Energy Nexus 12 (2023) 100248

Contents lists available at ScienceDirect

Energy Nexus

journal homepage: www.elsevier.com/locate/nexus

Full Length Article

Sustainability attributes from the water-energy-food nexus: An application to livestock systems in the Brazilian Pampa biome

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ARTICLE INFO

Keywords:
Agricultural indicators
Livestock
MESMIS
Nexus approach
Sustainable agriculture

ABSTRACT

The water-energy-food nexus (WEF Nexus) is a research issue still in progress, especially in agriculture. In the context of climate change and biodiversity loss, the study of the sustainability of agricultural production becomes urgent. Several international types of research have focused on measuring sustainability attributes in agricultural systems, but they have yet to include the Nexus approach in their construction. Thus, based on the WEF Nexus, the study aimed to construct and measure sustainability attributes for livestock systems in the Brazilian Pampa. The construction of the indicators was based on the MESMIS methodology, divided into three dimensions: water, energy and food. In data collection, one hundred twenty-one farming systems were sampled in the Ibirapuitã river basin of the Pampa biome. As a result, the 37 WEF Nexus indicators were distributed to compose the sustainability attributes of adaptability, self-management, equity, stability, and productivity. The elements of the triad water, energy and food are used efficiently in the livestock systems of the Pampa biome to generate self-management and productivity. However, they are limited to fairly distributing the benefits and costs of managing their natural resources (equity). The food dimension contributes the least to the sustainability scores of the attributes. In contrast, the water dimension presents the most significant contribution, expressing the importance of managing water and soil resources for the welfare of society and success in livestock production.

1. Introduction

The rapid population growth on the planet, the accelerated use of natural resources, and the economic and cultural globalization process are some of the factors present in the current stage of humanity's development. The triad water-energy-food is a crucial element in this context that can no longer be dissociated. So, the Nexus approach emerges, with the concern to propose articulated actions for the planet's sustainability focused on the populations' water, food, and energy security.

From an academic perspective, for [1], the water-energy-food nexus (WEF Nexus) remains a very new subject, with a multiplicity of progress yet to be defined. Agriculture is a sector with significant research gaps within the WEF Nexus [1], despite recent studies in conventional agriculture [2] and urban agriculture [3]. It is highlighted that these studies have very specific geographic delimitations and lack research proposals with a broader scope.

We propose the Pampa Nexus approach to study the recent transformations of the WEF triad in agriculture. The approach is based on a systemic, transdisciplinary, and participatory perspective of a regional reality in the Brazilian Pampa biome: the Ibirapuitã river basin.

Livestock systems have been the main form of economic exploitation of the natural grasslands of the Pampa biome [4]. However, since the late twentieth century, South America has experienced a significant

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https://doi.org/10.1016/j.nexus.2023.100248
Received 16 March 2023; Received in revised form 13 September 2023; Accepted 10 October 2023
Available online 14 October 2023

expansion of agriculture over areas of natural grasslands, especially in the Pampa [5]. Recent changes in land use impact the continuity of extensive livestock production systems and may accelerate soil degradation processes [6]. Further, Foucher et al. [5] assert that the environmental consequences of this massive land use conversion remain poorly documented. Furthermore, these changes impact the population's access to locally produced food, making local economies dependent on external markets for their nutrition [7].

Thus, the success of a given society or community depends fundamentally on the ability to manage local natural resources to generate prosperity without degrading them over time. To this end, production systems must be systematically monitored for sustainability attributes. In their MESMIS methodology, Masera et al. [8] and López-Ridaura et al. [9] define that for an agroecosystem to be economically, socially and environmentally sustainable, it should develop the capabilities of five sustainability attributes, which are: a) Adaptability; b) Self-management; c) Equity; d) Stability and; e) Productivity.

Therefore, the farming systems of the Brazilian Pampa should seek to develop capabilities to achieve these attributes to perpetuate for new generations, preserving the natural grasslands of the biome. Several studies worldwide have already focused on measuring sustainability attributes in farming systems [10–16], but they have yet to include the Nexus approach in their construction. Furthermore, the choice of the watershed as the unit of study provides an analysis that is more consistent with the processes that determine water availability for agricultural production and supply, as well as the mechanisms of soil degradation through erosion or contamination of water resources.

Thus, this study aims to build and measure sustainability attributes for the Ibirapuitã river basin livestock systems in the Brazilian Pampa based on the WEF Nexus. The study seeks to contribute to improving studies on the WEF Nexus applied to agriculture, besides expanding the knowledge on how this interrelation can influence the sustainability of rural areas under constant climate and land use change. We intend to propose alternatives to maximize food production by integrating water management and energy generation for the local community's welfare and respecting the biome's specificities.

2. Material and methods

The Pampa biome is characterized by grassland vegetation, also known as "campos sulinos", its pasture 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 the state of Rio Grande do Sul, Brazil [17]. Concerning Brazil, the Pampa biome represents 2.3 % of the national territory, occupying an area of approximately 190 thousand km^2 [18]. The Ibirapuitã River Basin (Fig. 1), with approximately 7,975km^2, was chosen for the study's development because the dynamics in this basin resemble the realities of other parts of the biome. The basin comprises extensive livestock systems, an urban agglomeration, and intensive land use for livestock and crops. In addition, the irregular rainfall distribution implies long periods of drought and high-magnitude rainfall events that generate frequent flooding. The physiographic characteristics of the basin, especially the susceptibility of the soils to erosion and the low water storage capacity of the soils, determine a high challenge for the expansion of intensive agricultural land use systems.

