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Assessing food, water, and energy security in the Atlantic Forest region of Brazil through the nexus approach

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ABSTRACT

Global agricultural production is on a trajectory to double by 2050 due to both increases in the global population and the dietary changes associated with growing incomes. This also means more pressure on water resources, as agriculture accounts for 70 % of global water withdrawal, and for energy production as the whole food supply chain accounts for about 30 % of total global energy consumption. Although there are ongoing discussions related to the sustainability of water, energy and food (WEF) sectors, the integration of all three are still rare and challenging. This paper presents a novel methodology framework based on accessible secondary data to evaluate the impacts of three rural practices - agroforestry, spring protection and pasture rotation - on the WEF nexus in Atlantic Forest, South-east of Brazil. The results of the business as usual scenario indicated concern regarding water security, particularly in relation to sewage treatment and water commitment. A comparable pattern was observed in energy security, where only two indicators exhibited positive performance in the analysis. Conversely, a scenario of reduced vulnerability was observed in food security, as evidenced by the indicators of food production, nutritional value, and annual gross revenue. However, in the scenarios proposed by experts the adoption of the rural practices that were assessed here can lead to consistent improvements in WEF security, evidencing the multifunctional capabilities of agriculture. Hence, the methodological framework presented here demonstrate its potential to be incorporated into decision-making processes to promote the multifunctionality of agriculture and sustainable use of rural areas.

1. Introduction

Humanity is experiencing difficult times due to the far-reaching effects of climate change, the worldwide deterioration of ecosystem functions and services, and rising poverty and inequality rates (Xu et al., 2020). The world's population surpassed 8 billion in November 2022, marking an increase of 1 billion since 2010 (WilmothU et al.,., 2023), which underscored the growing pressure on the planet's systems, particularly in terms of food, water, and energy production.

Between 2010 and 2050, total global food consumption is anticipated to rise by 35 %–56 %. When factoring in climate change, this range shift slightly to between +30 % and +62 %, although the overall statistical difference is minimal (van Dijk et al., 2021). However, the availability of land to produce this additional food would be reduced, owing primarily to deforestation, overgrazing, and poor farming techniques (Hemathilake et al., 2022). Further, climate change effects such as heavy rainfall and prolonged droughts reduce agricultural food production and have an impact on agricultural water management, which includes not only irrigation and drainage, but also other forms of water control aimed at optimizing growing conditions for crops and pasture

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(Hemathilake et al., 2022; FAO, 2011). Additionally, 344 million tons of global unnecessary food waste accounts for the depletion of 4 x 10ˆ18 J of energy and 82 x 10ˆ9 cubic meters of water (Coudard et al., 2021). This situation highlights the sector's necessity to enhance water and energy efficiency, minimise losses, and, crucially, augment agricultural output in relation to utilized water resources (WWAP, 2017).

An emerging strategy for achieving sustainability entails understanding interconnections between water and energy (Bortoleto et al., 2021), particularly in Brazil, where hydropower accounted for nearly 53 % of total energy generation in 2022 (EPE, 2022). However, the planet's changing climate is expected to alter hydrological patterns, river systems, and associated habitats, with the increased likelihood of droughts posing a significant threat to hydropower generation. This presents risks to both hydropower dams and power system operations (Opperman et al., 2022). According to the same authors, by 2050, 61 % of all global hydroelectric dams will be located in basins with a very high or extreme risk of drought, flood, or both.

The water, energy and food (WEF) nexus examine the interrelations among the three resource sectors, including the synergies, conflicts, and trade-offs that emerge from their management, such as water for food or energy food for energy beyond others (Simpson and Jewitt, 2019). The interconnections between WEF are extensive and significant. Managing one of them must not be treated in isolation, but rather as part of an interconnected system (El-Gafy, 2017).

Some authors argue that the nexus WEF is not a novel concept, since some concepts within the nexus philosophy were previously articulated in various debates that emerged in policy agendas during the 1990s (Benson et al., 2015). For example, upon the initial proposal of sustainable development, it was asserted that population growth, food security, energy, the environment, and urban expansion "are interconnected and cannot be addressed in isolation from one another" (WCED (World Commission on Environment and Development), 1987). The increased prominence of this notion since 2010, culminating in the 2024 introduction of the IPBES Nexus evaluation (IPBES, 2024), may be associated with the impacts of climate change on these three sectors. This encompasses increased occurrences of droughts, floods, landslides, and outbreaks of animal and plant pests and illnesses (IPBES, 2024).

The Nexus approach covers a wide array of interests, which Farmandeh & Choobchian (Farmandeh et al., 2024) categorized into seven primary domains: sustainability assessment of systems, integration of planning and decision-making regarding resource consumption, optimization of resource utilization, management of resource consumption systems, formulation of theoretical frameworks for the nexus, evaluation of the impacts of resource consumption, and assessment of related risks. Most of the studies considerate by the same authors (Farmandeh et al., 2024) are concentrate on the sustainability of systems concerning resource consumption, seeking to produce suitable solutions in accordance with resource planning and optimal management (Farmandeh et al., 2024). These multifaceted aspects of the nexus approach suggest that it is rapidly transitioning into an integrative concept and has been incorporating new topics over time (Lazaro et al., 2022). A particular emphasis has been placed on interdisciplinary and inter-sectoral analyses, which has resulted in the development of a variety of methodologies for WEF nexus research (Lazaro et al., 2022).

Nevertheless, the number of resource interactions evaluated in empirical applications is significantly lower than in theoretical studies, and the focus of research is still on physical resource interactions (Li et al., 2025; Niu et al., 2022). Consequently, studies that enhances the practical applications of the nexus approach that can be integrated into decision-making on sustainable land use represents significant progress in connecting theory with practice. Examples encompass spatial and temporal autocorrelation analysis, integrated with entropy weighting and hierarchical analysis weighting, to formulate indicators that precisely reflect real-world conditions (Wang et al., 2023), or a synthesis of primary and secondary data for WEF nexus assessment, executed through a consultative process involving regional teams and stakeholders, to determine the most contextually appropriate options (Fabiani et al., 2020).

Agriculture influences these three vital components of human livelihood that are being discussed here: food, water, and energy. Given that most of the food, water, and energy production transpires in rural settings, these regions encounter the greatest pressures to meet societal expectations (Duarte et al., 2021). The implementation of an ecosystem strategy to tackle agricultural food production can improve crop yield by utilizing ecosystem services that facilitate the decrease of external inputs, such as mineral fertilizers and pesticides (Bommarco et al., 2013). Conservation agriculture (CA) practiced at the farm level is associated with diminished labor demands, decreased energy usage, consistent yields, and enhanced soil quality (Food and Agriculture Organization of the United Nations - FAO, 2011). Conservation agriculture can enhance the utilization of agricultural resources by integrating the management of soil, water, and biodiversity, promoting the agriculture's multifunctionality, while also diminishing reliance on external inputs (Todorova and Parzhanova, 2021). It can create synergies to maximize natural resource efficiency in alignment with societal objectives, boosting the WEF nexus strategy (Mercure et al., 2019).

