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Water–Energy–Land–Food Nexus to Assess the Environmental Impacts from Coal Mining

Reginaldo Geremias [1] and Naoki Masuhara [2,*]

[1] Department of Energy and Sustainability, Federal University of Santa Catarina, Araranguá 88906-472, Brazil; reginaldo.geremias@ufsc.br
[2] School of Human Science and Environment, University of Hyogo, Himeji 670-0836, Japan
* Correspondence: nmasuhara@shse.u-hyogo.ac.jp

Abstract

The water–energy–land–food (WELF) nexus is an established framework that allows for a more holistic, systemic and integrated analysis of resources and territorial planning. The main objective of this study was to apply the WELF nexus approach to assess the environmental impacts from coal mining. Data on the water resource, electricity sector, food production and land occupation in the coal region of the Urussanga River basin (Brazil) were described and compared with the area without the coal industry (Canoas/Pelotas basin, Brazil). Indicators evaluating reliability, robustness, equilibrium and diversity (Shannon index-H) were used to evaluate the impacts of mining on the WELF system. The results indicate that coal provides socioeconomic development in the region; however, it has several negative environmental effects. WELF indicators showed that the Urussanga basin has less robustness in the subsystem of water consumption per capita (0.19), installed electrical capacity (0.01) and agricultural production per capita (0.22) compared to Canoas/Pelotas at 0.73, 1.0 and 1.0, respectively. The basin also presented lower diversity in the water consumption sector (H = 0.81) and in the variety of agricultural products (H = 1.58) compared to Canoas/Pelotas (H = 1.0; H = 1.69, respectively). It was concluded that coal mining can affect the WELF system globally, revealing the need to propose alternatives to prevent and mitigate its effects.

Keywords: water–energy–land–food nexus; coal mining; river basins assessment; Brazil

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Academic Editor: Dong Jiang

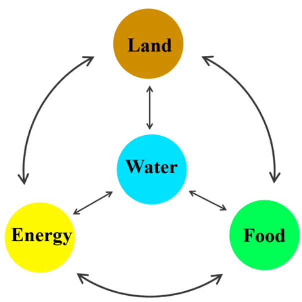
Received: 24 May 2025
Revised: 20 June 2025
Accepted: 23 June 2025
Published: 26 June 2025

Citation: Geremias, R.; Masuhara, N. Water–Energy–Land–Food Nexus to Assess the Environmental Impacts from Coal Mining. *Land* **2025**, *14*, 1360. https://doi.org/10.3390/land14071360

1. Introduction

The demand for water, energy, food and land use has been increasing, due to the increase in the global population, rapid urbanization, changing diets, economic growth and climate change [1]. In this context, the need for sustainable food production, overcoming water scarcity, resolving energy crises and mitigating environmental pollution have emerged as critical challenges [2]. The Sustainable Development Goals (SDGs) of the 2030 Agenda effectively encapsulate these challenges. According to the United Nations SDGs report 2022 [3], more than 733 million people live in countries with high and critical levels of water stress, and in the last 300 years, more than 85% of the planet's wetlands have been lost. Data indicate that 733 million people do not have access to electricity and 2.4 billion people still use inefficient resources and polluted cooking systems. About 1 in 10 people around the world are suffering from hunger, and about 1 in 3 people do not have regular access to adequate food. Furthermore, around 90% of global deforestation is due to agriculture, with 49.6% from agricultural land expansion and 38.5% from livestock grazing. Therefore, the United Nations and specialized agencies suggest actions for global development towards a sustainable and resilient society.