Supported by the MESMIS methodology, the study made adaptations transforming the sustainability triad (social, economic, and environmental), the object of the MESMIS evaluation, into the foundations of the water-energy-food nexus. The reasons for using the MESMIS methodology as a guide can be divided into: i) Methodology widely applied in rural studies in several regions of the world [19,20]; ii) Participatory methodology that involves the constitution of a multidisciplinary team capable of providing a holistic view of the sustainability of production systems [8]; iii) MESMIS evaluation cycle determines a continuous flow of assessment of the sustainability indicators [9]; iv) Provides

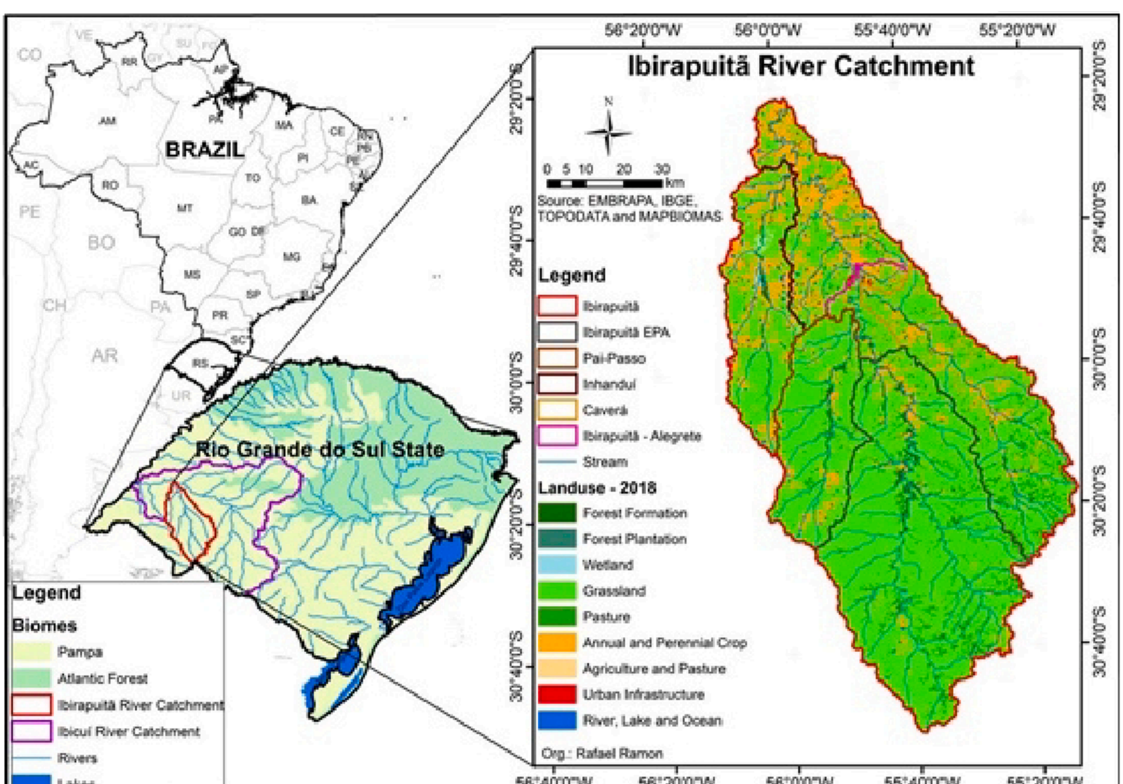

Fig. 1. Delimitation of the study area in the Pampa biome of Brazil: the Ibirapuitã river basin.
Source: Elaborated by the authors.

procedures for measuring sustainability indicators based on the characteristics of the reality observed [21].

We characterize the NEXUS-MESMIS methodology as an evolution of the MESMIS methodology by incorporating the water-energy-food nexus into the indicators. As the MESMIS methodology was developed at the end of the 1990s, its applications over the following decades focused on the economic-social-environmental sustainability triad. Thus, in this paper, we consider the NEXUS-MESMIS methodology as part of the results, as it brings the contribution of updating the MESMIS methodology to the new challenges of 21st-century agriculture by focusing on the water, energy, and food sustainability of production systems, as highlighted by the FAO [22]. Thus, our NEXUS-MESMIS proposal establishes a methodology for measuring sustainability indicators in agriculture in line with the current WEF Nexus challenges highlighted by Lalawmpuii [23] of sustainable development and global environmental change.

The construction of the indicators followed the six stages of the evaluation cycle proposed by MESMIS: i) determination of the object of evaluation; ii) determination of critical points; iii) selection of indicators; iv) measurement and monitoring of indicators; v) integration of results; vi) conclusions and recommendations [9].

The interdisciplinary and participatory approach was guaranteed through a group of extensionists and researchers from different areas of knowledge, totalling 70 members. In stage 1, the livestock systems to be studied were delimited. For stage 2, an analysis SWOT (Strengths, Weaknesses, Opportunities and Threats) of the systems under study was elaborated.

In stage 3, each of the dimensions (Water, Energy, Food) gave rise to working groups, which presented the proposals for indicators to be worked on collectively. Thus, the scopes and indicators for the three dimensions were defined, according to Table 1, totalling 37 sustainability indicators. A detail of the SWOT analysis and the indicators' descriptions and forms of measurement can be found in Silveira [7].

For stage 4, a questionnaire was designed to measure all indicators. The sampling plan of the research followed the calculation for a finite population sample, with a confidence level of 95 %. The sampling estimate for the Ibirapuitã river basin was 104 rural farms. In addition, a representation of the heterogeneity of the production systems and land use of the Ibirapuitã river basin was sought, totalling 121 questionnaires applied.

