and Santolini (2022)
Koiliaris River Basin, Crete, Greece	Riparian forest restoration	Enhanced runoff retention (+15%) (Water); improved carbon sequestration (+149%) (Ecosystems); and increased habitat quality (+372%) (Ecosystems).	Masiero et al. (2024)
Bayawan City, Philippines	Constructed wetlands for wastewater treatment	Improved water quality and reduced nutrient loads (Water); ecosystem service provisioning (Ecosystems); irrigation support for farming projects (Food); mitigation of untreated sewage impacts (Energy).	Agaton and Guila (2024)
Besòs River Area, Barcelona, Spain	Constructed wetlands and riverside park	Improved water quality and biodiversity (Water & Ecosystems); supported streamflow augmentation and recreational spaces (Water & Social Liveability); potential synergies with water reuse technologies (Energy).	Ramirez-Agudelo et al. (2021)
Lebanon	Strategic modeling for local Mediterranean food basket under compound shocks	Water stress and food security trade-offs managed through integrated planning across land, water, and food systems	Daher et al. (2022)
Morocco	Nexus-based modeling of phosphorus fertilizer supply chain	Optimization of water, energy, and food inputs in industrial fertilizer production and distribution	Lee et al. (2023)

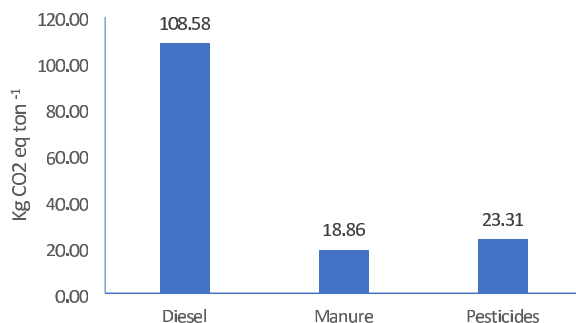
infrastructure projects, such as green roofs in Barcelona and sponge city initiatives in Shanghai, exemplify how NbS can mitigate urban flooding, enhance energy efficiency, and support sustainable development. These examples underscore the integrative nature of NbS, providing co-benefits across multiple Nexus components while being tailored to specific regional challenges. The evidence calls for stronger governance frameworks and cross-sectoral collaboration to scale and institutionalize NbS as pivotal tools for achieving sustainability and resilience.

Recent case studies have further expanded the application of NbS and WEF Nexus approaches to more complex contexts. For example, Daher et al. (2022) analyzed how Lebanon can manage food security under resource constraints through Nexus-aware food system modelling. Lee et al. (2023) examined the phosphorus fertilizer industry in Morocco, highlighting how NbS and supply-chain planning can mitigate water and energy burdens in food production. These cases extend the relevance of NbS from natural systems to national policy and industrial processes.

### 3.2 Sectoral footprint results for the vineyard case study

#### 3.2.1 Water footprint

The crop water use (CWU) of vineyards in Sant Pere de Ribes, reported as 571.2 mm, aligns well with the global patterns of water consumption for grape production under rainfed conditions (Mialyk et al. 2024). According to (Mialyk et al. 2024), CWU estimates for grapes vary based on climatic and soil conditions, with rainfed vineyards demonstrating efficiency due to their reliance solely on precipitation (green water) rather than irrigation (blue water). The reported CWU of 571.2 mm for Sant Pere de Ribes is consistent with the rainfed averages cited in the study, where CWU for grapes ranges broadly depending on environmental variables, but often falls below the global mean for irrigated vineyards.



**Fig. 4** Contribution of different vineyard inputs (fuel, fertilizers, pesticides, electricity) to the total carbon footprint per ton of grapes

The green water footprint of vineyards in Sant Pere de Ribes, estimated at 611 m<sup>3</sup>/ton, highlights the effective use of rainwater in grape production under agroecological practices. This value reflects rainwater absorbed by the soil and used by the vines through evapotranspiration, excluding irrigation and runoff. Such an efficient water footprint is achieved through agroecological methods, which include organic soil amendments, biodiversity promotion, and the reduction of chemical inputs. These practices not only optimize the retention and utilization of natural precipitation but also minimize the environmental impact by avoiding irrigation (blue water) and limiting pollution (grey water footprint).