At the global and local levels, there is recognition of the interconnection between the elements of water, energy and food. Water is essential for food production and hydropower generation. Energy is needed to transport and treat water, produce fertilizers and harvest and cook food. Sugarcane and corn crops can be used to produce biofuels. Any limitation on the inputs of one of these components disrupts the quantity, quality and access to the others [4,5]. The water–energy–food (WEF) nexus approach emerged in 2011 and proposed a synergistic interaction and greater governance between the dimensions of its elements. It offers an interdisciplinary approach that addresses the complexity of the connections between water, energy and food resources systems and sectors, highlighting trade-offs and synergies. In addition, it has a transdisciplinary dimension, which promotes cooperation with different groups of stakeholders and improves governance across sectors in the development of government policies [6]. The approach aims to balance the social, environmental and economic dimensions of sustainable development. To achieve the expected results, it requires the involvement of a wide range of social actors, the improvement of institutional arrangements, the implementation of alternative technologies and the development of intelligent indicators for monitoring the process [7]. Studies have added the soil element to the existing knowledge of the WEF nexus approach, forming a system called water–energy–land–food (WELF) (Figure 1). This is due to factors such as the use of large areas in the production of biofuels, which has increased the land–energy connection [8]. In addition, changes in land use can affect natural runoff processes and the water cycle, with consequent erosion events. Food production can be compromised by soil degradation, while the expansion of food cultivation converts non-agricultural land into arable land. The extraction and processing of fossil fuels, such as coal, also has detrimental effects on land. Therefore, the water, energy, land and food systems are interdependent and interact with each other, forming a complex coupled system [9].



Nexus units	Connections
W ↔ E	• Water for hydroelectric power, biofuel and coal production • Energy for water extraction, distribution and treatment and its reuse in the coal industry
W ↔ F	• Water for irrigation and food production in agriculture and horticulture, fish farming, livestock farming and their by-products
W ↔ L	• Water for moisture and transport of nutrients to soil • Land for surface runoff and water storage in aquifers
E ↔ F	• Energy for food production, processing, transportation and cooking • Food as fuel for thermal energy and biomass for biofuel production
L ↔ F	• Land for food production • Food waste for the production of biofertilizers and soil nutrients
L ↔ E	• Land for photovoltaic and wind farms, hydroelectric reservoir and coal industry installation

Figure 1. Water–energy–land–food (WELF) nexus (Source: Authors' illustration).

Several indicators are used for the qualitative and quantitative analysis of the WELF system, with different perspectives. Among them are indicators focused on three dimensions: reliability, robustness and equilibrium. The reliability evaluates the abundance of resources within the subsystem. The richer the resources, the greater the corresponding reliability, providing adequate resource guarantee for the sustainable development of the WELF system. The robustness characterizes the efficiency of resource distribution and production in each subsystem. The higher the efficiency, the greater the corresponding robustness, making the sustainable development of the WELF system less susceptible to external disturbances. The equilibrium is used to characterize the degree of coordination between pairs of subsystems, reflecting the conversion efficiency and impact between subsystems. The greater the coordination, the more balanced the subsystems are, making the development of the WELF system less susceptible to competition and internal conflicts [9]. Another indicator is the Shannon index (H) or a variation of it to assess a diversity. Studies have used this index, for example, to analyze energy and crop diversity and water quality. The higher the value of H, the more diverse the system [10–12]. In this context, this index can serve as a tool for analyzing the diversity of water and energy resources and their different consumption sectors and the diversity of agricultural and livestock food products, as well as land use and occupation.

Coal is one of the world's main sources of non-renewable primary energy. In 2023, global coal demand increased to a record 8687 Mt, marking an annual growth of 2.5%. Furthermore, the low hydroelectric production fueled the demand for this source in energy generation, causing an increase of 2.5%, equivalent to 5855 Mt. Its use for non-energy purposes grew 2.3%, reaching 2833 Mt [13]. In Brazil, the coal industry is concentrated in its southern region, with the state of Santa Catarina being the second-largest producer of the mineral, which majority use is for energy purposes [14]. Although the sector is of social and economic importance in the state, studies show that mining causes several negative impacts on the biotic and abiotic environment. Among the most affected areas is the Urussanga River basin. In this basin, mining waste has been compromising the quality, quantity and different uses of water and soil, including public supply, food production and the potential for energy generation [15]. However, there are still a few studies that address the effects of mining on the water, energy, food and land subsystems in a global and integrated way. The nexus approach and its correlation with coal mining has been used but focusing on specific subsystems.