The sample was selected by segmenting the river basin into six subbasins. Therefore, the producers interviewed operate different production systems and in different locations, making them representative of the spatial, economic, and social context of the Pampa biome (Fig. 2). The subdivision into sub-basins made studying the relationship between environmental fragility, the advance of agricultural activity and environmental degradation possible.

The sampled rural properties are fundamentally divided into three livestock systems: a) extensive livestock systems (cattle and sheep); b) livestock systems (cattle and sheep) integrated with agriculture (rice and/or soy) and; c) dairy livestock systems. All sampled rural properties were geo-referenced.

Stage 5 was carried out with the integration of the results. The sustainability scores range from 0 to 100. In a specific analysis of sustainability within the dimensions (water, energy, and food), the scores were measured from the weighted composition of each indicator. Ultimately, the closer the value is to 100, the greater the sustainability assigned to the attribute.

For the present study, the 37 measured indicators of the WEF Nexus were distributed to compose the five sustainability attributes of Lopez-Ridaura et al. [9]:

a) Adaptability: capacity of the production system to find stability after an adverse situation.
b) Self-management: capacity of the production system to regulate and control its relations with the external environment.

Table 1
Sustainability indicators for the water-energy-food nexus.

Dimension	Scopes	Weight	Indicators	Weight
Water	Human consumption	20	Water quantity	10
			Water quality	10
	Production	40	Water for production	10
			Water use efficiency	20
			Drought susceptibility	10
	Degradation	40	Existence of conservationist practices	30
			Perception of the erosive process	10
Energy	Electric	60	Generation	20
			Consumption	20
			Grid	20
	Thermal	20	Thermal energy use	10
			Thermal energy source	10
	Mechanical	20	Pumping	5
			Fossil fuel	15
Food	Organizational and institutional environment	20	Tradition and culture	2
			Supporting organizations	2
			Public policies	2
			Social and associative participation	2
			Cooperation in the markets	2
			Logistic and energy infrastructure	2
			Quality of life	4
			Succession/ transmissibility	4
	Productive and technological environment	50	Genetics of animal production	4
			Grassland management	6
			Crop management	6
			Feed management	6
			Dependence on external inputs	6
			Production diversification	6
			Economic management	4
			Dependence on the flow of capital	4
			Availability of labor force	4
			Cattle raiding	4
	Commercialization and consumption	30	Market structure and prices	8
			Commercialization chains	8
			Value addition	6
			Secondary products	4
			Self-consumption and direct sale	4

Source: Elaborated by the authors.

c) Equity: capacity of the production system to distribute fairly the benefits and costs resulting from the management of natural resources.
d) Stability: capacity of the production system to return to its production potential after suffering perturbations and to keep the productivity generated constant over time.
e) Productivity: the capacity of the production system to generate the required level of goods and services, represented by earnings or income at each time.

In a participative methodology, the attributes were constructed from the distribution of the WEF Nexus indicators by a group of eight researchers from the areas of animal production, soil and renewable

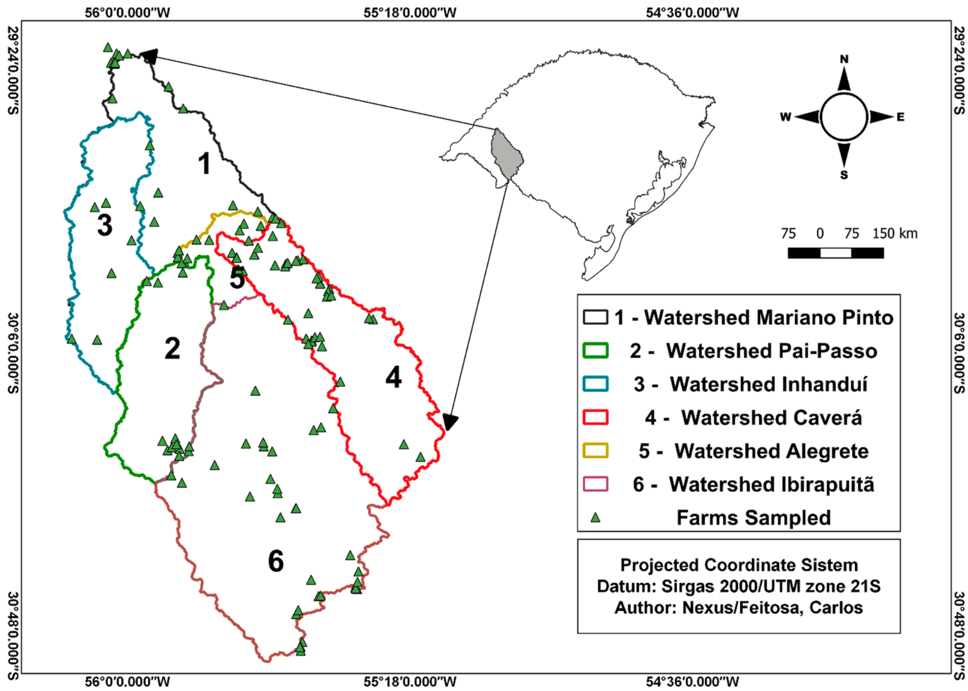

Fig. 2. Spatial location of the farming systems sampled in each sub-basin of the Ibirapuitã River in the Brazilian Pampas.
Source: Elaborated by the authors.

energies. The distribution considered the challenges of climate change and biodiversity loss in the biome. After this construction, the sustainability attributes were analyzed and statistically compared to each other to evaluate the systems' different sustainability levels. The normality of the scores was tested by the Shapiro-Wilk test ($p>0.05$). Due to normality in the data, the attributes 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 comparisons between attribute groups. The maximum significance level adopted was 5 %. Finally, stage 6 forwarded the discussions of the attribute scores with the literature.