When benchmarked globally, this value represents a sustainable and efficient use of water resources for grape production. Conventional grape farming systems often have higher water footprints, ranging from 700 to 900 m<sup>3</sup>/ton, as they rely on irrigation, leading to increased blue water use (Mialyk et al. 2024). Tomaz et al. (2025) found that, in certain Mediterranean regions of Portugal, the total water footprint ranged from 491 to 773 m<sup>3</sup> per ton, aligning with the values observed for Sant Pere de Ribes. Rhouma et al. (2025) reported a water footprint of 618 m<sup>3</sup>/ton for vineyards in Spain, which is very close to the value obtained in this study (611 m<sup>3</sup>/ton). In addition, the case study site of Raimat Farm is located in Lleida, Spain, approximately 150 km from Sant Pere de Ribes, indicating comparable Mediterranean climatic conditions and supporting the consistency of the results.

#### 3.2.2 Carbon footprint

The carbon footprint for grapes produced in the vineyard at Sant Pere de Ribes, employing agroecological practices, is reported to be 150.7 kg CO<sub>2</sub> equivalent per ton of grapes (Fig. 4). This value reflects the emissions associated with various farm activities, including cultivation, fertilizer application, and other agricultural inputs. Agroecological practices aim to reduce environmental impact by integrating biodiversity, minimizing chemical inputs, and improving soil health through techniques like composting and cover cropping (Nicholls and Altieri 2018). Compared to irrigated viticulture, which can have carbon footprints ranging from 280 to 850 kg CO<sub>2</sub> eq/ton (Litskas et al. 2017), depending on the intensity of chemical use and irrigation, the footprint at Sant Pere de Ribes represents a significant reduction, aligning with sustainability goals (IPCC 2019).

In the context of benchmarking, the carbon footprint of agroecological vineyards often falls within a lower range due to reduced reliance on synthetic fertilizers and pesticides, which are major contributors to greenhouse gas emissions in conventional systems. In Lleida, located at 150 km

from Sant Pere de Ribes, Rhouma et al. (2025) reported a carbon footprint ranging between 169.74 and 214 kg CO<sub>2</sub>e per ton. However, it is substantially lower than carbon footprint values reported for many conventional grape production systems, which typically range between 300 and 360 kg CO<sub>2</sub> eq/ton depending on climatic conditions and management practices (Hefler and Kissinger 2023).

The lower carbon footprint at Sant Pere de Ribes can be attributed to specific agroecological interventions, such as reduced tillage, the use of organic fertilizers like compost, and the promotion of natural pest control through biodiversity. Additionally, practices such as efficient water use, achieved through rain-fed systems or precise irrigation, contribute to minimizing emissions from energy use (Montanaro et al. 2017). Benchmarking against other agroecological vineyards in Europe, particularly in Mediterranean climates, indicates that the vineyard's performance aligns with best practices, though there may still be room for improvement by integrating renewable energy sources for machinery or further optimizing irrigation efficiency.

In summary, the carbon footprint of 150.7 kg CO<sub>2</sub> eq/ton for the Sant Pere de Ribes vineyard demonstrates the environmental benefits of agroecological viticulture. It not only outperforms conventional systems in terms of emissions but also aligns closely with the benchmarks of sustainable grape production in comparable agroecological settings. This performance underscores the potential of agroecological practices to significantly contribute to climate change mitigation while maintaining productive and resilient vineyard systems.

### 3.2.3 Energy footprint

The energy footprint of 0.71 MJ/kg for grapes produced in the vineyard at Sant Pere de Ribes, employing agroecological practices, is notably low compared to benchmarks for vineyards operating under other systems. This value reflects the energy efficiency of agroecological practices, which minimize the use of synthetic inputs, optimize irrigation, and rely on techniques such as composting and biodiversity integration. In comparison, conventional vineyards typically exhibit energy footprints ranging from 1.5 to 3.5 MJ/kg, depending on the intensity of mechanization, irrigation practices, and use of synthetic fertilizers and pesticides (Rugani et al. 2013). The significant reduction in energy consumption in the Sant Pere de Ribes vineyard highlights the potential of agroecology to promote resource efficiency and sustainability.