Given the intricacies involved in an integrated approach like nexus, it is essential to develop an assessment framework that incorporates both natural, socioeconomic and institutional factors. For example, as environmental risks, such as floods and droughts, can both originate from and influence institutional risks, exemplified by consumers' capacity to pay water tariffs, which in turn affects local authorities' ability to sustain operations and maintain critical infrastructure (Kurian, 2017). Alouche (Allouche, 2011) added more layers to this debate and states that while resource scarcity may be associated with malnutrition, hunger, and water insecurity, in most instances, water and food insecurity seldom stem from competition over resources; instead, they are indicative of the politics of allocation and inequality. In this regard, wars and conflicts exacerbate these fears both in the short term and the long term. Consequently, effective management of the WEF nexus interconnections necessitates a thorough comprehension of key stakeholders, incorporating essential information about the WEF nexus and its interrelations, which can be improved through stakeholder identification and participatory methods, such as interviews and workshops. (Daher et al., 2019). This dynamic reveals the synergies and trade-offs among nexus sectors, which can either facilitate or hinder the advancement of an institutional framework (Mathetsa et al., 2023; Balaican et al., 2023).

Considering that the nexus approach advocated for moving away from siloed management approaches that focus on individual components of the WEF nexus, we propose a methodology for evaluating how rural practices can impact the WEF security in the Atlantic Forest of Brazil in an integrated manner. Through this approach, we aim to address the following research question: Is it possible to develop a framework to assess the impact of land use practices in rural areas at the nexus WEF that combines the use of secondary data and participatory methods?

We conducted this research in the Brazilian Atlantic Forest biome because it has the highest population density in the country, supporting 72 % of the population and contributing to 70 % of Brazil's GDP (Fundação SOS Mata Atlântica), which results in a significant demand for water, energy, and food. Additionally, the intensive use of land for agriculture, urbanization, and industrialization has led to high rates of deforestation, causing the loss of many ecological functions, particularly those related to WEF supply (Rezende et al., 2015), which are crucial for ensuring WEF security.

There is evidence that basic tools provide a significant function in identifying nexus "hotspots," an essential element in the preliminary phases of any nexus evaluation or implementation in new or current policy (Dargin et al., 2019). Thus, this study delineates a comprehensive methodology outlining the development phases of the framework designed to evaluate the impact of agricultural practices on the WEF nexus, together with the results achieved and the advantages and

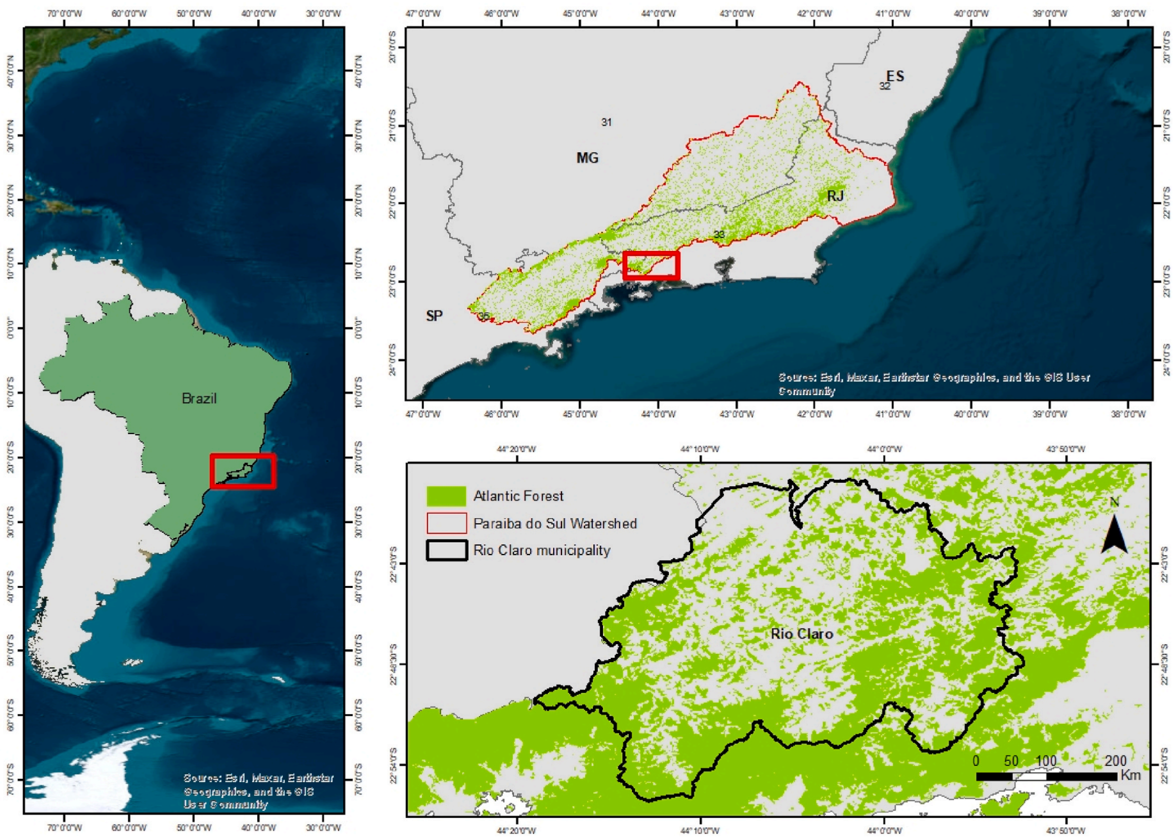

Fig. 1. Study area in Rio Claro municipality – Rio de Janeiro state, Brazil.
Source: The authors.

disadvantages of the used approach.

2. Methodology

2.1. Study site

The study site is the municipality of Rio Claro, located in Rio de Janeiro state, in the southeastern of Brazil (Fig. 1). It is a typical municipality within the Paraíba do Sul watershed, which is covered by the Atlantic Forest biome. Currently, remnants of the Atlantic Forest occupy less than 11 % of the watershed's territory (Fundação COPPETEC). The deforestation of forests began in the second half of the 18th century, with the introduction and expansion of coffee plantations in the Paraíba do Sul valley. Similar to the earlier sugarcane cycle in Brazil, coffee cultivation developed under the colonial model – characterized by monoculture, large estates, and slave labor – where little to no attention was given to soil and water conservation practices (Fundação COPPETEC).