3. Results and discussion

The sustainability attributes of the livestock systems of the Pampa biome were constructed based on their relevance at a global level. Climate change and biodiversity loss are two of the most pressing issues of the Anthropocene. In June 2021, the Intergovernmental Panel on Climate Change [24] and the Intergovernmental Platform on Biodiversity and Ecosystem Services [25] emphasized that while there is recognition that both are interlinked, in practice, they are treated as being confined to their domains. On the other hand, the research community devoted to investigating the climate system is somewhat, but only partially, distinct from that studying biodiversity [26]. Therefore, when elaborating on the sustainability attributes, we considered the two scenarios proposed by the IPCC and IPBES, aiming to associate the problem of climate change and the loss of biodiversity and, consequently, ecosystem services in livestock production systems.

Fig. 3 expresses the proposed construction of the sustainability attributes of production systems from the WEF Nexus. Thus, it is evident that the WEF Nexus is involved in the diffuse social, economic and environmental environment of production systems, which we call the NEXUS-MESMIS methodology [27]. However, the sustainability attributes are permeated (discontinuous line) by the WEF Nexus, thus expressing the complementarity and impact of the indicators measured in the composition of the attributes.

The following topics present and discuss the results of constructing

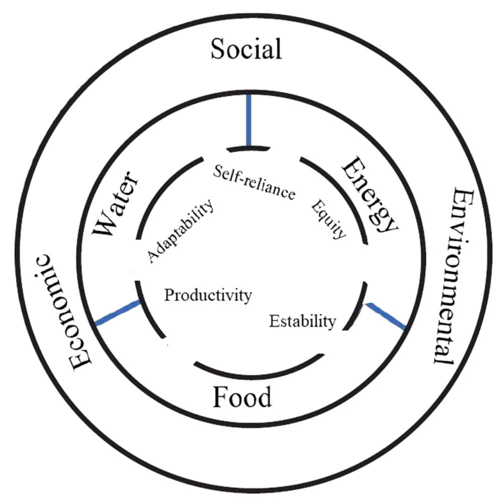

Fig. 3. Composition model of sustainability attributes for livestock systems from the WEF Nexus.
Source: Elaborated by the authors.

the five sustainability attributes (Adaptability, Self-management, Equity, Stability and Productivity) for the livestock systems of the Brazilian Pampa biome. The attributes were formed by allocating different WEF Nexus indicators (Table 1), determining the necessary capabilities of the systems to achieve sustainability. We emphasize that the weighting of the indicators considered the challenges imposed by climate change and the potential loss of biodiversity and its impacts on the biome, thus motivating the definition of the relative importance of each indicator for the composition of each sustainability attribute.

3.1. Adaptability

The adaptability attribute was formed by indicators that express the ability of the production system to find stability after an adverse situation [8,9]. Table 2 presents the construction of the adaptability attribute, composed of one indicator of the water dimension, two indicators of the energy dimension, and four indicators of the food dimension. The indicator "existence of conservation practices" considers that using such practices will imply the system's adaptability to resist extreme events (excess or scarcity of rain). In excess rainfall, the system will resist degradation to erosive processes by controlling surface runoff. In the absence of rain (droughts), the system will resist by increasing infiltration and water storage in the soil. This indicator assumed a relatively high value to the others due to the fragility of the soils to erosive processes and the frequent occurrence of droughts that significantly impact economic activities in the region.

The energy dimension contributes to the indicator's "generation" and " grid". Thus, when the farm has its electricity generation, regardless of the source, it will suffer less with any adverse situation, maintaining production capacity. Regarding the energy grid, the more independent of the electrical distribution grid the property is, the greater the adaptability to adverse situations.

From the food dimension, the indicator "productive diversification" refers to the number of activities the farmer develops in his production system. Therefore, the more dependent a system is on a single activity, the greater its economic and production risk. On the other hand, the more productive activities are being developed, the greater the system's capacity to adapt to adversities.

To measure the relationship of the production system with the markets, the indicator "structure and commercialization chains" was created, composed of indicators for market structure and commercialization chains. This indicator aims to measure how the production system is associated with markets, especially the ability of the producer to form or negotiate prices and its proximity to final consumers. It also considers the market structure, i.e., whether this system's main product has few or many buyers. Thus, it is a crucial indicator because in any adverse situation, the closer to the consumer or the more significant the producer's ability to negotiate or set market prices, the faster it adapts to market instabilities.

The "support organizations" indicator measures the degree of relationship between farmers and organizations in the sector, such as universities, research and extension agencies. In adverse situations, the organizations help farmers search for productive stability more quickly than other systems that do not have this relationship. The "succession/transmissibility" indicator measures the successor's existence and capacity to manage the productive system, besides the measure of area to be transmitted to each heir. If there is the possibility of succession, the greater the predisposition of the farming system to adapt to instability.

