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RESEARCH ARTICLE

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Sustainability indicators for farming systems in Pampa biome of Brazil: a methodological approach NEXUS-MESMIS

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Abstract

Aim of study: To develop and measure sustainability indicators for the water-food-energy nexus in the Ibirapuitã river basin production systems in the Brazilian Pampa biome. The research seeks to contribute to the area of agriculture and sustainability along two lines: a) develop a methodology of sustainability indicators that can be applied to farming systems globally; and b) increase understanding of the interrelationship between water, food and energy and how it affects rural areas' sustainability.

Area of study: The study was conducted in the Ibirapuitã river basin in the Brazilian Pampa biome.

Material and methods: The construction of the indicators was based on the MESMIS methodology (Framework for the Evaluation of Management Systems incorporating Sustainability Indicators). In research, 121 farming systems were sampled. The sustainability indexes of the indicators between and within each dimension were analyzed using analysis of variance (ANOVA) and Tukey's test.

Main results: A significant difference was found between the averages of the indices of the dimensions in the production systems of the basin ($p<0.05$). The water dimension presented the highest level of sustainability, classified as "ideal". The energy dimension presented an intermediate level of sustainability, classified as "acceptable". Furthermore, the food dimension presented the lowest sustainability index among the nexus, classified as "alert". These indexes contribute to identifying the main action points for improving the systems, being an essential tool for local rural extension.

Research highlights: The study consolidated a methodology for measuring sustainability indicators based on farming systems' water, energy, and food production characteristics, capable of being replicated in other realities.

Additional keywords: energy; food; grassland; sustainable farming; water; WEF Nexus.

Abbreviations used: ES (Ecosystem Services); EDS (Ecosystem Disservices); LCA (Life Cycle Assessment); MESMIS (*Marco para Evaluación de Sistemas de Manejo de Recursos Naturales Incorporando Indicadores de Sustentabilidad;* Framework for Evaluating Natural Resource Management Systems Incorporating Sustainability Indicators); SWOT (Strengths, Weaknesses, Opportunities and Threats); WEF (water-energy-food).

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Introduction

The effects of globalization separate the world into interdependent and connected economies and those that experience drastic consequences. Economic and social disparity intensifies, bringing dissension between strategies and ways to promote sustainable and inclusive growth. These discussions were guided by World Economic Forum (2011), which indicated economic disparity and global governance failures as potential elements to generate other socioeconomic problems. These two elements unfold into three groups, punctuated as an essential agenda of policies and actions: the nexus of "macroeconomic imbalances", the nexus of "illegal economy", and the nexus of "water-energy-food" (WEF Nexus) (World Economic Forum, 2011).

The Nexus approach arises from the concern to propose articulated actions for these elements since some national and international policies bring solutions for isolated parts of the systems, unbalancing their effects (Mohtar & Daher, 2012). Therefore, in the case of the WEF Nexus, the water, food, and energy security of populations must be observed considering the understanding of the interdependencies between them. Researchers and policymakers warn about the implications of isolated actions, especially emphasizing poor populations' limited access to the three resources (Bizikova et al., 2013). And the relevance of the nexus approach for the sustainability of global economies (Morales-Garcia & Rubio, 2023). Although actions and policies that value the interrelations between water-food-energy are increasingly urgent, it is in the operational field that the main difficulties remain, either in the absence of indicators to evaluate these complex relationships or in terms of propositions adapted to such a need (Bizikova et al., 2013).

The impacts of climate change require an integrated approach to manage resources sustainably. This approach must consider the relationship between the main elements that sustain human life: water, energy and food (Nhamo et al., 2020). Shifting the focus from the single sectors to the complex interactions between them is extremely important for the sustainability and security of human societies (Moreira et al., 2022). From a theoretical point of view, for Correa-Porcel et al. (2021), the WEF Nexus remains a very new subject, with a multiplicity of progress still to be defined, and agriculture is a sector with significant research gaps in this field. Therefore, a paradigm shift in assessing the sustainability of agroecosystems is essential, introducing the WEF Nexus.

Several studies around the world have focused on the measurement of sustainability indicators in agricultural systems (Nahed et al., 2006, 2019; Gaspar et al., 2009; Reig et al., 2010; Ripoll-Bosch et al., 2012; Maqueda et al., 2021; Avilez et al., 2021). They include analyzing rice systems, dairy goats, organic dairy cattle, beef cattle, and sheep production. Most studies use the MESMIS method, formulating indicators that reproduce environmental, social and economic issues, but none included the Nexus approach in their construction.

Currently, Life Cycle Assessment (LCA) is recognized as a fundamental approach to investigating the sustainability of food production and consumption (Notarnicola et al., 2012, 2017). It is widely used to assess sustainability in agriculture systems (Haas et al., 2000; Ruviaro et al., 2012; Van der Werf et al., 2020). After decades of application, authors have highlighted important limitations in using LCA and the need for new approaches based on the current challenges of agroecosystems. Caffrey & Veal (2013) pointed out that the LCA methodology was initially developed for industrial operations. As a result, it has limitations for determining the impacts associated with agricultural production, including multiple products in a single system, regional and crop-specific management techniques and temporal variations (seasonal and annual).