Simpson and collaborators applied the water–energy–food nexus approach and coal, focusing on competition for land [16]. In another study, the land–energy nexus was used with the incorporation of substance flow to establish a new model for coal life cycle analysis [17]. Wu and collaborators used the water–energy nexus approach incorporated into substance flow analysis and life cycle assessment for cities with coal resources [18]. In Brazil, the approach has been directed towards qualitative aspects with a focus on the biofuels sector [8,19].

The main objective of this study was to apply the water–energy–land–food nexus approach to assess the environmental impacts from coal mining in the system in a more global and integrated way. The reasons for choosing this study area and the WELF approach are the following: studies of the impacts of mining on water, energy, food and land subsystems are incipient at the study site; the local population has realized the risks of mining; coal activity has generated conflicts of interest involving representatives of the public and private sectors, academia, non-governmental entities and environmental movements and the WELF is a consolidated instrument and allows for a more holistic, systemic and integrated analysis of mining impacts. The period analyzed took into account the most up-to-date and consolidated official statistical data on water, energy, food, soil and coal resources in the study area. The data were obtained from technical reports prepared and published by the Brazilian government. The method used allowed a quantitative analysis of these data, which was fundamental for the application of the WELF nexus in evaluating the impacts of mining on its systems.

This work is relevant, because it aims to consider the global WELF system to investigate how coal mining activity can affect the balance of interrelationships between water, energy, food and land resources. It is also innovative, since research in the region has been limited to analyzing the impacts of contaminants on water resources and soil. Furthermore, in the study area, there have been few studies evaluating the effects of mining on the diversity, availability and occupation of different environmental matrices, using the indicators and metrics proposed here. It is also worth noting that national and local public policies for energy transition have been directed towards these mining areas, with a view to gradually replacing fossil coal with clean and renewable sources. However, for this process, the implications of the transition on the entire WELF system should be considered. In this way, these studies can suggest public policies aimed at water, food and energy security and the ecological protection of environments affected by coal mining.