From 1940 onwards, with the rise of industrial activity, the population of the basin transitioned predominantly rural to urban within just a few decades. Agricultural activity, already struggling due to the lack of attention to natural land-use restrictions, entered a period of clear decline.

Today, much of the land is degraded and unproductive, and rural exodus is ongoing in the municipalities of the basin, with some now having over 90 % of their population concentrated in urban areas (Fundação COPPETEC).

The municipality of Rio Claro has approximately 20,000 inhabitants (IBGE, 2020) and its area contributes directly to the Ribeirão das Lajes reservoir, a crucial source of water and energy for the metropolitan region of the city of Rio de Janeiro, which is the second most populous metropolitan region in Brazil (IBGE, 2020).

2.2. Background for the methodological framework

We chose to develop participatory research because it promotes and incorporates local opinions and priorities through direct interaction (Ohly et al., 2023) and because it is a recommended approach for a nexus assessment (Daher et al., 2019; Mathetsa et al., 2023; Balaican et al., 2023). The WEF nexus methodology framework presented in this study was adapted from the Framework for Participatory Impact Assessment (FoPIA) (König et al., 2013). FoPIA is designed to facilitate the impact assessment of policies that are sensitive to national, regional, and local sustainability priorities, leveraging the knowledge and experience of stakeholders at different scales who play a central role in the analytical and decision-making process. This approach allows for the analysis of specific sustainability challenges, leading to the creation of realistic scenarios regarding national and regional policy and land use changes (König et al., 2013). As such, FoPIA has proven instrumental in the participatory assessment of land use change, aiding in the identification of pivotal elements in our research.

2.3. Participatory workshops

Two workshops were organized to develop the WEF nexus assessment: the expert workshop (EW), conducted in the beginning of the methodology framework development, and the stakeholders' workshop (SW), held in the final phase to validate the research procedures and results.

Both expert knowledge and stakeholder participation are essential for conducting impact evaluations of land use scenarios within the sustainability framework (König et al., 2013). In this study, the term "expert" encompasses anyone with extensive knowledge about the specific circumstances of a location, such as local farmers or external specialists, who contribute their expertise to the evaluation. This expertise is crucial for defining complex human-nature linkages in land use systems and integrating interdisciplinary knowledge in impact assessment. Stakeholders, on the other hand, are defined as organizations and individuals who are directly impacted by policy decisions, such as farmers and other land users, or those responsible for designing or implementing policies, such as planners and decision-makers. Stakeholder preferences are particularly important when establishing regional sustainability goals, as they reflect cultural norms (König et al., 2013).

Forty professionals participated in the EW held on April 16th and 17th, 2019 at the Embrapa Solos auditorium, Rio de Janeiro, Brazil, with the primary purpose being to adapt part of the FoPIA methodology. The meeting followed these stages: (1) Preparation for the workshop: this involved compiling and reviewing literature and materials to gain an initial understanding of land use issues in the study area, as well as selecting and inviting experts; (2) During the meeting: the workshop began with a presentation on the state of the art in the WEF nexus, followed by a description of the current land use situation in the study area. Based on this foundation, the relevant rural practices for the area were defined, and the landscape attributes (LAs) were identified. The participants also selected relevant assessment indicators for the LAs, using secondary open data. The landscape attributes were proposed based on the concept of "land use functions" (Pérez-Soba et al., 2008; Costa Coutinho et al., 2017), which relates to how each land use class can contribute to specific objective. In this study, the concept is understood as how each land use and land cover can enhance the availability and stability dimensions of WEF securities.

The experts were organized into three thematic groups: water, energy and food. Within in these groups, the experts discussed and identified the most appropriate LAs and indicators for assessing the impact of the selected agricultural practices on each nexus security. The criteria for selecting LAs focused on potential to influence the availability and stability dimensions of WEF security. Indicators were chosen based on their appropriateness for the project objectives and its accessibility to official databases.

The final stage of the methodology involved the SW, organized at the end of the nexus assessment development. The SW was held online, due to restrictions imposed by the COVID-19 pandemic, on November 4th, 2021, and was attended by 24 participants. The goal of this workshop was to present the methodology framework and results to potential end users, identified by Melloni et al. (2020), including representatives from various municipal sectors such as the agriculture and environment secretariats, rural extension technicians, river basin management committees, and rural producer associations.

During the workshop, stakeholders shared their questions and suggestions, leading to a few proposed adjustments. The results presented in this paper reflects the version that has been validated by the stakeholders.

2.3.1. Preparation for the workshop

2.3.1.1. Literature review - compilation and examination of available literature. A bibliographic survey was conducted to identify scientific literature that investigates the interactions between agricultural techniques and their impacts on WEF nexus. The focus was on publications related to the Atlantic Forest Biome. We explored the Web of Science database employing combinations of keywords, ensuring that each search included at least one of the following conservation practices: protection of springs/protection of headwaters, restoration of riparian forest, no-till farming, conventional cultivation/conventional agriculture, minimum tillage, organic cultivation/organic fertilization/organic agriculture, green manure/green fertilization, crop rotation, terracing, contour farming, septic tanks, basic sanitation, rural tourism/agrotourism, agroforestry/agroforestry systems, fallow, soil management, pasture rotation/rotational grazing, and manure treatment. Additionally, the searches included a security aspect (water, energy/hydroelectricity, food, agricultural production, plant production) and a location-related term (Brazil; Atlantic Forest). The search was restricted to studies focused on territorial landscapes situated in rural areas, rural-urban transition zones, or natural habitats within the Atlantic Forest Biome, excluding urban areas and marine landscapes (Duarte et al., 2021).

2.3.1.2. Project database. A key priority in developing the evaluation methodology for the WEF nexus was the use of open secondary data available in official databases. Secondary data analysis can be conducted using any previously gathered data, encompassing data obtained by quantitative or qualitative methodologies for original research, national survey data, and data collected for non-research purposes. This may encompass cross-sectional or longitudinal data, geographic or regional data, educational data, and numerous other options. Public data, including information gathered from national surveys, may consist of data derived from a complete or nationally representative sample of individuals or entities, and is provided to researchers in a deidentified format at no cost (Kelly et al., 2024). For these reasons, this solution was chosen to reduce evaluation costs and to ensure that the methodology could be utilized by professionals who may not have specialized training in certain equipment or software required to obtain some data. By focusing on accessible data, the methodology aims to enhance its potential for widespread adoption and contribute effectively to the sustainable planning of rural landscapes.