3.2. Self-management

The self-management attribute was formed by indicators that express the capacity of the production system to regulate and control its relations with the external environment [8,9]. Table 3 presents the construction of the self-management attribute, composed of two indicators of the water dimension, two of the energy dimension, and three of the food dimension. The indicators of water quantity and quality were grouped into "water for human consumption", emphasizing the importance of water for people to remain in the communities, avoiding rural exodus. Similarly, the indicators of water for production and efficiency of use were grouped under "water use efficiency for production", which combines water availability with the ability to manage the resource, reflecting the system's capacity in its self-management. Again, the two indicators in the water dimension assume a high relative proportion due to the essential condition of water availability for the community's well-being and farmers' welfare.

In energy, the "generation" indicator relates to the system's independence from the external source of electricity. Consequently, the more generation there is in the system, the less dependent on the consumption of energy coming from the power distribution company. The "thermal energy use and source" indicator is the grouping of the indicators for this type of energy. Its principle is that of energy independence. In other words, the origin of thermal energy is valued, especially that which is not causing environmental problems (the use of renewable forests, for example).

The "management and capital flow" indicator was formed from the food dimension by combining the economic management and capital flow dependence indicators. It seeks to represent the economic self-management of the system. That is, the greater the information about the capital generated, the greater its independence from the external financial system. The "management of the production system" indicator incorporates all the management of agricultural and livestock activities developed in the farm from the efficiency point of view. The better the management, the lower the dependence on external inputs. The indicator "Participation and social environment" was formed by grouping the indicators of social and associative participation, tradition and culture, and support organizations, which indicates that if the property is proactively inserted in the external environment, it will be better able to make decisions about its self-management.

Table 2
WEF Nexus indicators that compose the adaptability attribute.

Nexus	Indicator	Weight
Water	Existence of conservationist practices	30
Energy	Generation	25
	Grid	10
Food	Productive diversification	15
	Structure and commercialization chains	10
	Support organizations	5
	Succession/transmissibility	5

Source: Research data.

Table 3
WEF Nexus indicators that compose the self-management attribute.

Nexus	Indicator	Weight
Water	Water for human consumption	15
	Water use efficiency for production	25
Energy	Generation	15
	Thermal energy use and source	15
Food	Capital flow and management	10
	Production system management	15
	Participation and social environment	5

Source: Research data.

3.3. Equity

The capacity of the production system to fairly distribute the benefits and costs resulting from managing its natural resources is measured through the Equity attribute [8,9]. The attribute comprised two indicators from the water dimension, three from the energy dimension, and four from the food dimension (Table 4).

On the watershed scale, water availability depends on more than just

Table 4
WEF Nexus indicators that compose the equity attribute.

Nexus	Indicator	Weight
Water	Water for human consumption	15
	Water for production	15
Energy	Generation	10
	Consumption	15
	Thermal energy use and source	10
Food	Social and associative participation	5
	Cooperation in the markets	10
	Economic management	5
	Self-consumption and direct sale	15

Source: Research data.

the activities developed on the farms but also on the micro basin in which the property is located, both in terms of receiving or generating benefits. Thus, if a farm has a good soil and water management and conservation system, the water quantity and quality of all the farms located downstream in the watershed will benefit. Otherwise, problems may be related to the quality and quantity available in the watershed. These problems are reflected in soil and water degradation processes, either by its excess and lack of practices aimed at its control or by the scarcity of this natural resource that will hinder its access to plant growth and animal and human watering. Thus, the "water for human consumption" and "water for production" indicators express what was previously discussed.

In energy, the "generation" indicator demonstrates the farm's capacity to generate benefits by producing renewable energy, either by reducing its external dependency or sending energy to the grid to benefit other consumers. The same logic for the "consumption" indicator linked to resource management efficiency can be explored. For example, reducing energy consumption on the farm through energy efficiency actions favors access to other consumers. Similarly, with the indicator "use and source of thermal energy", the more thermal energy is used from renewable sources, the lower the electricity use will be, with positive internal and external effects on the farm. In this case, alternatives such as rice hulls and biodigesters can be considered in addition to firewood from forested forests.

In the food dimension, it is also considered that managing its resources and generating benefits through its products for society is an important social aspect. That is reflected in the indicator "social and associative participation". Farmers more involved in social entities generate more equitable benefits in the local communities. Also, the "cooperation in markets" indicator is important because it reflects the ability of farmers to cooperate within market structures for greater bargaining power, price determination, and scale of production, generating mutual benefits. In the "economic management" indicator, the better and more efficient the use of capital, the greater the social benefit, avoiding the inefficient use of resources, especially those linked to rural public credit. Finally, the " self-consumption and direct sale " indicator relates to production. If the farm consumes food from its system and, at the same time, can commercialize it in more direct channels to the consumer, the system will generate more equitable benefits.

3.4. Stability

The stability attribute is formed by indicators that express the capacity of the production system to return to its production potential after suffering disturbances and maintain constant productivity generated over time [9]. Thus, stability is the attribute with the highest number of indicators, with four coming from the water dimension, four from the energy dimension, and eight from the food dimension, as shown in Table 5.

In the water dimension, "water use efficiency" and "the existence of conservationist practices" are fundamental for the stability of the production systems by incorporating practices that contribute to the efficient use and management of water, as previously discussed. Also, avoiding soil loss via erosion is fundamental for the stability of the production systems. Thus, the indicator "perception of the erosive process" was incorporated. On the other hand, "drought susceptibility" is an important indicator when aiming to return to its production potential after suffering disturbances, especially from climatic phenomena.

Regarding energy, the indicator "fossil fuel" was included because it considers the intensity of use, access and storage of fuel, contributing to stability and avoiding decreased production due to lack of electricity. The "generation" indicator is important because renewable energy sources have an estimated duration of more than 20 years, bringing stability and security to energy use. The "grid" indicator provides the base for the development of all activities and is essential to support the demands of different energy inputs of the production systems. The "use and source of thermal energy" is essential for human welfare and the production process, considering the origin of the raw material used.