The inherent variability of the agricultural system is one element affecting the assessment in LCA. Also, aspects of sustainability considered relevant, such as working conditions and animal welfare, are largely neglected in LCA (Notarnicola et al., 2017). Furthermore, there is a gap in assessing the impacts of energy, water and land use on agriculture, as well as incorporating social and cultural factors that have a direct bearing on the sustainability of rural communities (Caffrey & Veal, 2013; Fan et al., 2022). In addition, measures that take into account the multipurpose nature of agriculture and its intangible results must be developed (van der Werf et al., 2014).

Human interference in agricultural practices can influence human well-being by producing both Ecosystem Services (ES) and Ecosystem Disservices (EDS) (Alcon et al., 2022). These are two examples of the intangible outputs of agroecosystems. From this perspective, Hardaker et al. (2020) proposed an integrated qualitative and quantitative economic evaluation approach, evaluating the supply of ES and EDS. In turn, Alcon et al. (2022) evaluated the contribution of irrigation water to human well-being by determining the value of the supply of ES and ESD in irrigated agroecosystems.

Ecosystem services are intrinsically linked to the WEF Nexus. Understanding how this triad interacts in a farming system can be considered a breakthrough in sustainability assessment methodologies. As summarized by Moreira et al. (2022), indicator-based assessments of the nexus can serve to (i) provide a comprehensive view of current and future resource access and availability, (ii) monitor the anthropogenic and natural pressures on natural resources, (iii) synthesize data to support decision-making in favour of sustainability, and (iv) communicate relevant information and provide guidance for policymaking.

In this paper, we present an integrated approach called NEXUS-MESMIS for build and measure sustainability indicators for the water-food-energy nexus in the Ibirapuitã River basin farming systems of the Brazilian Pampa biome. This proposal is not intended to replace sustainability assessment approaches, but to complement current methodologies and serve as an alternative for contemporary rural realities.

The research seeks to consolidate the Nexus proposal by contributing to the area of knowledge of agriculture and sustainability in two lines: a) develop a methodology of sustainability indicators that can be applied to farming systems globally; and b) increase understanding of the interrelationship between water, food and energy and and how it affects rural areas' sustainability, considering the watershed as a unit of study. Therefore, the study seeks to contribute to FAO's (2014) objectives of developing a Nexus assessment approach to understanding the interactions between water, energy and agricultural systems in each context. The study hypothesizes that indicators based on the WEF nexus help assess the sustainability of farming systems in the Brazilian Pampa, with the potential to be replicated in other rural areas.

Material and methods

Study area and the NEXUS-MESMIS approach

The Pampa biome is characterized by grassland vegetation, also known as southern grasslands. Its pastoral regions extend over part of Argentina (provinces of Buenos Aires, La Pampa, Santa Fe, Entrerríos and Corrientes), the entire of Uruguay and part (63%) of Rio Grande do Sul, Brazil (Suertegaray & Silva, 2009). In Brazil, the Pampa biome represents 2.3% of the national territory, occupying an area of approximately 19 million hectares (MapBiomas, 2021).

Livestock systems have been the main form of economic exploitation of the natural grasslands of the Pampa biome (Viana et al., 2021). Recent changes in land use, especially from the expansion of soybean production in the Pampa biome region, concern the continuity of extensive livestock production systems and may accelerate soil degradation processes (Minella et al., 2020). This expansion is based on agricultural export production sustained by a globalized model governed by financialization and competitiveness (Elias, 2016), replacing areas of extensive livestock with the production of non-food commodities. In addition, these changes impact the population's access to locally produced food, making local economies dependent on supplier markets (Silveira, 2022).

Thus, the implications of climate change potentiated by changes in land use determine a process of high degradation of natural resources (water, soil, and biodiversity). The knowledge about the historical origin of the grasslands and their functionality in preserving the productive capacity of the soils are fundamental to indicate actions to be developed for their maintenance. Cattle grazing has been indicated as an alternative for conserving natural grassland vegetation (Behling et al., 2009). However, as it is an ecosystem that does not find the climatic conditions to maintain itself, some anthropogenic interventions have been defended as an alternative for conservation. These interventions generated what Viana et al. (2021, p. 3) called the "rangeland dilemma", that is, the paradoxical conservation of slightly "anthropized" ecosystems.

The Ibirapuitã River basin (Fig. 1) was chosen for the development of the research because the dynamics found in