The main sources of data used in this study include: The Brazilian Institute of Geography and Statistics (IBGE), the Environmental Institute of the State of Rio de Janeiro (INEA), the National Sanitation Information System (SNIS), the National Department of Transport Infrastructure (DNIT), the National Water Security Plan, the National Water Agency (ANA), the National Electric Energy Agency (ANEEL) and the National Electric System Operator (ONS), the Brazilian Health Ministry, and MapBiomas (a multi-institutional initiative involving NGOs, universities, think-tanks and tech companies dedicated to mapping the land-cover and land-use changes (LCLU) of the Brazilian biomes).

2.3.1.3. During the workshop.

- Definition of the rural practices

Aligned with the historical and current land use of the region and the municipality of Rio Claro, along with the information gathered and observations from two field trips to these areas, agroforestry, spring protection and pasture rotation were identified as the most relevant agricultural practices, in the municipality of Rio Claro.

- Landscape attributes indicators

The experts had access to the project database to define the most appropriate indicators to assess the impact of the selected rural practices on the WEF nexus. The FoPIA approach identifies three indicators for each land use function associated with the Las (König et al., 2013; Pérez-Soba et al., 2008; Costa Coutinho et al., 2017). However, considering the reliance on the appropriateness of the indicators, particularly concerning spatial scale, and their accessibility in the referenced databases, the experts established seven indicators for food security,; ten indicators for water security; eight indicators for energy security (Tables on the results).

2.4. Data integration

The process of data integration involved a quantitative analysis approach, utilizing collected data to identify and assess the interconnections between WEF systems. The methodology for evaluating

Table 1
LAs and indicators of water security.

LAs	Indicators	Indicator value	Threshold/ Standard	Δ of the indicator value	Index	Source
Dynamic flows of ecosystem functions.	Permanent Preservation Area (PPA) with native vegetation (%)	53	100	−47 %	1.53	IBGE, INEA, MapBiomas, 2019
	Municipal roads with good practices (%)	18	100	−82 %	1.18	DNIT, IBGE, INEA
	Areas undergoing forest restoration (ha)	358.84	29517.94	98.78 %	1.01	INEA
Water Resource Availability	Water Security Index	4	5	−20 %	1.80	National Water Security Plan
	Percentage of the population served by a water supply network.	75.04	100	−24.96 %	1.75	SNIS
Water Quality	Population served by a sewage system (%)	99.30	100	−0.70 %	1.99	SNIS
	Sewage treatment (%)	0.00	100	−100 %	1.00	SNIS
	Water quality index	69.99	100	−30.01 %	1.70	INEA
	Water commitment (%)	112	40	180 %	1.00	Ilha Grande Basin Water Resources Plan 2020 (PLANO de Recursos Hídricos da, 2020)
	Rate of Acute diarrheal diseases in the population (%)	0.00	1.62	100 %	3.00	Brazilian Health Ministry (2019)

Of the ten indicators analyzed, only one - acute diarrheal diseases – was within the limit established by Brazilian legislation.

the indicators was based on the framework provided by Flammini et al. (2014).

For each indicator, it was necessary to define a threshold or standards to indicate the sustainable limit that should not be exceeded within each nexus element. Thresholds signify certain points that, when surpassed, will trigger a particular effect or reaction, encompassing upper or lower limits beyond which an influence will transpire. Standards establish guidelines that regulate the influence of an activity, usually human activity, on a receptor (Glasson et al., 2008).

Thresholds and standards establish critical criteria that underpin decision-making throughout the various stages of an environmental assessment process. They may vary from those explicitly enshrined in statute to those that broadly embody the ideals and conventions of a society; from precise quantitative thresholds to more ambiguous and indistinct criteria (Glasson et al., 2008). In accordance with these principles, thresholds were determined for each WEF indicator based on existing literature or Brazilian legislation; for indicators lacking such references, the average values of the indicators within the administrative region of Rio Claro municipality (Vale do Paraíba Fluminense region) were utilized.

Thus, the thresholds for water security were determined in accordance with current Brazilian legislation regarding water resources standards; for energy security, the indicators were evaluated using ideal standards as benchmarks (such as reservoir volume), or the average of the last 10 years in the municipality of Rio Claro, for certain indicators – e.g. Equivalent Interruption Duration (DEC); and for food security indicators were established based on data from the municipality of Rio Claro, with the evaluation using the average of corresponding data from the Vale Paraíba Fluminense region as reference values.

The variation between the current value of the indicator and its threshold value was calculated, with values ranging from −100 % to 100 %. Negative values indicated a deterioration of the current state in relation to the threshold, signaling a less sustainable scenario (Flammini et al., 2014). Conversely, positive values indicated the presence of a more sustainable scenario. A value of “0” indicated no variation between the current state and its threshold. To further evaluate the indicators, a scale of 1–3 was applied: a value of 1 represented a −100 % variation, a value of 2 indicated no variation between the current state and its threshold, and a value of 3 represented a positive variation of 100 % (Flammini et al., 2014). This evaluation framework corresponds to the "business as usual" scenario.

In addition to the "business as usual" scenario, an alternative scenario was developed using weights determined by experts, who had access to the bibliographic study produced by Duarte et al. (2021). The Delphi method guided this process. Ten selected experts analyzed and weighted the impact of conservation practices following this weighting system: 1 for low impact, 2 for moderate impact, and 3 for high impact.

Accordingly, the values from the "business as usual" scenario were multiplied by the assigned weight for each rural practice. The resulting values in this scenario ranged from 1 to 9, with 1 representing the worst outcome and representing the best. The purpose of this supplementary scenario was to highlight the practices that, according to the experts, would have the most significant influence on each WEF nexus. This approach aims to provide decision-makers with more informed and feasible options for improving sustainability outcomes.

Table 2
Expert -defined weights for evaluating conservation practices in water security.

Attributes	Indicators	Relevance (Expert Result)		
		Spring Protection	Pasture Rotation	Agroforestry
Dynamic flows of ecosystem functions.	APP with native vegetation (%)	3	1	2
	Municipal roads with good practices (%)	1	1	1
	Areas undergoing forest restoration (active and in regeneration) (ha).	3	1	2
Water Resource Availability	Water Security Index	3	1	2
	Percentage of the population served by a water supply network.	1	1	1
Water Quality	Population served by a sewage system (%)	1	1	1
	Sewage treatment index (%)	1	1	1
	Water quality index	3	1	1
	Water commitment (%)	2	2	1
	Rate of Acute diarrheal diseases in the population (%)	1	1	1

3. Results and analysis

3.1. Water security evaluation

Regarding water security, the results of the indicators revealed a situation of vulnerability in municipality of Rio Claro (Table 1).

Table 3
Attributes and indicators for energy security.