When benchmarked against organic vineyards, which generally report energy footprints between 0.8 and 1.2 MJ/kg, the energy use at Sant Pere de Ribes remains at the lower end of the spectrum (Rhouma et al. 2025). This performance

**Table 3** Resource footprints for nexus analysis

Sector	Baseline (Conventional)	Agroecological practices
Blue water footprint (m <sup>3</sup> /ton)	700	0
Green Water footprint (m <sup>3</sup> /ton)	800	611
Energy footprint (MJ/ton)	2500	710
Carbon footprint (kg/ton)	350	150.7
Productivity (Tons/Ha)	7	4

**Table 4** Total estimated resource use (blue water, energy, and CO<sub>2</sub> emissions) for 100 tons of grape production, based on intensity values in Table 3

Sector	Baseline (Conventional)	Agroecological practices
Blue water (m <sup>3</sup> )	70,000	0
Green water footprint	80,000	61,100
Energy (MJ)	250,000	71,000
Carbon emissions (kg)	35,000	15,070
Productivity (Tons/hectare)	700	400

can be attributed to agroecological practices that emphasize resource cycling, reduced machinery reliance, and natural pest control methods, which further reduce energy demands. For instance, studies in Mediterranean organic vineyards report average energy footprints of 1.0 MJ/kg, influenced by additional field operations like weeding and pest management, which are minimized in agroecological systems (Montanaro et al. 2017). The 0.71 MJ/kg footprint demonstrates the effectiveness of agroecology in achieving high energy efficiency while maintaining productivity, underscoring its role as a sustainable alternative to conventional and organic viticulture practices.

**3.2.3.1 Quantitative assessment of scenarios** Key data on resource use and productivity were collected to evaluate the resource efficiency and environmental impacts of conventional and agroecological vineyard systems in Sant Pere de Ribes. The analysis focuses on critical inputs such as blue water, energy, and CO<sub>2</sub> emissions. The resource intensities, or footprints, for these inputs under both scenarios are summarized in Table 3.

To meet a total production target of 100 tons of grapes, the required blue water, energy, and resulting CO<sub>2</sub> emissions were calculated using the intensity-based Eq. (7).

While Table 3 provides the resource intensity per ton of grape production, Table 4 presents the extrapolated total resource use for a standardized production goal of 100 tons. This scaling exercise allows for a clearer comparison of the cumulative environmental impacts of conventional and agroecological practices. Although the values in Table 4 are derived by multiplying those in Table 3, this transformation

offers practical insight into real-world implications, especially for planning or policy applications. Presenting both tables enables readers to interpret both per-unit efficiencies and absolute system-wide impacts. The calculated total resource use for each scenario is presented in Table 4.

### 3.3 Nexus trade-offs and synergies between WEF E components

While Tables 3 and 4 present sectoral resource footprints, the intensity-based framework allows the analysis of interdependencies across the Water–Energy–Food–Ecosystems components rather than treating them as independent indicators.

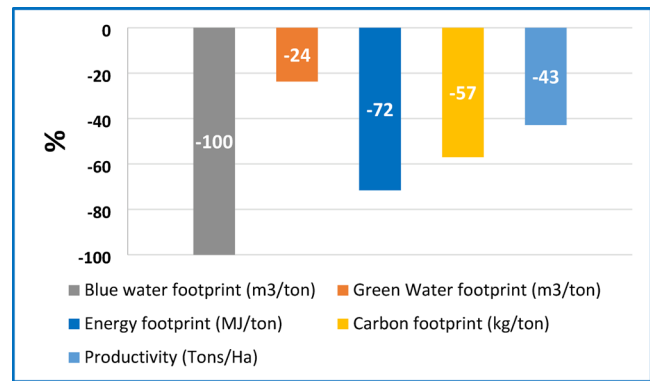
The agroecological scenario reveals several important nexus interactions. The complete elimination of blue water use removes the need for irrigation pumping. This directly explains the 72% reduction in energy consumption observed in Table 3, demonstrating a strong water–energy linkage. The reduced energy demand subsequently contributes to the 57% decrease in carbon emissions, establishing a clear water–energy–carbon chain of effects within the system.