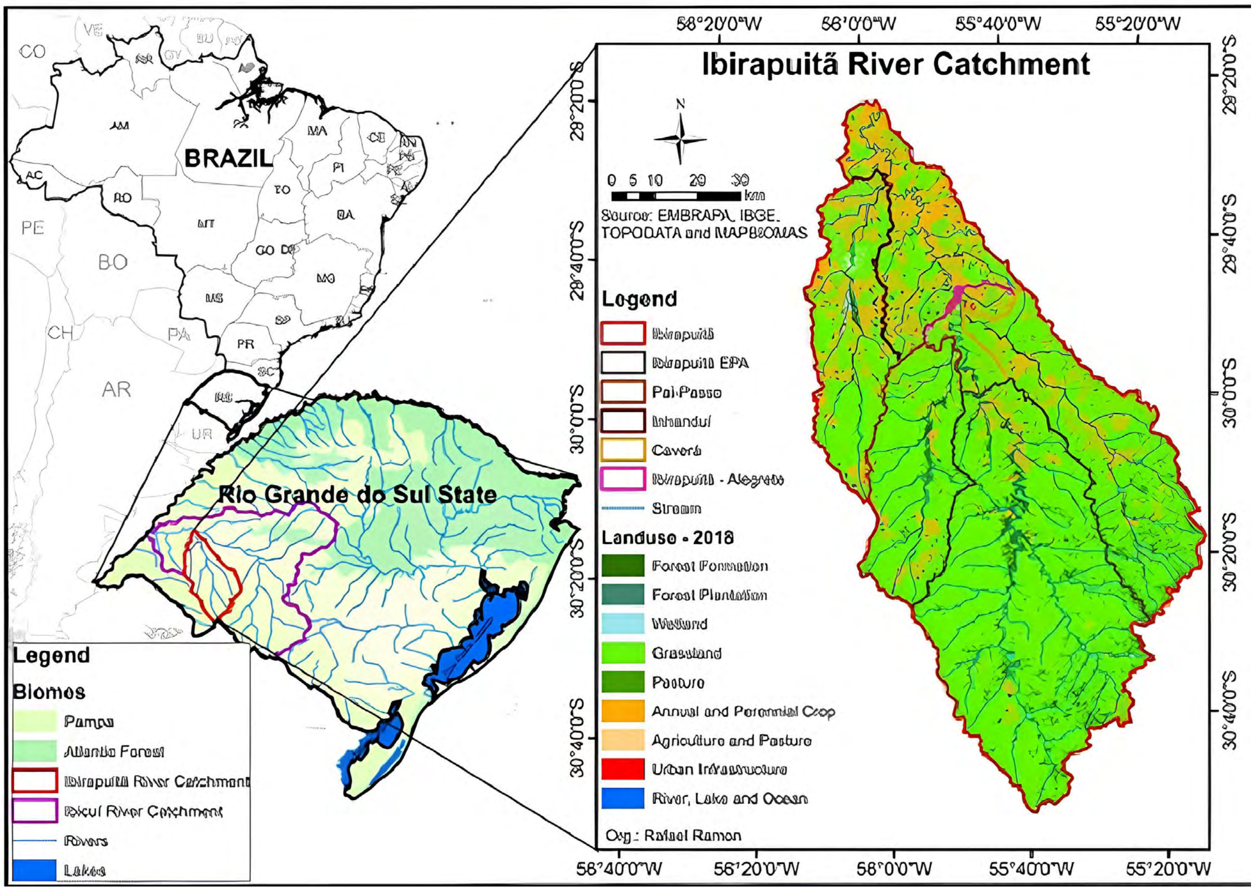

Figure 1. Delimitation of the study area in the Pampa biome of Brazil: the Ibirapuitã River basin.

this basin resemble the realities of other parts of the biome: livestock systems, urban agglomeration, and intensive land use for crops (Silveira, 2022).

The construction of sustainability indicators of the Ibirapuitã River Basin was based on the MESMIS methodology proposed by Masera et al. (1999). This method understands that sustainability should be measured from each socio-environmental and temporal context based on a systemic, participatory, and interdisciplinary approach.

Supported by the MESMIS methodology, we made adaptations transforming the tripod of sustainability (social, economic, and environmental), the object of evaluation MESMIS, in the fundamentals of the water-energy-food nexus, which form the methodological proposal for measuring sustainability indicators of this study, called NEXUS-MESMIS. However, the correspondence between the tripod of MESMIS sustainability and the NEXUS dimensions is not linear since social, economic, and environmental factors are present simultaneously in the three NEXUS dimensions - water, energy and food (WEF). The WEF indicators are constructed by experts and measured from farmers' perceptions of each variable in the survey. In the end, the variables' composition and respective weights in each indicator result in an assessment of the agroecosystem's sustainability.

The construction of the indicators followed the six stages of the evaluation cycle proposed by MESMIS: i) determination of the evaluation object; ii) determination of critical points; iii) selection of indicators; iv) measurement and monitoring of indicators; v) integration of results; vi) conclusions and recommendations (López-Ridaura et al., 2002, pp. 28-29).

The interdisciplinarity and participatory approach were guaranteed through a group of extension workers and researchers from different areas of knowledge, totalling 70 members. The members were professionals from higher education in agriculture, scientists from research institutions and professors from Brazilian public universities. In stage 1, the farming systems to be studied were delimited. For stage 2, a SWOT matrix (Strengths, Weaknesses, Opportunities and Threats) of the production systems under study was elaborated. A breakdown of the matrix can be found in Silveira (2022).

In stage 3, each water, energy and food dimension was divided into working groups presenting proposals for developing indicators collectively. The interdisciplinary view enriched the process, especially in attributions of the weights of the indicators, avoiding overlapping interests in disciplinary processes. Thus, the scopes and indicators for the three dimensions were defined, totalling 37 sustainability indicators. Appendix 1 [suppl.] shows the dimension, the indicators, the variables that composed each indicator, a description of the variables, their weights, how the variable was measured and the question number of the questionnaire that measured each variable. The weights of the indicators were assigned by the experts within the working groups for the water, energy and food dimensions. The assignment followed the criterion of the relative importance of each indicator in the sustainability of each dimension.

Farm sampling and data analysis

After, a questionnaire was elaborated to measure the totality of indicators. The data collection instrument underwent a pre-test with four farmers to adjust the research questions. Subsequently, a pilot study was conducted with 45 previously sampled rural farms because the study area needed data regarding sustainability. After the pilot study, the research sampling plan was defined according to the sampling method for a finite population (Eq. 1).

$$n = \frac{\sigma^2 \cdot Z^2 \cdot N}{\varepsilon^2 \cdot (N-1) + \sigma^2 \cdot Z^2} \qquad (1)$$

where: n = sample size; σ = standard deviation; Z = confidence level; N = population size; ε = margin of error.