Attributes	Indicators	Indicator Value	Threshold/Standard	Δ of the Indicator value	Index	Source
Reservoir lifespan	Average Reservoir Volume % 2010 e 2021	86.97	100	−13.03 %	1.87	ANA
	Turbidity (uT)	20.14	13.30	−51.44 %	1.49	INEA
Generation capacity	Energy generated in Complex Lajes (Mwh/year) 2018–2021	454.36	655.00	−30.63 %	1.69	ONS
	Interruption Equivalent Duration (DEC)	12.30	13.20	6.82 %	2.07	ANEEL
	Interruption Equivalent Frequency (FEC)	8.70	10.30	15.53 %	2.16	ANEEL
	Electricity access (% pop)	99.42	100.00	−0.58 %	1.99	IBGE
Reservoir flow	Influent Flow (m^3/s)	13.5	13.5	0.00 %	2.00	ANA
	Outflow (m^3/s)	13.75	16	−14.06 %	1.86	ANA

Table 4
Expert weights for energy security indicators.

Attributes	Indicators	Relevance (Expert Result)	Relevance (Literature)				
		Spring Protection	Pasture Rotation	Agroforestry	Spring Protection	Pasture Rotation	Agroforestry
Reservoir lifespan	Reservoir Volume % 2010 e 2021	2	1	2	2	1	2
	Sediment Transport to Reservoir (Turbidity)	2	3	3	2	1	2
Generation capacity	Energy generated in Complex Lajes and Potential (Mwmed/year) 2018–2021	1	1	1	1	1	1
	Interruption Equivalent Duration (DEC)	1	1	1	1	1	1
	Interruption Equivalent Frequency (FEC)	1	1	1	1	1	1
	Electricity access	1	1	1	1	1	1
Reservoir flow	Influent Flow (m^3/s)	2	2	2	2	1	2
	Effluent Flow (m^3/s)	2	1	2	2	1	2

Four indicators showed significantly negative variations: the indicator "areas undergoing forest restoration" shows that of the 29,517.94 ha (ha) identified as priority areas for forest restoration (both active and regenerating), only 358.84 ha are currently at some stage of restoration; the sewage treatment index indicates a complete absence of sewage treatment in the municipality of Rio Claro, despite nearly the entire population having access to some type of sewage collection system; the PPA indicator reveals that a mere 53 % of the designated protected areas are currently conserved. This shortfall directly undermines water security, as a many of these areas are vital for providing ecosystem functions connected to water; and the water compromise indicator for the Ribeirão das Lajes Reservoir showed that more than 112 % of the water volume is compromised, despite the expected usage being only 40 %.

According to the analysis, the worst-performing indicators in the business-as-usual scenario are sewage treatment (%) and water commitment. The low sewage treatment percentage indicates that untreated sewage is being discharged directly into rivers. At the same time, the water commitment reveals that the amount of water required to meet the population's needs is higher than anticipated. Despite the discharge to untreated sewage into rivers, the water supplied to the population appears to be free of contaminants and diseases. This is evident from the indicator related to diarrheal diseases, which showed lower values compared to the threshold established based on the regional average in which the municipality of Rio Claro is located (Table 1).

Based on the business-as-usual Water security scenario for the municipality of Rio Claro, scenarios related to the adoption of selected rural practices were defined using experts' consultation (Table 2).

Overall, the evaluation conducted by experts indicates that the adoption of spring protection practices could potentially provide the most significant benefits for water security, followed by the introduction of agroforestry, and lastly, the use of pasture rotation (Table 2). The adoption of spring protection is expected to improve 5 out of the 10 evaluated indicators. Indicators related to vegetation preservation – such as riparian forest with native vegetation and areas undergoing forest restoration - will experience the most positive effect. Additionally, indicators related to water provision, including Water security index, Water Quality Index, and Water Commitment, will also be significantly and positively impacted.

3.2. Energy security evaluation

The analysis of energy security indicated that only two of the selected indicators - Equivalent Interruption Duration (DEC) and Equivalent Interruption Frequency (FEC) - showed a more positive current scenario in Rio Claro compared to the reference (Table 4). For these indicators, the average of the historical data series for the Rio Claro municipality was used as a reference and compared to the most

Table 5
Food safety attributes and indicators.

Attributes	Indicators	Indicator value	Threshold/ Standard	Δ of the Indicator value	Contents	Source
Diversifying production	Nutritional value	3801,92	2000	90,10 %	2,43	IBGE/ FAO
	Landscape Diversification	0.45	0.5	−10.00 %	1.90	IBGE
Productivity	Average yield (corn) (Kg/ha)	1600.00	2443.00	−34.51 %	1.65	IBGE
	Technical assistance (%)	37.41	100.00	−62.59 %	1.37	IBGE
	Gross revenue/ha/year	2141.55	1271.10	68.48 %	2.68	IBGE
Conservation practices and production stability	Food production (kg/inhab/year)	240.33	26.19	817.61 %	3.00	IBGE
	% of establishments with some conservative practice	13.73	32.41	−57.63 %	1.42	IBGE

Table 6
Weight of experts for food security indicators.

Attributes	Indicators	Relevance (Expert Result)	Relevance (Literature Result)				
		Spring Protection	Pasture rotation	Agroforestry	Spring Protection	Pasture rotation	Agroforestry
Diversifying production	Nutritional value	1	2	3	1	3	2
	Landscape Diversification	3	1	3	3	1	3
Productivity	Average yield (corn) (Kg/ha)	1	1	1	1	1	1
	Technical assistance (%)	1	1	1	1	1	1
	Gross revenue/ha/year	1	2	2	1	2	1
Conservation practices and production stability	Food production (kg/inhab/year)	1	2	3	1	2	1
	Adoption of conservation practices	3	3	3	3	3	3