At the same time, the lower productivity of the agroecological system (4 t/ha compared to 7 t/ha) increases the resource intensity per ton of grapes. This illustrates an inherent food–water and food–energy trade-off: while total resource use declines, the reduced yield increases the per-unit footprint, highlighting the balance between environmental efficiency and production output.

In addition, agroecological practices such as increased soil organic matter, biodiversity enhancement, and the absence of chemical inputs improve soil structure and rainwater infiltration. This enhances green water retention and explains the improved water-use efficiency. This demonstrates how ecosystem improvements directly influence water performance and agricultural output, linking the ecosystem component to both water and food dimensions.

These interactions confirm that the improvements observed in the agroecological scenario are not isolated sectoral gains but interconnected nexus effects captured through the intensity-based framework.

The environmental benefits of the agroecological scenario are further illustrated in Fig. 5, which shows the percentage changes in key outputs relative to the baseline scenario. The transition to agroecological farming resulted in a complete elimination of blue water use, a 72% reduction in energy consumption, and a 57% decrease in CO<sub>2</sub> emissions. These findings emphasize the capacity of agroecological practices to reduce dependency on irrigation and fossil fuels while mitigating greenhouse gas emissions. Such improvements highlight the potential of agroecological farming to enhance



**Fig. 5** Percentage change in resource use and emissions between conventional and agroecological vineyard scenarios, illustrating WEF E Nexus trade-offs

sustainability through resource efficiency and minimized environmental impacts.

### 3.4 Integrated WEF E Nexus Index results

Following the identification of nexus trade-offs and synergies, the integrated WEF E Nexus Index was calculated to aggregate these interactions into a single systemic performance indicator. The WEF E Nexus Index calculated is 0.61 for the vineyard studied which reflects a moderate-to-good performance in integrating water, energy, food, and ecosystem sustainability. This value indicates that the vineyard effectively balances resource use and environmental impact, particularly given its reliance on agroecological methods that emphasize biodiversity, reduced chemical inputs, and natural water availability. The absence of irrigation likely contributes positively to the water efficiency component, as rain-fed systems generally have lower water footprints compared to irrigated ones, especially in Mediterranean climates.

When benchmarked, vineyards employing conventional practices often achieve WEF E Index values in the range of 0.4 to 0.6, reflecting inefficiencies due to high water and energy inputs and greater carbon emissions. In contrast, organic or agroecological vineyards typically score higher, between 0.6 and 0.8, owing to their emphasis on sustainable practices, reduced reliance on synthetic inputs, and improved ecosystem services (Rugani et al. 2013). In this study, the agroecological vineyard scenario achieved WEF E Index values above 0.65, which aligns with sustainability benchmarks observed in Mediterranean viticulture systems (Rhouma et al. 2025).

## 4 Discussion

This study sheds light on the critical role of Nature-Based Solutions (NbS) in addressing the multifaceted challenges of the Water-Energy-Food-Ecosystems (WEFE) Nexus. The review of theoretical concepts and empirical studies emphasizes that NbS offer integrated approaches that enhance resource efficiency, support ecosystem services, and foster resilience. The findings demonstrate that agroecological NbS such as those applied in the vineyard case deliver measurable co-benefits across WEFE Nexus dimensions, including significant reductions in water, energy, and carbon footprints. For instance, constructed wetlands improve water quality while contributing to carbon sequestration and habitat restoration (IUCN 2020).

The integration of NbS in WEFE planning frameworks facilitates trade-off mitigation and enhances cross-sectoral synergies, as shown in the vineyard case through the elimination of blue water use and reduced emissions. However, standardized methodologies for such quantitative integration are still lacking. NbS enable synergies between components; for example, agroecological practices simultaneously enhance soil fertility, reduce water consumption, and lower carbon emissions. However, the review also reveals a lack of standardized frameworks for quantifying these contributions, which hampers the ability to systematically compare and scale NbS applications (Lupp et al. 2021). The need for quantitative assessment frameworks that capture the interconnected benefits and trade-offs of NbS across the WEFE Nexus remains a pressing research and policy priority.