All farming systems in the Ibirapuitã River basin (N=2,685) come from data from the Agricultural Census of the Brazilian Institute of Geography and Statistics (IBGE, 2017). A confidence level of 95% was used (Z=1.96). With the data from the pilot study, it was possible to measure the sustainability indexes' standard deviation and margin of error. The energy indexes showed the highest variability; therefore, we used them to calculate the sample size (σ = 7.94; ε = 1.5). With these parameters, the sampling estimate in the Ibirapuitã River basin was 104 farming systems.

In addition, we sought to represent the heterogeneity of the farming systems and land use of the Ibirapuitã River basin, totalling 121 questionnaires applied. The samples were fundamentally divided into three farming systems: a) extensive livestock systems (cattle and sheep); (b) livestock systems (cattle and sheep) integrated with agriculture (rice and/or soy); and (c) dairy farming systems. All farming systems sampled were geo-referenced. Thus, Fig. 2 presents a spatial view of the stratification of the sample in the Ibirapuitã River basin. The interviews were conducted face-to-face. Due to the long distances, it was possible to conduct a maximum of two interviews per day, each lasting an average of six hours. The interviews took place between October 2020 and December 2021.

Stage 5 was conducted with the integration of the results. Sustainability indices range from 0 to 100. In a specific analysis of sustainability within the dimensions (water, energy and food), the indices were measured from the weighted composition of each indicator. In the end, the closer the value of 100, the greater the sustainability attributed to the index. Thus, it was possible to perform a scale of sustainability levels for the WEF Nexus, as shown in Fig. 3.

Data analysis was performed following the NEXUS-MESMIS methodological principles. At the first level (social, economic, and environmental), bibliographic research was conducted to contextualize the significant transformations in Brazil's Pampa biome. In the second level, the indices of each dimension (water, energy and food) were analyzed

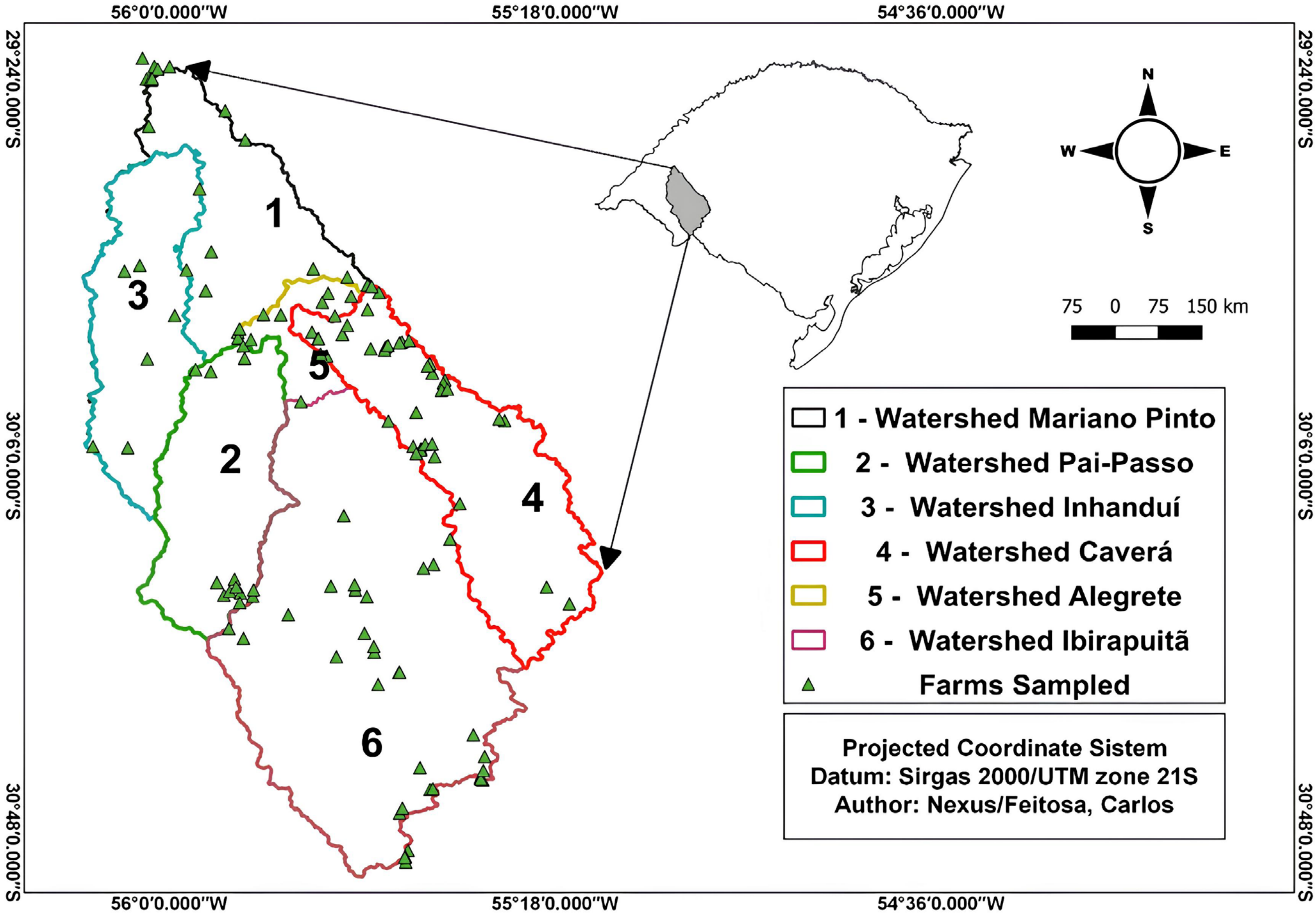

Figure 2. Spatial location of the farming systems sampled in each sub-basin of the Ibirapuitã River in the Brazilian Pampas.