The contribution of the indicators of the food dimension to the stability attribute is very expressive. The indicators of cattle raiding, dependence on external inputs, availability of labor and succession/transmissibility directly affect the system's stability.

The mixed indicators "welfare", "market structure", "production system management", and "participation and social environment" are several aggregate indicators in their composition. Welfare refers to the situation of the farm in terms of infrastructure, logistics, and conditions that allow comfort both at a personal level and at work. These elements are considered necessary for the maintenance of the farm over time. Another critical factor is the relationship between the production activities and the commercialization of their products, determined by the "market structure" indicator. The "management of the production system" is fundamental in the maintenance of the activities developed in the farm, generating its success or failure. Finally, the indicator "participation and social environment" brings together the social interaction of the farm with its external environment, as well as the tradition and culture in the activities developed.

Table 5
WEF Nexus indicators that compose the stability attribute.

Nexus	Indicator	Weight
Water	Water use efficiency	10
	Existence of conservationist practices	10
	Perception of the erosive process	4
	Drought susceptibility	4
Energy	Fossil fuel	4
	Generation	4
	Grid	10
	Thermal energy use and source	4
Food	Cattle raiding	4
	Welfare	10
	Dependence on external inputs	4
	Availability of labor force	4
	Market structure	10
	Production system management	10
	Participation and social environment	4
	Succession/transmissibility	4

Source: Research data.

3.5. Productivity

The productivity attribute is formed by indicators that express the capacity of the production system to generate the required level of goods and services, represented by the gains in a given time [8,9]. In the productivity attribute, two indicators were selected from the water dimension, four from the energy dimension, and three from the food dimension, according to Table 6.

The importance of water in productivity is indicated by the indicators "water for production" and "water use efficiency". Water for production is vital in the system as a primary element in any productive

Table 6
WEF Nexus indicators that compose the productivity attribute.

Nexus	Indicator	Weight
Water	Water for Production	10
	Water use efficiency	20
Energy	Generation	5
	Grid	5
	Pumping	10
	Fossil fuel	10
Food	Production system characteristics	20
	Availability of labor force	5
	Market structure	15

Source: Research data.

farm. In turn, water use efficiency deals with water management and should be considered to maximize productivity by minimizing its use. The Pampas region has a rainfall regime significantly lower than other regions of the state of Rio Grande do Sul. Because of this, it is restrictive to the development of production systems more demanding in water availability.

In the energy dimension, own generation can reduce the cost of electricity and add value to your product by using renewable sources through a product with a green label. The better the reliability and quality of the grid power, the better the conditions to achieve productivity in the system. As for pumping", the issue of water use in production systems is directly linked to productivity, especially in the case of irrigated rice cultivation in the Ibirapuitã river basin in the Brazilian Pampas. The "fossil fuel" is an important indicator because it indicates its intensity of use in the production system.

The efficiency in generating results from productivity gains is materialized in the indicators of the food dimension. The composite indicator "characteristics of the production system" aggregates all indicators related to the management of animals and crops, as well as the productive diversification on the farm. The indicator "availability of labor force" points to the quality and quantity of human resources for production, directly affecting farms' productivity. Another composite indicator linked to productivity is "market structure", which indicates how the system's products relate to consumer markets regarding marketing channels, local sales and consumption, value-added, and access to public policies. Therefore, livestock systems tend to gain productivity when they present greater market efficiency.

3.6. Sustainability attributes of the WEF Nexus for the livestock systems of the Brazilian Pampa

The development of sustainability attributes made it possible to integrate various aspects of the WEF Nexus into the livestock systems of the Brazilian Pampa biome. Thus, applying the questionnaire in 121 livestock farms, the indicators were measured and formed the scores of the sustainability attributes presented in Table 7. Therefore, the closer to 100, the greater the capacity of the livestock systems to achieve sustainability in that attribute.

The attributes self-management and productivity achieved the highest scores and did not differ from each other but differed from the rest. On a second level, the attributes of adaptability and stability did not differ among themselves but differed from the others. Moreover, the attribute with the lowest score and significantly different from the others was equity ($p<0.05$). Similar results were also found in livestock systems in Spain [11,12,28] and Chile [16], which may determine a global pattern of these systems: the antagonism between sustainability levels of productivity and equity attributes in livestock production.

The livestock systems of the Ibirapuitã river basin in the Pampa of Brazil present high levels of sustainability related to self-management and productivity. In the case of self-management, the systems present the capacity to regulate and control their relationships with the outside environment. For productivity, the results indicate that the farms can generate the required level of goods and services, represented by the gains in a given time. Thus, we can affirm that the production systems practiced in the basin present satisfactory product performance. These results align with the findings of Nicoloso et al. [15], who found high sustainability in the productivity attribute in two groups of production systems in southern Brazil.

Table 7
Scores of the different sustainability attributes of the livestock systems in the Ibirapuitã river basin of the Pampa biome in Brazil.

Attributes	Sustainability score*
Self-Management	72,31^{a}
Productivity	70,37^{a}
Adaptability	66,66^{b}
Stability	65,85^{b}
Equity	62,75^{c}

* Different letters indicate a significant difference between means by Tukey's Test ($p<0.05$).

Source: Research data.