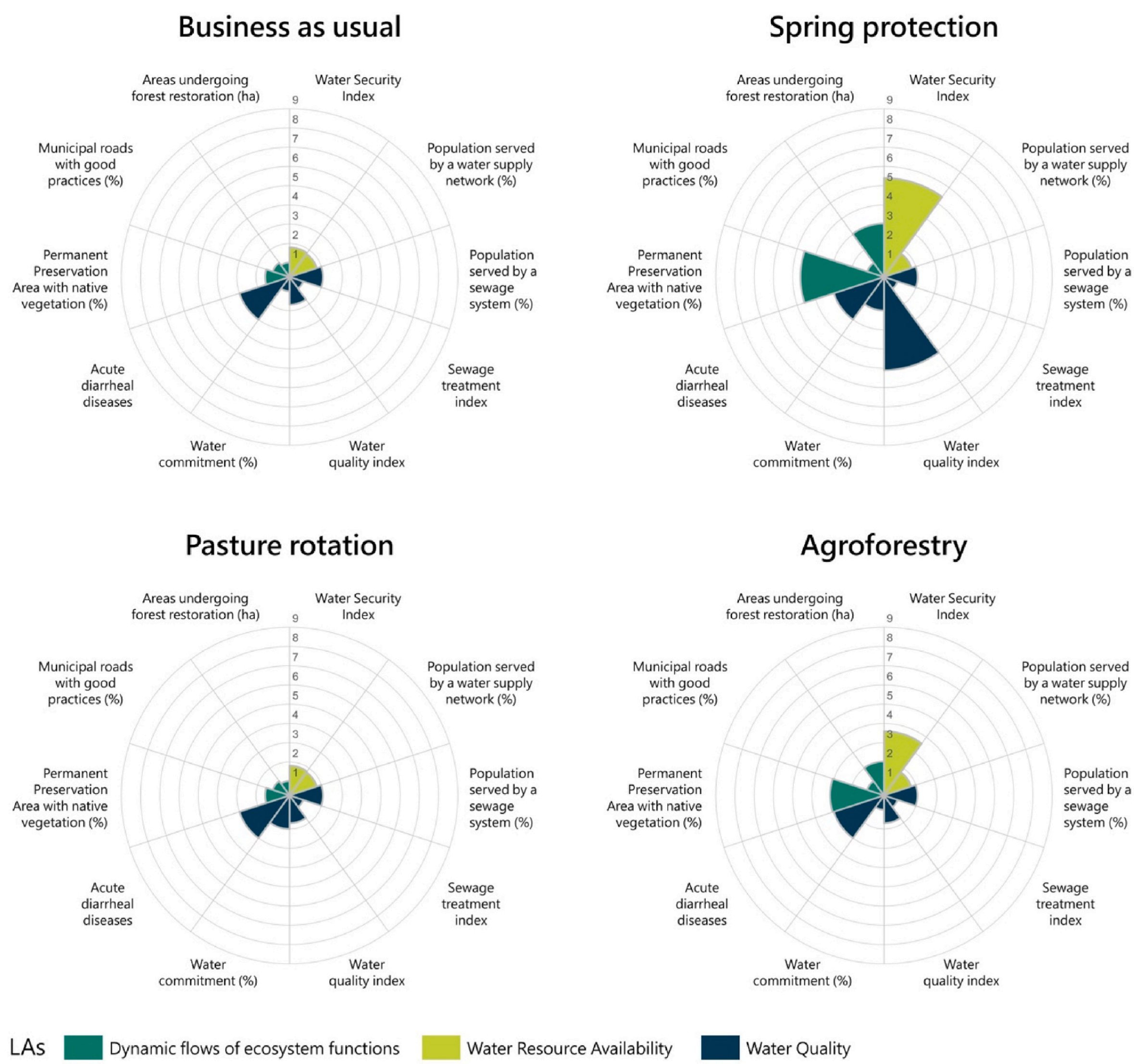

Fig. 2. Business as usual and scenarios for water security evaluation by experts in Rio Claro, Rio de Janeiro State, Brazil.
Source: The authors.

recent available year, 2020. This positive variation indicates that, compared to the average of the previous 10 years (2010–2019), the frequency of power interruptions was lower in 2020. Additionally, the only indicator that showed no difference between the reference and the current value was related to influent flow. However, the remaining indicators displayed a negative variation between the reference and the current value (Table 3).

The evaluation conducted by experts indicated that the adoption of spring protection or agroforestry practices has a significantly positive impact on four out of the eight established indicators for energy security

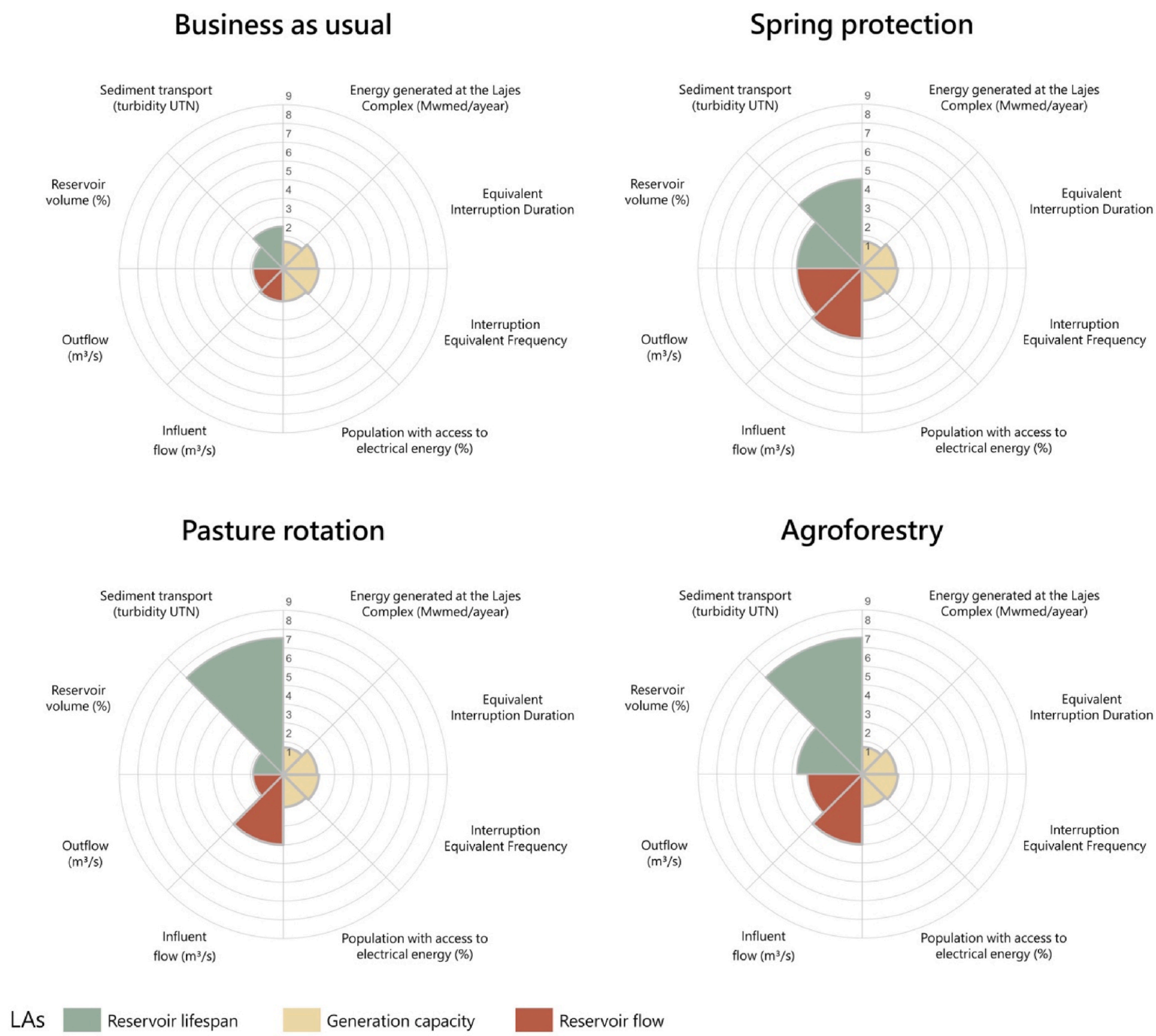

Fig. 3. Business as usual and scenarios for energy security evaluation by experts in Rio Claro, Rio de Janeiro State, Brazil.
Source: The authors.