Figure 3. Levels of sustainability for the water, energy, and food nexus of farming systems.

and compared. Finally, the indices within each dimension were analyzed and compared at the third level. The Shapiro-Wilk test assessed the indices' normality (p>0.05). Due to normality in the data, the indices between dimensions and scopes were compared from the Analysis of Variance (ANOVA). When the null hypothesis of equality of means was rejected, Tukey's test was used for multiple group comparisons. The maximum significance level adopted was 5%. The statistical software used was IBM SPSS Statistics 20. Finally, stage 6 forwarded the discussions of the indices found in the NEXUS-MESMIS methodology.

Results

The results presented demonstrate the applicability of the NEXUS-MESMIS methodology in the general context of the Ibirapuitã River basin of the Pampa biome. Table 1 presents the results regarding the sustainability index for each dimension of the WEF for the Ibirapuitã River basin production systems in Pampa of Brazil.

There was a significant difference between the means of the indices of the dimensions in the farming systems of the basin (p<0.05). The water dimension presented the highest

Table 1. Sustainability index for the water, energy, and food nexus (WEF) of the farming systems sampled in the Pampa of Brazil.

Dimension	Sustainability index[1]	Coefficient of variation (%)
Water	87.98[a]	6.98
Energy	63.52[b]	14.69
Food	50.47[c]	14.02

[1] Different letters indicate a significant difference between means by Tukey's Test (p<0.05). *Source:* Research data.

Table 2. Sustainability index of the scopes of the water, energy and food dimension for the farming systems sampled in the Pampa of Brazil.

Dimension	Scopes	Sustainability index [1]	Coefficient of variation (%)
Water	Water for consumption	97.06[a]	8.18
	Water for production	86.03[b]	9.13
	Degradation	85.39[b]	14.60
Energy	Electrical	69.81[a]	16.44
	Mechanical	66.65[a]	24.48
	Thermal	41.49[b]	42.59
Food	Product. and technolog. environment	53.80[a]	18.39
	Organizat. and institut. environment	53.61[a]	24.62
	Commercialization and consumption	42.81[b]	32.56

[1] Different letters indicate a significant difference between means by Tukey's Test (p<0.05). *Source:* Research data.

level of sustainability, classified as "optimal". The energy dimension presented an intermediate level of sustainability, classified as "acceptable". Moreover, the food dimension presented the lowest sustainability index among the nexus, classified as an "alert" situation.

Table 2 presents the sustainability indexes of the scopes that compose the water, energy and food dimensions. There was a significant difference between the means of the indexes of the water scopes in the farming systems ($p<0.05$). We highlight the highest level of sustainability for the "water for consumption" scope. However, all the indices of the areas of the water dimension were classified as " optimal".

The energy dimension presented an index significantly lower than the water dimension and significantly higher than the food dimension ($p<0.05$), therefore, in an intermediate situation of sustainability (Table 1). There was a significant difference between the means of the indexes of the energy dimension's scopes in the basin's farming systems ($p<0.05$). The indexes of the electrical and mechanical energy scopes were not statistically different, being classified as "acceptable". The lowest index found was in the thermal energy scope ($p<0.05$), classified as "alert" (Table 2).

In turn, the food dimension presented a significantly lower index than the water and energy dimension ($p<0.05$), therefore at a level of sustainability in a situation of "alert" (Table 1). This result draws attention, especially to the fact that the farming systems of the Ibirapuitã river basin of Pampa primarily aim to produce food for consumer markets. Among the systems sampled, beef, sheep, milk, rice, and soy production stand out. Furthermore, it is precisely in food production that farming systems present the lowest level of sustainability in the water-energy-food nexus.

There was a significant difference between the means of the indexes of the food dimension scopes in the farming systems ($p<0.05$). The indexes of the productive and technological environment and the organizational and institutional environment were not statistically different (Table 2). The lowest index was in the commercialization and consumption scope ($p<0.05$). However, despite this difference, all the indexes of the food dimension were classified in an "alert" situation.

The radar chart exemplifies the sustainability indices measured by the NEXUS-MESMIS methodology (Figs. 4 & 5). This tool is helpful for farmers and extensionists to visualize the results. Fig. 4 shows the sustainability indicators for the water and energy dimensions. Water for human consumption, both in quality and quantity, satisfies farmers' demands. Water for production and its efficiency of use was perceived as sustainable in farming systems. However, farmers had a limited capacity to perceive the erosion process. The indicator with the lowest value in the water dimension was drought susceptibility, in an alert