2. Methodology

2.1. Study Areas

The state of Santa Catarina is located in Southern Brazil and is divided into 10 hydrographic regions (HRs), which are subdivided into hydrographic basins. In this study, a basin with coal industry presence and another without mining activity were selected for comparative purposes and a better assessment of the effects of mining on water–energy–land–food systems. The chosen mining area was the Urussanga River basin (Figure 2), located in the south region of the state and covering 10 municipalities (2 fully and 8 partially inserted). The total territorial area of the municipalities is 1666.485 km^2, and the population is 391,069 inhabitants, corresponding to an average population density of 226 inhabitants/km^2. Of this total, the basin occupies an area of 679.75 km^2 [20–23]. The coverage area has two climate types: Cfa—Clima Subtropical (mesotérmico úmido e verão quente), occurring in approximately 98.65% of the area, and Cfb—Clima Temperado (mesotérmico úmido e verão ameno). The total annual precipitation varies between 1100 and 1700 mm. The Urussanga River is the main surface water source, formed by the confluence of the Maior and Carvão Rivers, and subsequently receives water from 11 other rivers until reaching the estuarine environment. Surface water resources comprise approximately 1158 km of watercourses. The drainage density is 1.70 km/km^2, with an average flow rate of 12.1–113.4 m^3/s. In the coastal region, there are lake systems, notably the Urussanga Velha Lagoon, Lagoa do Réu Lagoon and Lagoa Bonita Lagoon. Regarding underground resources, 11 aquifer systems have been identified to date, with a total area of approximately 664 km^2 and underground availability from active reserves estimated at 0.145–0.21 km^3/year. The region presents a great lithological variation, which physical and chemical weathering generates several classes of soils: Clay soils (48.67%), Gleysols and Plinthosols (17.38%), Cambisols (16.33%), Red-Yellow neosols (5.97%), Marine neosols (4.27%), Dunes and Sand on beaches (3.46%), Spodosols (2.27%) and Organosols (1.65%). Land use is mainly forestry, agricultural activity and urbanization. Agriculture. In the region, small rural properties prevail, and the main food products grown in agriculture are corn, rice, cassava, sugar cane, watermelon, potato, banana, soy, grape, passion fruit, peach, orange, tomato, bean, wheat, pineapple, onion, persimmon, guava and nuts. In horticulture, the planting of cabbage, strawberry, lettuce, carrot, beetroot, broccoli, pepper, chives, cauliflower, zucchini, kale, cucumber, parsley, chard, arugula, chicory, chayote, watercress and chicory stands out. Other economic activities are forestry production; aquaculture; livestock; industry (mining, ceramics, plastics, metallurgy, mechanical engineering, electrical equipment, paper and cardboard packaging, furniture, construction, clothing, food and beverages); retail and wholesale trade [24,25]. The basin's main energy resources are coal, followed by water sources that supply small hydroelectric plants, as well as plant biomass and, to a lesser extent, solar energy used in industrial, commercial and residential projects. The basin is located in a region of coal deposits, the mining of which has left a major environmental liability with the degradation of soil, water resources and ecosystems. It is estimated that an area of 903 ha and a watercourse of 265 km are impacted by coal activity. In addition, there are a large number of abandoned mines, which are responsible for a high contaminant load, even reaching the estuarine environment [22,26]. The area without coal mining selected was the Canoas/Pelotas Rivers basin, located in the central portion of the state (Figure 2). This region was chosen for comparative purposes, because its environmental matrices (water, soil and air) present better quality and preservation of their attributes in the state of Santa Catarina. In addition, it has lower risks of impacts from human activities, and its energy resources are mainly from renewable sources. It covers 32 municipalities and has a total area of approximately 22,248 km^2 and a population of 438,010 inhabitants, corresponding to a population density of 19.7 inhabitants/km^2 [27]. The climate is characterized by the Cfb type in the largest portion of the basin (96.46%), with average temperatures below 22 °C in the hottest month. The remainder of the basin (3.54%) is of the Cfa type, defined by average temperatures greater than 10 °C in the coldest month and greater than 22 °C in the hottest month. The total annual precipitation varies between 1100 and 2100 mm. Its surface water resources include the Canoas and Pelotas Rivers and their tributaries, which have approximately 47,000 km of watercourses. The drainage density is 1.14–2.85 km/km^2. The groundwater resources are formed mainly by a free to semi-confined aquifer system of regional extension and fractured, discontinuous, heterogeneous and anisotropic. They occupy approximately 22% of the basin area and are considered to have good productivity, with flows between 5 and 40 m^3/h and static levels ranging from 5 to 30 m. Regarding soil types, the predominant classes are Humic Cambisol and Litholic Neosol, which correspond to 41.74% and 33.68% of the total area of the Canoas River basins and Santa Catarina tributaries of the Pelotas River, respectively. Another common soil class in the region is the Bruno Nitossolo, which represents approximately 19.96% of the total area. The land is predominantly occupied by forests and agriculture. The region is dominated by small rural properties, and the main food products grown in agriculture are soy, corn, apples, wheat, onions, tomatoes, beans, potatoes, oats and garlic. In horticulture, the most important are carrots, cabbage, strawberries, lettuce, cucumber, zucchini, pepper, broccoli, cauliflower, chives, chard and arugula. Other economic activities are aquaculture and livestock. In the industry timber and forestry, manufacturing of alcoholic beverages, paper and cardboard packaging stand out [27]. Its main energy resources are of renewable origin, with emphasis on hydroelectric, biomass, wind and solar energy. Coal is not representative, and other fossil sources have very little contribution.