(Table 4). In contrast, the adoption of pasture rotation affects only two indicators.

3.3. Food security evaluation

Regarding food security, the results indicate that of the seven indicators evaluated, three showed a positive variation, meaning that the current scenario in the municipality of Rio Claro is more sustainable when compared to the Vale do Paraíba Fluminense region, considering the region's average value used as the threshold (Table 5). This positive variation reflects a favorable relationship between total food production, nutritional value, and annual gross revenue. On the other hand, the indicators for landscape diversification, technical assistance, and the adoption of conservation practices showed a less favorable scenario for the municipality compared to the Vale do Paraíba Fluminense region.

According to experts' scenarios for food security, the agroforestry system can improve five of the seven indicators (Table 6). The spring protection scenario shows higher potential benefits for the indicators of landscape diversification and the adoption of sustainable practices, which are directly influenced by the adoption of conservative practices. While the scenario for pasture rotation was the only practice that did not impact landscape diversification.

4. Discussions

The results of this investigation showcase the impact of rural practices on the WEF nexus, relevant to subsidize decision on land use in agriculture areas located at Atlantic Forest biome, Brazil. The LAs and indicators used on the methodological framework were able to demonstrate the performance of each rural practices on the availability and stability dimensions of water, energy and food security (Fig. 2).

In the business-as-usual scenario for water security, the indicators for sewage treatment (%) and water commitment exhibited the poorest performances in the case study. Around 39.7 % of Brazilian municipalities lack sewage services, as reported by the National Basic Sanitation Survey (PNSB) (IBGE, 2021). The 2014 municipal basic sanitation plan of Rio Claro (RJ) (CEIVAP, 2014) emphasizes the inadequate infrastructure of the current sanitation service and the insufficient operational capacity for the existing sewage treatment facilities. Leaks in sewage systems, obsolete latrines, and municipal garbage in landfills can result in elevated levels of nitrate, chlorine, and CO_2 in groundwater (Javan et al., 2024), what indicates that the occupation of the Paraíba do Sul river floodplain could provide a complicated element if compensatory measures for urban drainage and the restoration of permanent protection areas are not implemented.

This advice aligns with the scenario anticipated by experts concerning the safeguarding of springs, which is the rural practice

Fig. 4. Business as usual and scenarios for food security evaluation by experts in Rio Claro, Rio de Janeiro State, Brazil.
Source: The authors.

exhibiting the most significant potential for enhancement across all LAs. It is important to highlight that according to the Brazilian Forest Code, Law N^{o}. 12,651/2012 (BRASIL, 2012), Article 3, II, the Permanent Preservation Area (PPA) is a "protected area, covered or not by native vegetation, with the environmental function of preserving water resources, the landscape, geological stability and biodiversity, facilitating the gene flow of fauna and flora, protecting the soil and ensuring the well-being of human populations", which includes perennial springs as a PPA Even though it is a law, many of the springs in Brazilian territory are located on degraded land, which compromises their water supply capacity and, consequently, contributes to water security vulnerability. Pieroni et al. (2019) studying the springs condition in a watershed in Atlantic Forest (São Paulo State) found that 75 % of the springs in the watershed were in some stage of degradation, and even the 25 % assessed as being in good and excellent conservation status showed vulnerabilities in relation to some of the parameters assessed. And the proximity to roads and degradation of vegetation were the most relevant factors to the spring degradation (Costa Coutinho et al., 2017). The payment of ecosystem services can be an alternative to stimulate the spring protection as a strategy to improve water security. For example, in 2015, the system comprising the National Confederation of Agriculture of Brazil and the National Rural Learning Service initiated the National Spring Protection Program, had preserved 1782 springs in rural regions across Brazil (Confederação da Agricultura e Pecuária do Brasil (CNA)). Such a program is expected to have positive effects on natural capital, since the value of ecosystem services is positively connected with vegetation and water areas but adversely correlated with barren land area (Wang et al., 2021).

Nonetheless, it is crucial to acknowledge that these actions enhance overall water security, delivering beneficial effects for society. However, concerning the enhancement of sewage services, public officials must engage in executing the requisite projects to develop such infrastructure, demonstrating the need for the nexus to consider an integrated vision, including for its governance (Daher et al., 2019; Mathetsa et al., 2023; Balaican et al., 2023). Spring protection had similar performance regarding energy security scenarios, specially related to reservoir lifespan LA (Fig. 3). However, following the expert's scenarios, agroforestry and pasture rotation would have the potential to impact positively the indicator "sediment transport" on the same LA. Sedimentation significantly affects the performance and longevity of reservoirs and is a mounting concern for those involved (Sedláček et al., 2022; Patro et al., 2022). The literature review validated the potential for erosion management using agricultural practices, which guided the methodology developed herein (Duarte et al., 2021). Agroforestry has been

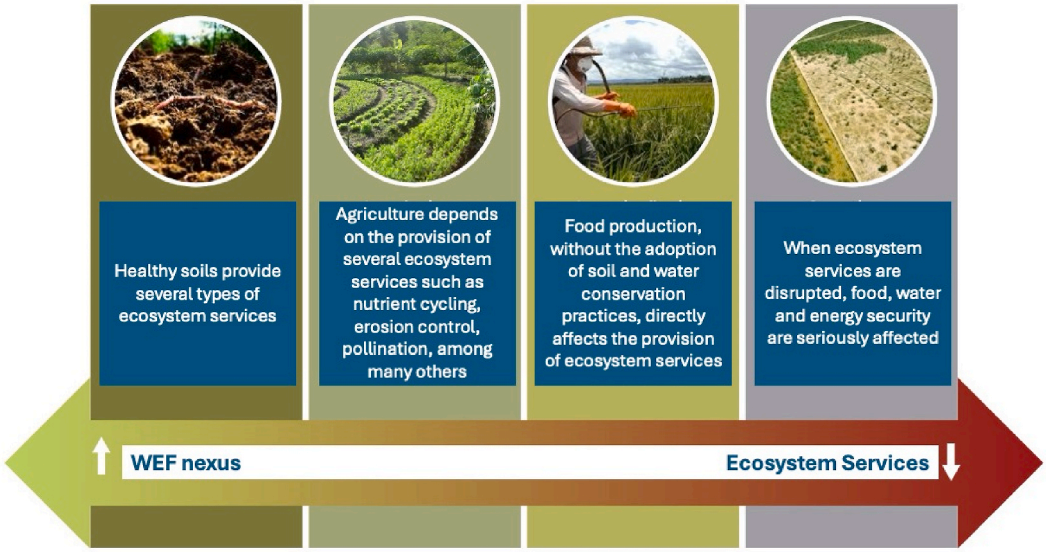

Fig. 5. Soil quality, impacts on the provision of ecosystem services and food, water and energy security.
Source: Turetta, A.P.D.