The data from these two attributes demonstrate that the elements of the triad water, energy and food are used efficiently in the livestock systems of the biome in order to generate self-sufficiency and income gains. Intermediately, we find the attributes of adaptability and stability. According to Masera et al. [8], stability refers to the capacity of an agroecosystem to return to its production potential after suffering perturbations and to keep the productivity generated constant over time. Adaptability refers to the agroecosystem's capacity to find stability after an adverse situation. The attributes interact directly. For a system to adapt to new climatic conditions, for example, it must be able to find stability after perturbations to its production system. Therefore, a system that does not find productive and organizational alternatives in the face of climate change and biodiversity loss will not find stability and, in turn, will not adapt to the new conditions, which could result in the end of the livestock system.

For Ripoll-Bosch et al. [13], stability and adaptability are critical attributes in understanding how farms can face changes in the future. Therefore, WEF Nexus elements of livestock systems in the Pampa biome may not be able to return to their initial characteristics after facing productive, economic, and/or climatic instabilities. In terms of energy, the use of biofuels [29] can help improve the stability of systems. However, it must be stressed that the growing use of biofuels has developed a direct competition with global food, energy and water resources [30]. Thus, an alternative to increase the sustainability of this nexus is the pursuit of the production of bioenergy from agro-industrial waste [31,32].

With the lowest sustainability score, we find the equity attribute, which means that the livestock systems have a low capacity to distribute fairly the benefits and costs resulting from managing their natural resources. Therefore, the benefits and costs inherent to using elements of the WEF Nexus in production systems are not shared appropriately with society, translating into a distancing of the farms' production from the local communities, with limited cooperation and social participation. This fact can increase the distance between the rural and urban environments, aggravating these two realities' economic and social disparities.

Among the social, economic and political factors that contribute to unequal distribution are: i) Land concentration; ii) Unequal access to knowledge; iii) Few or almost non-existent public policies targeted at Brazil's Pampa biome; iv) Deficient infrastructure (roads in bad condition, lack of access to education and health in the rural areas, lack of rural public transport). All these factors end up having an unequal influence on people who have access to different resources. As strategies, it can be said that it is necessary, first of all, to highlight this reality in the different structures of society (political, governmental and producer representation) and to establish awareness and forms of joint action in order to mitigate the unequal distribution of priorities.

Fig. 4 presents the WEF Nexus' contribution to each sustainability attribute of the sampled livestock systems. Although the food dimension has the most significant weight in the composition of most of the attributes, it is evident that in the reality of the livestock systems of the pampa biome, food production is the one that contributes minor to the sustainability scores of the attributes, except for stability.

This lower contribution is fundamentally associated with low social and associative participation of livestock systems and their limited articulations in favor of more efficient marketing channels. The marketing indicators showed the lowest values. This is because livestock systems in the Pampa biome have low value added to their products, long commercialization chains and low negotiation power. In order to improve this situation, farmers should look for alternatives such as: i) establishing marketing cooperation in order to increase their negotiating

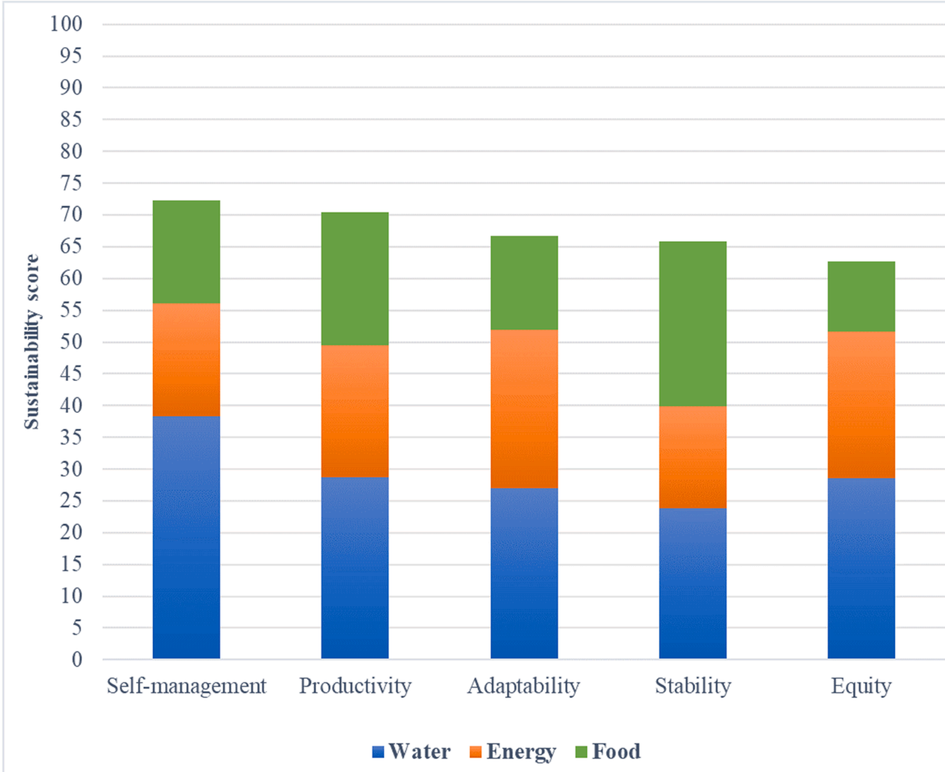

Fig. 4. Contribution of WEF Nexus in the sustainability attributes of livestock systems in the Pampa biome of Brazil.
Source: Research data.

power in the markets [33,34]; ii) seeking differentiation by informing consumers of their form of sustainable production in order to add value to the meat produced in the biome [35,36] and; iii) structuring short supply chains in order to get closer to the end consumer [37,38].