Recent research has increasingly highlighted the role of Nature-Based Solutions (NbS) in operationalizing the WEFE Nexus framework. For instance, Maragkaki et al. (2024) demonstrated how NbS can optimize interactions within the WEF nexus at the basin scale through hydrological and ecosystem-based modelling approaches. Similarly, Vanino et al. (2024) emphasized the strategic importance of NbS for enhancing resilience, improving water distribution, and supporting sustainable agrifood systems across Mediterranean contexts, integrating participatory governance and policy dialogue within the Nexus framework. Together, these studies underscore the growing strategic importance of Nature-Based Solutions (NbS) and the WEFE Nexus in shaping sustainable development pathways. They also reflect the progressive maturation of the field, which is increasingly moving beyond conceptual and theoretical debates toward implementation-oriented research, impact evaluation, and governance-focused approaches.

The WEFE Nexus Index value of 0.61, calculated for the rainfed vineyard in Northern Spain, demonstrates a balance between resource efficiency and environmental performance. This score reflects the vineyard's reliance on

sustainable practices, such as biodiversity enhancement, reduced chemical input use, and efficient water management. Compared to conventional vineyards, which often score lower (typically ranging from 0.4 to 0.6 due to higher resource footprints), the agroecological approach illustrates its capacity to improve sustainability outcomes (Rugani et al. 2013). While this value aligns with benchmarks for similar systems in Mediterranean climates, it also indicates opportunities for improvement, particularly in energy use and productivity optimization.

The vineyard case exemplifies common trade-offs in sustainable agriculture: a reduction in productivity (4 tons/ha vs. 7 in conventional systems) but substantial gains in water, energy, and emission efficiency. Similar tensions are documented in other Nexus studies. Daher et al. (2022) showed that in Lebanon, food self-sufficiency requires trade-offs with limited water and land resources. Lee et al. (2023) analyzed Morocco's phosphorus industry, demonstrating that aligning food production with energy and water constraints requires systemic coordination across sectors. These examples reinforce the need for tools like the WEFE Nexus Index to capture such interactions and guide decision-making.

### 4.1 Cost-benefit implications for farm-level decision making

The observed trade-off between reduced productivity and improved environmental performance raises an important practical question for farmers and policymakers: whether the reduction in yield is economically compensated by lower input costs.

Conventional vineyards incur significant operational costs related to irrigation pumping, fuel consumption for mechanized operations, and the purchase of synthetic fertilizers and pesticides. In contrast, the agroecological system eliminates irrigation entirely and substantially reduces fuel use and chemical inputs. These reductions translate into lower recurring expenditures and reduced dependency on external inputs, which are particularly costly in Mediterranean regions facing increasing water scarcity and rising energy prices.

Although a full economic assessment was beyond the scope of this study, the results suggest that agroecological systems may achieve a form of economic resilience by lowering production costs while maintaining acceptable productivity levels. This highlights that the WEFE nexus assessment is not only an environmental evaluation but also a decision-support perspective, where reduced resource dependency can partially or fully offset lower yields.

This perspective enhances the practical relevance of the WEFE Nexus framework by linking environmental trade-offs with farm-level economic considerations.

## 4.2 Environmental performance and resource efficiency

The analysis highlights the substantial improvements in environmental performance and resource efficiency achieved through agroecological farming practices compared to conventional methods. The agroecological scenario demonstrated a complete elimination of blue water use, emphasizing the effectiveness of rainfed systems in reducing dependency on irrigation. This transition aligns with sustainable water management practices, ensuring efficient utilization of natural precipitation while alleviating stress on water resources. Additionally, the 72% reduction in energy consumption reflects the decreased reliance on mechanization and fossil fuel use, showcasing the potential for energy efficiency in agroecological systems.

The 57% decrease in CO<sub>2</sub> emissions further underscores the environmental benefits, as lower energy demands and the use of organic fertilizers minimize greenhouse gas emissions. These findings reinforce the role of agroecological farming in achieving resource-efficient and environmentally sustainable agricultural production, providing a viable pathway to meet climate and resource conservation goals.