recognized as a feasible approach for alleviating and restoring degraded environments and reduce (Jinger et al., 2022), with significant reduction soil erosion, e.g. a 4-year investigation demonstrated that implementing an agroforestry system resulted in a significant reduction of 19.1 % in total runoff and 37.1 % in soil loss (Marques et al., 2022). Pasture rotations systems have been also demonstrating their potential to increase soil health and reduce erosion besides to collaborate with animal well-being (Baronti et al., 2022; Teague and Kreuter, 2020).

The experts' projections for food security indicate the significant potential of the assessed practices to enhance this security. Agroforestry's potential is evident, having shown a beneficial effect on five of the seven assessed indicators. Nevertheless, it is noted that LA "productivity" is the least affected by this practice (Fig. 4). This prognosis aligns with the prevalent discourse on agroforestry, wherein farmers, landowners, and other stakeholders regard environmental elements like biodiversity and soil protection as advantageous components of agroforestry systems, whereas cash flow and management expenses are viewed as detrimental factors (Staton et al., 2022). The same authors recommend that ways to address this issue involve endorsing public initiatives aimed at establishing these systems. In Brazil, this approach is outlined in the Sectoral Plan for Adaptation to Climate Change and Low Carbon Emissions in Agriculture, aimed at Sustainable Development (2020–2030) - ABC+", a program associated with sectoral policy to combat climate change in agriculture. Consequently, by 2021, nearly 1.22 million hectares of integrated systems were financed by the ABC program across all regions of Brazil (Palauro and Harfuch, 2022). Another approach to augment income for producers utilizing agroforestry systems is to compensate them for environmental services associated with carbon sequestration, for instance. The estimates of carbon stored in agroforestry systems vary from 0.29 to 15.21 $MgCha^{-1}$ yr^{-1} aboveground, and from 30 to 300 $MgCha^{-1}$ at a depth of up to 1 -m in the soil. Recent research across multiple agroforestry systems in different ecological contexts demonstrated that tree-based agriculture systems store more carbon in deeper soil layers adjacent to the trees than in areas distant from them (Ramachandran Nair et al., 2010). Moreover, additional advantages encompass the restoration of soil health through soil stabilization and enhancement of aggregate formation - fundamental for water infiltration into the soil and water regulation - augmentation of nutrient availability and retention, and the promotion of beneficial biota (Eddy and Yang, 2022).

Our findings revealed the extensive potential impact of conservative agriculture on WEF attributes, as a crucial approach for integrating key connections within socio-ecological systems and facilitating alterations in soil functions, which are closely related to water, energy, and food, thereby serving as a foundation for promoting operational actions that concurrently affect the WEF nexus (Duarte et al., 2021; Food and Agriculture Organization of the United Nations - FAO, 2011; Lal et al., 2017; Helming et al., 2018) – Fig. 5. Consequently, enhancing the sustainability of rural landscapes is both feasible and imperative through agricultural management methods that optimise soil resource utilization and augment ecosystem service supply, as related to WEF security (Fabiani et al., 2020; Turetta et al., 2016).

5. Conclusions

Our study offers a novel addition in the Nexus approach debate by presenting a methodological framework developed to evaluate the impacts of rural practices on the WEF nexus, hence supporting integrating the use of secondary data and participatory approach thorough the two workshops organized during the project. The biggest advantages of the methodology are to use free data available on public platforms and its flexibility for the definition of LAs and indicators, meaning a tailored methodology for different goals. As the case study was developed in a representative area of the Atlantic Forest, it is possible to replicate the methodology in other municipalities in the same biome. Additionally, it serves as a solid foundation for the development of efficient policies and regulations on sustainable land use in rural areas.

However, the methodology may be negatively affected if there is no availability of reliable data and information in adequate temporal and geographical scales that can be used as indicators. Furthermore, a possible advancement is including other data sources, such as those processed from remote sensing.

The scenarios generated illustrated that the adoption of the rural practices assessed here can lead to consistent improvements in WEF security. It was also feasible to observe that in Brazil, there are already programs in progress that can encourage the adoption of conservationist practices in agriculture, thereby creating an environment that is conducive to the adoption of the WEF nexus approach in decision-making.

Additionally, it is crucial to emphasise that nexus is not a confined methodology, but rather an approach that considers the interactions between natural resources and socioeconomic systems. It encompasses interdependencies (i.e., these resources are interdependent), constraints (i.e., these resources are often subject to conditions or compensations), and synergies (i.e., the benefits are shared and enhanced). In the context of WEF, there are a variety of stakeholders who are involved in the interactions, interdependencies, constraints, and synergies that comprise these systems. These interactions take place in the context of globally relevant drivers, or change inducers, including population growth, the greening of processes and products as a component of technological innovation, dietary diversification and changes, and climate change, among many other causes that can result in significant changes in the relationship between society and environment, both in rural and in urban areas.

Consequently, the nexus's message is that it is consistently crucial to assess the integration of the elements considered in the nexus and to comprehend the positive or negative impacts of the drivers on the relationship between society and nature. This approach allows us to optimise positive impacts and mitigate negative impacts on the system.

CRediT authorship contribution statement

Ana Paula Dias Turetta: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gabriel Garcia Távora:** Writing – original draft, Validation, Methodology, Formal analysis, Data curation. **Elaine Cristina Cardoso Fidalgo:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Maria Tereza Leite Montalvão:** Writing – review & editing, Methodology. **Rachel Bardy Prado:** Writing – review & editing, Methodology, Formal analysis. **Cláudia Moster:** Writing – review & editing, Methodology, Formal analysis. **Bernadete da Conceição Pedreira:** Writing – review & editing, Formal analysis. **Joyce Maria Guimarães Monteiro:** Writing – review & editing, Formal analysis. **Alba Leonor da Silva Martins:** Writing – review & editing.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Data availability

Data will be made available on request.

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