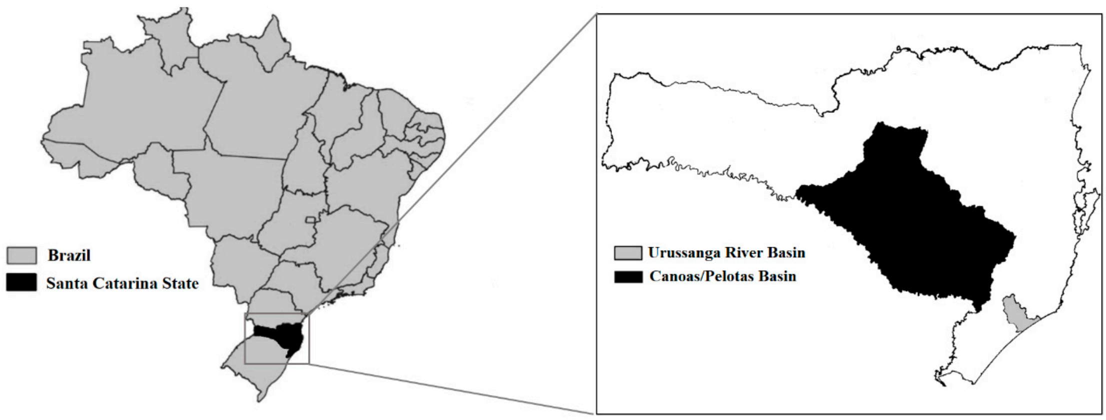


Figure 2. Study areas (Source: Authors' illustration based on [21,27]).

2.2. Data on Water, Energy, Food and Land

Data on surface water resources and consumption by sector in Urussanga (2019) and the Canoas/Pelotas (2023) basins were presented. The energy sector was described with information on installed power electricity by source in 2024. Data on food production (2022/2023 harvest) in agriculture, horticulture, fish farming and livestock were presented. Finally, the different uses of land were informed in Urussanga (2019) and the Canoas/Pelotas (2023) basins. Databases from the National Water Agency, Energy Research Company, National Electric Energy Agency, Brazilian Institute of Geography and Statistics, Agricultural Research and Rural Extension Company of Santa Catarina and Santa Catarina State Water Resources Information System were used. This information was relevant for the analysis of the interrelationships between water, energy, food and soil in the region.

2.3. Coal Mining and Environmental Impacts

The coal industry in the study region was described, focusing on estimated deposit reserves, the extraction process, beneficiation, coal products and by-products and their uses, as well as economic indicators of the sector. The main negative environmental impacts of mining that can affect the quality, quantity and different uses of water resources, food production and land quality and use were presented. The statistical data were sourced from reports published by the Coal Extraction Industry Union of the State of Santa Catarina and coal companies. The environmental impacts of mining are described in national and international articles of work carried out in the study regions. This information served as a basis for the application of the WELF nexus approach, focusing on the impacts of the coal industry.

2.4. WELF Nexus Application

The application of the WELF approach was used to compare the water, energy, food and land subsystems in the two basins and analyze how coal mining can affect them individually and the system as a whole. To this end, indicators focused on reliability, robustness and equilibrium dimensions were considered (Table 1).

Table 1. WELF system robustness, equilibrium and robustness indicators.

Subsystem	Indicator	Unit	Dimension	Reference
Surface waters	Annual water consumption per capita	1000 m^3/person	Robustness	[21,23,27,28]
	Annual water consumption per cultivated area	1000 m^3/ha	Equilibrium	[21,27,28]
Energy	Installed power electricity per capita	kW/person	Robustness	[23,29]
Food	Annual agricultural production per unit area	ton/ha	Reliability	[23,24]
	Annual agricultural production per capita	ton/person	Robustness	[23,24]
Land	Area degraded by coal mining	1000 km^2	Robustness Reliability Equilibrium	[21]

Due to the different units of measurement between assessment indicators, the raw data were standardized (Equation (1)) using the range normalization method, where Xij is the standardized result of the i-th data for the j-th indicator, x_{max} is the maximum value of the j-th indicator and x_{min} is the minimum value of the j-th indicator [9].

$$x_{ij} = \frac{x_i - x_{min}}{x_{max} - x_{min}} \quad (1)$$

To have greater data representativeness, the maximum and minimum values of each indicator were obtained from a total of 14 river basins in Santa Catarina, including those in the present study (Santa Catarina Water Resources Information System 2024). By representing all the results of the standardized indicators in radar charts, the unique characteristics of each river basin were identified. In this step, the Shannon index (H) was also applied to compare the diversity of four dimensions between the two basins: water consumption sector, electricity source, agricultural products and land occupation. For this, the data obtained in Section 2.2 were considered. The calculations were carried out using Equation (2), where *pi* represents the share of indicator i in the system [10].

$$H = \sum_{i} pi \ln pi \quad (2)$$

By integrating these indicators, a comprehensive analysis of the diversity of the resources and distinctive characteristics can be performed. This assessment makes it possible to propose actions that could be adopted for water, energy, food and land preservation security and indicate the future implications of mining activity in the region.