The carbon footprint of 150.7 kg CO<sub>2</sub> eq/ton observed in the vineyard highlights the effectiveness of agroecological practices in reducing greenhouse gas emissions. This value is significantly lower than those reported for conventional systems, which often exceed 300 kg CO<sub>2</sub> eq/ton due to reliance on synthetic fertilizers, pesticides, and irrigation infrastructure ((Hefler and Kissinger 2023). Practices such as composting, cover cropping, and natural pest control reduce emissions by avoiding energy-intensive synthetic inputs and enhancing soil carbon sequestration (Nicholls and Altieri 2018). Benchmarked against organic systems, which typically report carbon footprints between 120 and 180 kg CO<sub>2</sub> eq/ton, the vineyard performs competitively, reaffirming the sustainability benefits of agroecology (Ghiglieno et al. 2023).

Similarly, the vineyard's energy footprint of 0.71 MJ/kg positions it among the most energy-efficient systems, with organic and agroecological systems typically ranging from 0.8 to 1.2 MJ/kg and conventional systems often exceeding 1.5 MJ/kg (Montanaro et al. 2017). This low footprint is attributed to minimal reliance on mechanization and fossil fuel inputs, as well as the absence of irrigation. The energy efficiency underscores the advantages of rainfed systems and locally adapted agroecological techniques.

The water footprint of 611 m<sup>3</sup>/ton, derived from CROPWAT modeling, emphasizes the vineyard's reliance on green water resources, further enhancing its sustainability credentials. This value aligns with benchmarks for rainfed vineyards, which generally range between 500 and 700 m<sup>3</sup>/

ton, and is significantly lower than that of irrigated systems, which can exceed 900 m<sup>3</sup>/ton (Tomaz et al. 2025, p. 4). Effective water management is particularly critical in Mediterranean regions, where water scarcity poses significant challenges. By avoiding irrigation and utilizing rainfall efficiently, the vineyard exemplifies the potential of NbS to address water-related constraints in viticulture.

## 4.3 Integration of NbS in the WEFE Nexus

Agroecological farming inherently incorporates Nature-based Solutions (NbS) into the WEFE Nexus by integrating ecological processes into agricultural systems. Practices such as rainfed farming, the use of organic fertilizers, and biodiversity enhancement exemplify NbS that align with water, energy, food, and ecosystem sustainability. By replacing synthetic inputs with natural alternatives and leveraging green water resources, agroecological systems optimize resource use while maintaining ecosystem health. These approaches also contribute to building climate resilience by improving soil quality, enhancing carbon sequestration, and reducing the vulnerability of agricultural systems to climatic extremes. The integration of NbS into the WEFE Nexus not only supports resource sustainability but also promotes synergies across sectors, reducing trade-offs and fostering holistic solutions. This study highlights the potential of agroecological farming as a model for NbS-driven resource management, offering actionable insights for scaling such practices in regions facing water scarcity and environmental challenges.

NbS provide critical co-benefits that extend beyond resource efficiency. In the vineyard's case, biodiversity enhancement through agroecological practices contributes to ecosystem health, carbon sequestration, and pest control, demonstrating the synergies inherent in NbS (IUCN 2020). However, the lack of standardized frameworks for quantifying these co-benefits within the WEFE Nexus limits the scalability of such solutions. Current assessments often focus on isolated components (e.g., water or carbon footprints) and fail to capture the complex trade-offs and synergies across the Nexus (Juwana et al. 2012).

## 4.4 Governance and policy barriers

The scalability and institutionalization of NbS are further constrained by governance and policy barriers. Fragmented institutional frameworks and a lack of cross-sectoral coordination impede the implementation of integrated solutions like NbS. For instance, funding mechanisms for NbS are often siloed within specific sectors (e.g., agriculture, water management) rather than addressing the holistic needs of the WEFE Nexus ((Wickenberg et al. 2021). Strengthening

participatory governance, aligning NbS with regional development priorities, and integrating them into existing policy frameworks are critical steps toward overcoming these challenges (Zingraff-Hamed et al. 2021).