In turn, the water dimension plays a fundamental role in the sustainability of the systems, reaching the highest contribution in most attributes. The ability to control the water flows in the landscape is determinant to promote the increase of productivity and avoid soil degradation that will also influence the reduction of production costs and increase of production. As the food dimension is intrinsically dependent on the water dimension in both the production and degradation scopes, the attributes expressed the importance of managing water and soil resources for the welfare of society and the success of livestock production.

However, it should be pointed out that the only practice of surface runoff management in the livestock production system in the pampa biome is the construction of small reservoirs for animal watering. This practice aims to reserve water exclusively for animal watering during severe droughts when many intermittent streams dry up. Despite this, there are no practices to maximize the storage of water in the soil to maximize the system's productive capacity.

Despite the importance of small reservoirs for making water available to animals and humans, this practice alone is not enough to adapt production systems to the soil fragility of the pampa biome and climate change (severe droughts and extreme rainfall events). Managing surface runoff during periods of excess rainfall by maximizing infiltration and controlling runoff is fundamental to avoiding soil degradation through erosion and increasing the water availability in the soil and subsoil, which will be essential during periods of drought [39,40].

The permanent soil cover provided by grassland in livestock systems leads to the false perception that there is no need for runoff control practices, either to increase soil water availability to plants or to prevent degradation processes such as soil erosion, sediment yield or river contamination. Small reservoirs are essential for the sustainability of the livestock production system, but they are ineffective in controlling soil and river degradation processes related to runoff. In addition, it does not promote water availability for plants, which are also essential for feeding animals during periods of drought when pasture growth is drastically reduced. Other soil and water conservation practices are essential to control runoff and to increase productivity [41,42], such as terraces, buffer strips, detention dams, protection of hydrologically fragile areas such as wetlands and riparian forests, readjustment of roads, readjustment of paddocks.

Among production systems, livestock systems are more environmentally sustainable, especially in terms of water and energy. This is because beef cattle have been farmed extensively in the Pampa for over 300 years. However, when it comes to assessing sustainability in the food sector, the indicators show the lowest levels. Factors that prevent greater sustainability in this axis are: organizational factors, such as social and associative participation and cooperation in the markets; production factors, such as low diversification and limited economic management [43] and; marketing and consumption factors, such as concentration of production in just one product (beef) and long commercialization chains. About the obstacles, it can be stated that: a) Production technology already exists to improve the production of beef cattle systems based on native grasslands, which, if applied, would increase production and improve the low economic sustainability indicators. What is needed to break down this obstacle is for this knowledge to reach the sector's technicians and producers; b) In the last 15 years, new activities have emerged in the region [44,45] and are being presented as new alternatives for local producers, which would diversify production and increase the sustainability of the food axis; c) New organizational forms, such as the *Alianza del Pastizal* [46], can be an alternative to bring together producers with a common goal - sustainable meat production in the biome. New arrangements can bring improvements in organizational factors, increasing the sustainability of the systems.

Livestock systems in the pampa biome need to be better diversified. Diversification occurs only within animal species (cattle and sheep) and by substituting natural grassland areas for soybean or rice crops. This is an intrinsic characteristic of production systems in southern Brazil. As Vasconcelos et al. [47] point out, livestock systems in the pampa biome, developed extensively and efficiently, can contribute to reducing greenhouse gas emissions and, simultaneously induce the intensification of food production. Contrary to what occurs with intensive livestock in other parts of the world [48,49]. In this way, livestock systems would act in synergy with the local biome, promoting the maintenance of services related to the conservation of water resources, pollination and the provision of genetic resources that contribute to the development of the economy [47]. However, the authors highlight the potential for off-farm diversification, such as rural tourism. In a study in the pampa biome of Brazil, Cipolat and Bidarte [50] demonstrated that rural tourism was a viable activity and an income supplement with development potential for the region. In addition, Weyland et al. [51] state that rural tourism is a form of productive diversification that generates additional economic income for farmers and can encourage biome conservation. Thus, agroecosystems could provide a greater variety of ecosystem services, achieving their multifunctionality and sustainability.

Therefore, as recommendations for livestock systems in Brazil's Pampa biome, we can point to alternatives evidenced in the study by Escribano [52]. Productive diversification in farms is an alternative for retaining people in rural areas, generating higher equity in the systems. Furthermore, greater attention to the economic management of livestock farming will enable greater efficiency in marketing products, generating market opportunities and increased social interaction.

4. Conclusions

This study allowed the integration of the sustainability assessment of farming systems with the WEF Nexus approach. The proposal 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.

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.

In the case of livestock systems in the Pampa biome, there are some thoughts for decision-makers and stakeholders: a) The need for specific public policies for this region of Brazil; b) Encouraging the development of producer associations to obtain new technologies and knowledge, negotiating power and joint marketing; c) Creating differentiation strategies for beef produced in the Pampa biome. Green meat labels linked to environmental preservation can differentiate meat from the Pampa from other meats produced in Brazil; d) Introduce productive diversification on farms, exploring new alternatives in the region, such as fruit, wine, olive growing, and rural tourism.

Funding

This research was funded National Council for Scientific and Technological Development (Conselho Nacional de Desenvolvimento Científico e Tecnológico, CNPq, projects 441428/2017-7 and 428709/2018-4)—Brazil.

CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors acknowledge the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for providing financial support for this work. We acknowledge Prof. Dr Fernando Luiz Ferreira de Quadros (in memorian) for his essential participation in the Nexus-Pampa project and the research results.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nexus.2023.100248.

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