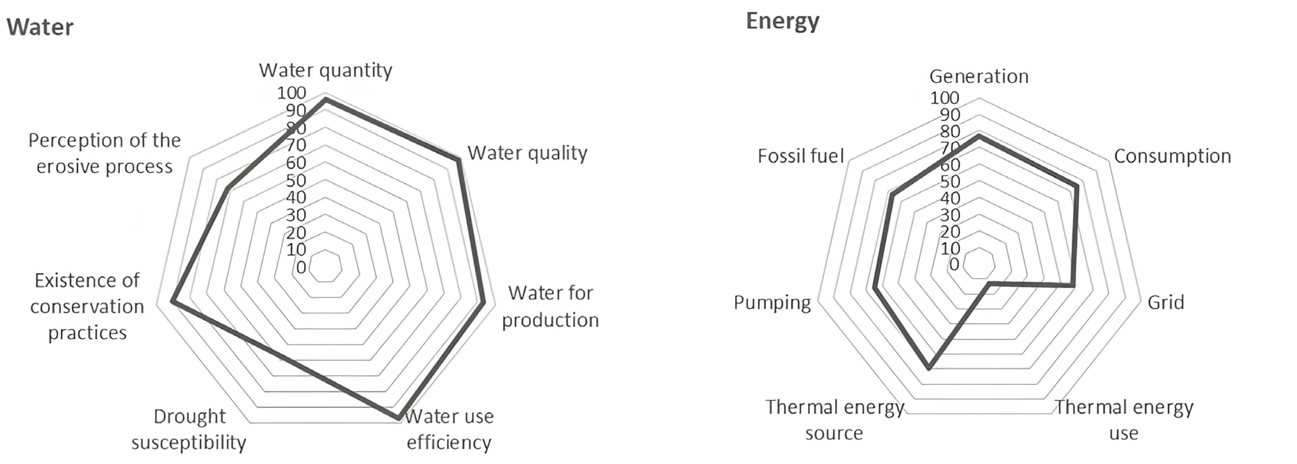

Figure 4. Sustainability indicators of the water and energy dimensions of farming systems in the Brazilian Pampa biome. *Source*: Research data

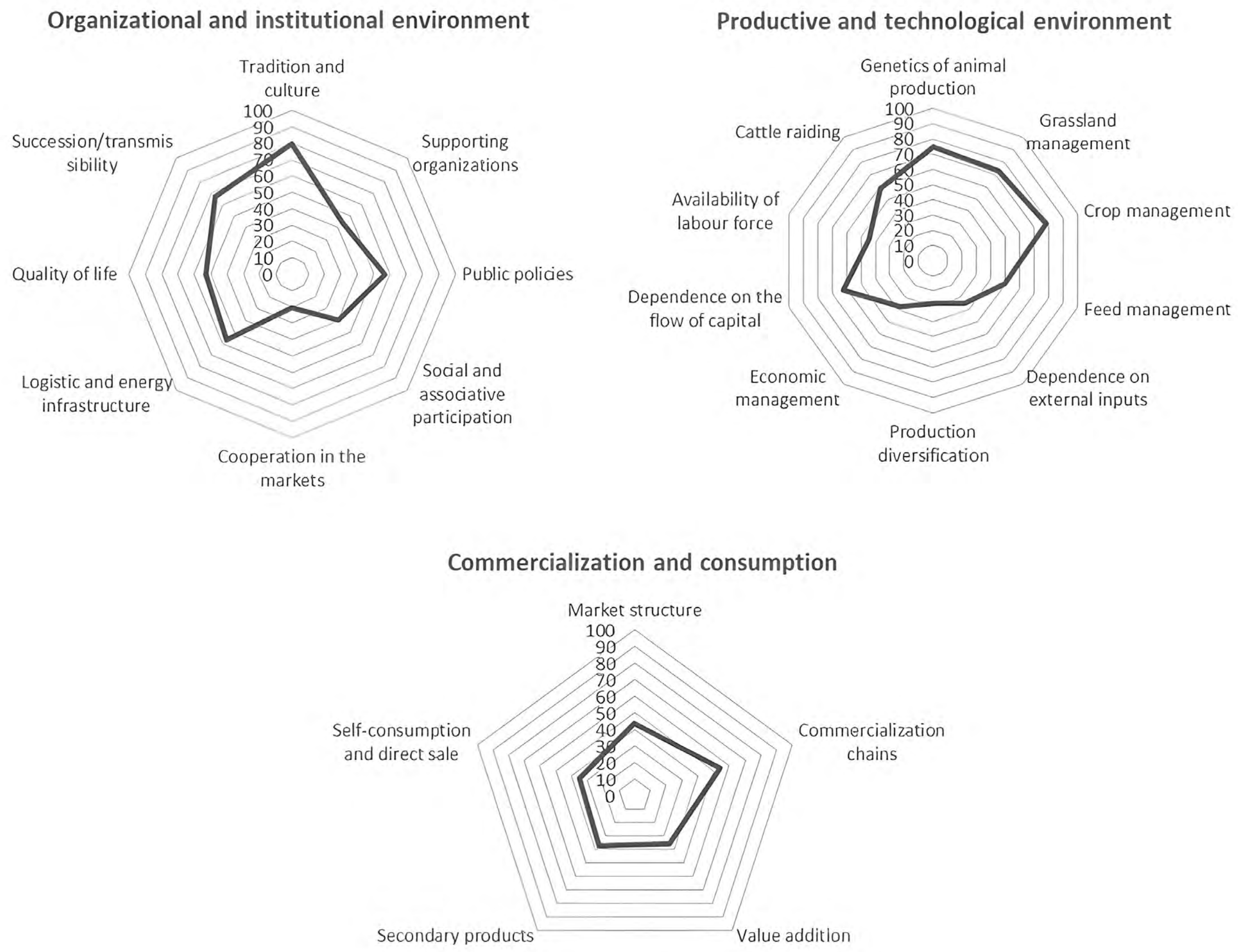

Figure 5. Sustainability indicators of the food dimension of farming systems in the Brazilian Pampa biome. *Source*: Research data.

situation. Periods of drought have occurred more frequently in recent decades. This may be associated with the effects of climate change in southern Brazil.