#### 4.5 Governance and policy implications for scaling NbS within the WEF Nexus

Beyond the quantitative assessment, the findings of this study have important governance and policy implications. The ability to quantify NbS performance within the WEF Nexus provides a practical foundation for integrating agroecological practices into cross-sectoral planning and policy frameworks. An innovative pathway to mainstream NbS in cross-sectoral policies involves the development of a WEF-NbS Policy Integration Framework. This framework should prioritize the following key actions:

- **Cross-Sectoral Policy Alignment:** Harmonize policies across water, energy, agriculture, and ecosystems sectors by embedding NbS objectives into regional and national development plans. This requires establishing cross-sectoral coordination bodies to ensure policy coherence and shared objectives.
- **Participatory Governance:** Enhance stakeholder engagement by including farmers, community groups, policy-makers, and scientists in the decision-making process. Participatory governance ensures that NbS are tailored to local needs, promoting ownership and long-term sustainability.
- **Incentive Mechanisms:** Introduce financial incentives, such as subsidies, grants, or tax benefits, to encourage the adoption of NbS. Payment for ecosystem services (PES) schemes can also provide direct financial rewards for practices that enhance ecosystem health and resource efficiency.
- **Monitoring and Assessment Tools:** Develop integrated tools to quantify the synergies and trade-offs across the WEF Nexus. These tools should evaluate NbS impacts using metrics such as resource footprints, productivity, and ecosystem service enhancements, enabling evidence-based decision-making.
- **Capacity Building and Knowledge Sharing:** Invest in training programs and knowledge-sharing platforms to disseminate best practices and innovative NbS approaches. This will empower stakeholders to implement and scale NbS effectively.
- **Pilot Programs and Scaling Strategies:** Initiate pilot projects to demonstrate the effectiveness of NbS in various contexts. Successful pilots can serve as models for scaling up, attracting investment, and informing policy development.

By implementing this framework, NbS can be mainstreamed into cross-sectoral policies, reducing trade-offs and maximizing synergies within the WEF Nexus. This pathway not only promotes sustainable resource management but also aligns with global sustainability goals, contributing to climate change mitigation, food security, and ecosystem resilience. Future efforts should focus on fostering interdisciplinary collaboration and leveraging technological innovations to further advance the integration of NbS into policy and practice.

#### 4.6 Implications and future directions

The findings of this study have significant implications for the adoption and integration of NbS within the WEF Nexus. The agroecological vineyard in Northern Spain serves as a model for sustainable viticulture, demonstrating how NbS can enhance resource efficiency, support ecosystem services, and mitigate environmental impacts. However, advancing the adoption of NbS requires addressing critical gaps in quantitative methodologies, governance, and stakeholder engagement. Future research should prioritize the development of integrated assessment tools capable of capturing the full spectrum of NbS benefits and trade-offs across the WEF Nexus.

This study demonstrates that agroecological Nature-Based Solutions, when assessed within a WEF Nexus framework, offer measurable resource efficiencies and environmental benefits. The vineyard case in Northern Spain illustrates how rainfed systems can eliminate blue water dependency, cut emissions, and minimize energy inputs without compromising core production goals. More importantly, it validates the use of a practical, intensity-based Nexus Index as a decision-support tool for farm-level sustainability. To advance the mainstreaming of NbS, future efforts must focus on expanding this framework across multiple farms and regions, integrating socio-economic and governance indicators, and embedding such tools into regional and sectoral policy planning.

##### Limitations of the study

This study presents a farm-level application of an intensity-based WEF Nexus framework; however, several limitations should be acknowledged. First, the quantitative assessment is based on a single vineyard case study, which limits statistical generalizability. The objective was methodological demonstration rather than regional representativeness.

Second, the Nature-Based Solution analyzed in this study corresponds specifically to agroecological practices implemented within an agricultural production system. Nature-Based Solutions encompass a broader range of interventions, including wetland restoration, urban green infrastructure,

riparian buffers, and watershed-scale ecosystem management. These different NbS categories may generate distinct nexus dynamics, particularly in relation to ecosystem service provisioning, spatial scale, and governance complexity.

Therefore, while the intensity-based WEFE framework is transferable and adaptable to other NbS contexts, the magnitude and direction of trade-offs observed in this study should not be directly generalized without context-specific assessment.

Future research should expand this framework to multiple farms, regions, and NbS typologies to validate and refine the index for broader policy application.

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## Declarations

**Conflict of interest** Prof. Rhouma is a member of the editorial board of this journal. He was not involved in the editorial handling, peer-review process, or decision-making related to this manuscript. The remaining authors declare that they have no competing interests.

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