The energy indicators show that the systems are less energy-sustainable than their water conditions. A first highlight is the grid indicator. The farms were very dependent on electricity supplied by just one company (a monopoly). The quality of the grid was considered insufficient and had a negative impact on production activities. The thermal energy use indicator was in a critical situation. Essentially, farmers relied on a single thermal energy source for heating their homes, cooking, personal hygiene, and production processes. This source was firewood, which in most cases came from native forests or planted exotic forests.

Figure 5 shows the sustainability indicators for the food dimension. The commercialization and consumption scope had the lowest sustainability indexes. The value addition, secondary products and self-consumption and direct sale indicators were in an unacceptable situation. These results indicate farming systems with commoditized production, i.e. homogeneous products with no added value, with a predominance of one production activity and low capacity for self-consumption and direct sale. In the other scopes, the indicators of cooperation in the markets and production diversification were also in an unacceptable state of sustainability. Farmers trade individually, with limited experience of cooperative relations. Production diversification was low, with a focus on specialization.

Discussion

The sustainability indicators derived from the NEXUS-MESMIS methodology were measured by matching objective data with the perception of the farmers. This mix allowed us to determine more assertive sustainability indexes, incorporating measures observed by experts together with conditions perceived by the individuals involved in the agroecosystem. The water dimension presented the highest index among the three dimensions. These results indicate that the interviewed farms did not consider the limitations imposed by the lack of water and/or its capacity to cause damage, such as erosion or contamination of water sources.

The sustainability index of the scope "water for consumption" was very close to the value of 100. It is believed that even though there are sporadic climatic phenomena such as La Niña, which imposes water scarcity through rationing, farmers did not consider drinking water a problem. The lack of perception of the problem may be related to the condition the community usually faces, adapting to an unfavourable or inadequate condition, even if infrequent. In addition to the scarcity in terms of quantity, the farmers did not perceive water quality problems due to the lack of continuous monitoring of surface and subsurface water sources by public agencies. The farms were supplied mainly by cisterns or artesian wells, so there was no legal control of the quality as in the case of urban supply. In addition, natural springs were another significant water source in rural areas. These also require care so that the water is not contaminated by polluting sources such as domestic effluents, animal waste, etc.

The problems of soil degradation by surface runoff were also strongly influenced by the rural farmer's perception of the existence of the erosive process. Farmers generally neglected diffuse soil loss. Moges & Holden (2007) stated that farmers understand issues in an interconnected and holistic way and do not clearly distinguish erosion processes in the reductionist way scientists tend to do. Furthermore, farmers are inclined to perceive soil erosion when there is a decrease in productivity (Tesfahunegn et al., 2021), a reduction that has not yet occurred on the farms sampled. Farmers and technicians did not face concentrated erosion due to the difficulty of intervention and control. In a similar situation in Brazil, the study by Telles et al. (2022) indicated that most farmers did not know soil conservation techniques.

The results of the sustainability indexes of the scopes of the water dimension bring essential reflections on the environmental point of view of the farmers of the basin: i) the availability of water, both in quantity and quality, is not a limiting aspect or that causes restrictions for development; ii) the levels of degradation caused by water are at a level that farmers do not perceive. On the other hand, when analyzing the data that generate the scopes, the indicators of susceptibility to drought (water for production) and perception of erosive processes (degradation) present the most significant variability. In other words, some places manifest greater sensitivity to these two indicators. This result is significant because current debates about water security, as stated by Staupe-Delgado (2020), focus on disaster risk, such as severe droughts, a scenario experienced in recent years in the Brazilian Pampa biome.

The generation, consumption, and grid indicators form the "electric energy" scope in the energy axis. From the point of view of sustainability, generation reflects the possibility of self-production of energy. Its importance is high, not only because it considers the use of renewable energy sources but also because of the energy independence of the producer, even considering diesel or gasoline generators as a complement in situations of energy shortage. This indicator showed a predominance of intermediate and high values, demonstrating that an essential part of the farmers had alternative forms of energy generation. The consumption indicator, formed by variables related to the equipment installed in the farming systems and their form of use, demonstrated no problems related to their low energy efficiency or misuse.

In turn, the grid indicator showed more significant variability and a value slightly below the previous ones due to farmers' perception of limitations of access and quality of the electric power grid of the energy company. According to Van Els et al. (2012), electricity distribution has been implemented in Brazil through large centralized production systems with radial distribution and economies of scale. This model is inappropriate for rural electricity supply systems, mainly characterized by dispersed low-income consumers and low electricity demand. These factors, combined with the high installation cost, make rural electrification commercially unattractive. Market-based models will not induce companies to invest in these consumers (Van Els et al., 2012). Added to this is that the universalization of electricity connection has its most significant barrier in social problems, not technological limitations (Pereira et al., 2010). Therefore, access and grid quality are elements to be explored to improve the sustainability of the electric power scope.

In summary, the indicators of the scope of "electric energy" indicate that producers have access to energy through energy companies or generators, most of which are supplied by fossil fuels. Despite this, there is low reliability in the grid, and the lack of electricity is noticeable to farmers, contributing to the indicator being at an intermediate level. In addition, the diversity of productive characteristics and the structures of the farming systems within the basin, associated with relative distances between these locations and the connection points of the electric power distributors, are also important factors to be considered. The result of low reliability of access to electricity can constrain the performance of productivity-enhancing agricultural technologies, as identified in the study by Adebiyi et al. (2021).

The scope of "mechanical energy" is formed by the pumping and fossil fuel indicators. Both indicators had similar values and variability, demonstrating that the use of mechanical energy was relatively homogeneous throughout the farming systems. In systems integrated with agriculture, pumping is needed, especially in rice crops. In these same systems, there was intensive use of fossil fuel in places of difficult access and with storage limitations. These aspects were determinants for an index in intermediate value.

The index for the "thermal energy" scope was statistically lower than the electrical and mechanical energy indices and was at an "alert" sustainability level. The scope consists of two indicators: thermal energy use and thermal energy source. The thermal energy source concerns the access and the type of material used as fuel for energy generation and presented a value close to the mean of the energy dimension, proving to be acceptable for the region. On the other hand, when analyzing the final use of thermal energy, whether for cooking, personal hygiene, or a production process, a limitation in diversifying sources for this type of energy was evident. Especially since firewood is the main source of cooking in Brazil (Pereira et al., 2010), these results indicate that thermal energy was a crucial problem to be addressed in farming systems inserted in the Ibirapuitã river basin. Mainly because of the need for diversifying sources of use to raise the sustainability level.

In the food axis, the productive and technological environment scope is formed by indicators that reflect aspects related to farm food production. They measure grassland, nutrition, crop management methods, herd characteristics, production diversification, and economic management. A higher level of sustainability stands out in the indicators for the genetics of animal production, grassland management, and crop management. In other words, the bovine and/or sheep herds present a defined racial pattern, with suitable adjustment of animal load and low incidence of invasive species in natural grasslands, besides a low percentage of the area with the introduction of crops. However, the sustainability index of the productive and technological environment was in a state of alert due to the low level of sustainability of the indicators of dependence on external inputs, productive diversification, and economic management. All were situated at an unacceptable level of sustainability. That is, the farming systems were very dependent and impacted by the scarcity of external inputs. They were not very diversified systems, with a predominance of one or, at most, two productive activities, which determines dependence on the price fluctuation of a few markets. Studies highlight the potential for off-farm diversification, such as rural tourism. Weyland et al. (2021) stated that rural tourism is a form of productive diversification that generates additional economic income for farmers and can encourage biome conservation. In a research study in the pampa biome of Brazil, Cipolat & Bidarte (2022) demonstrated that rural tourism was a viable activity and an income supplement with development potential for the region.

Furthermore, most farming systems did not use economic planning and control tools. The scope of the organizational and institutional environment was composed of indicators that measure the relationship of the productive units with support organizations, as well as the importance of institutional aspects in agricultural exploitation. The indicators of tradition, culture, and succession/transmissibility were positively highlighted in an ideal situation. Tradition and culture were essential values for developing livestock activity, and rural establishments had successors predisposed to manage the property. However, social participation and cooperation indicators in the markets were unacceptable. It is verified that the livestock systems present difficulty in acting in an associative way with other producers, either from the social point of view or from the commercialization of their products.

In turn, the scope of commercialization and consumption presented the lowest performance in the food dimension ($p<0.05$), positioning itself as an index of sustainability in alert. Although the farming systems of the Ibirapuitã river basin in Pampa have a tradition in beef cattle raising, their relationship with the markets was still incipient. Farmers are removed from the consumer market and placed in lengthy supply chains as price takers.

The farming systems were in an unacceptable sustainability situation in value addition, secondary products, self-consumption, and direct sale indicators. Therefore, the systems still standardized market products without additional value associated with racial or biome characteristics, produce none or little food for their consumption, and trade at most one agricultural product in addition to beef cattle.

These results indicate the need to formulate marketing strategies that strengthen regional and environmental aspects of the meat produced in the Pampa biome, which would bring a competitive edge in the globalized market where farmers are inserted. These results corroborate and explain the conversion of areas of the Pampa biome into soybean crops according to the studies by Silveira et al. (2017) and Viana et al. (2022).

From a methodological point of view, it was possible to build and measure sustainability indicators by integrating the MESMIS and NEXUS approaches. As Staupe-Delgado (2020) highlighted, the nexus approach would greatly benefit from community-based empirical studies that could contribute to a site-based model of nexus interactions, overcoming isolated forms of analysis. Thus, the NEXUS-MESMIS approach proposed contributes to an integrated view of the water-energy-food triad applied to agricultural systems.

In conclusion, the study proposes integrating the sustainability assessment of farming systems with the WEF Nexus approach. The paper consolidated a methodology called NEXUS-MESMIS by building and measuring sustainability attributes from indicators of water, energy and food production characteristics empirically collected from livestock systems of the Brazilian pampa biome. That is, the methodology is a combination of the NEXUS approach, which determines that water, energy and food production cannot be observed as single and separate phenomena but instead through a systemic and integrated vision; and the MESMIS approach, which allows the construction of sustainability indicators in a participatory way based on the characteristics of the object of study. Furthermore, the proposal allows aspects of the production systems' social, economic, and environmental to be considered in the indicators, mediated by the WEF Nexus triad, helping explain the results obtained.

Supplementary material (Appendix) accompanies the paper on SJAR's website

Data availability: The corresponding author can provide the data from this study upon request.

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