3. Results and Discussion

3.1. Water Data

The Urussanga basin comprises the rivers Maior, Carvão, Urussanga, América, Caeté, Cocal, Ronco D'Água, Linha Torrens, Linha Anta, Três Ribeirões, Lagoa da Urussanga Velha, Barro Vermelho, Ribeirão da Areia and Vargedo. The data indicates that the extension of the basin's watercourses is 1150 km. The annual water resources and consumption are 0.104 and 0.074 billion m^3, respectively, corresponding to a supply/demand ratio of 1:4 [21,28]. Canoas/Pelotas basin's main resources are the rivers Caveiras, Marombas, Correntes, Antoninha, Capivaras, Rio das Contas, Invernadinha, Lava Tudo, Vacas Gordas and Pelotinhas. The annual water resources are 2.043 billion m^3 and consumption is 0.155 billion m^3, which represent a supply/demand ratio of 13:1 [27]. The main sector of surface water consumption in both basins is agriculture (Figure 3), which has an estimated value of 0.106 billion m^3/year, followed by industry and human [23,29].

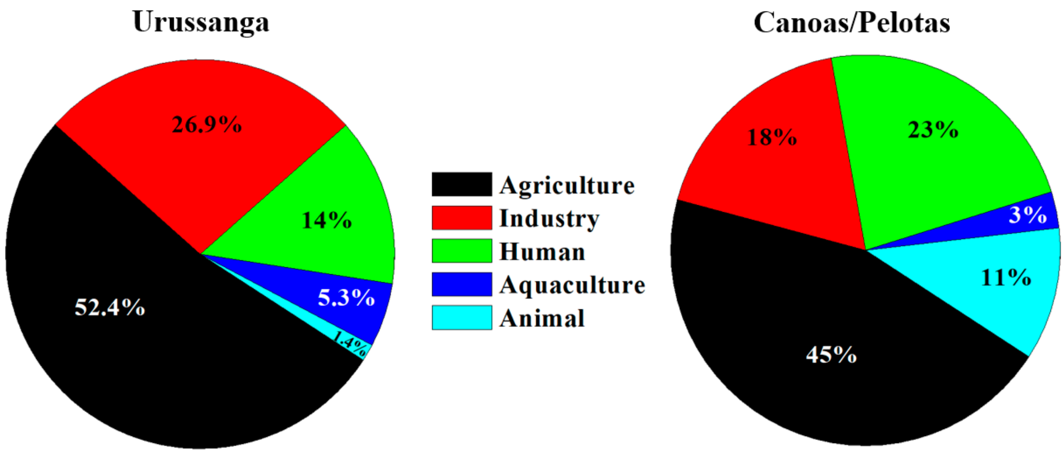


Figure 3. Water consumption by sector in the basins (Source: Authors' illustration based on [23,29]).

These data reveal that the supply/demand ratio for surface water resources in the Urussanga basin presents a significantly lower value (approximately 10 times), which demonstrates a lower availability of this resource for its different uses, with an emphasis on agriculture and industry consumption, revealing a potential impact on water security in the region. This profile can be aggravated by compromised water quality due to its contamination by waste generated by coal activities. Therefore, better planning of the distribution and use of water resources is necessary to meet the demands of different sectors.

3.2. Energy Data

Figure 4 shows the installed power electricity in the two basins. A fossil source is predominant in the Urussanga basin, followed by hydropower, biomass and solar, with values of 5740 kW, 4430 kW, 3766 kW and 308 kW, respectively. Wind energy is not utilized in this region. In the Canoas/Pelotas basin, the water source is very significant (1,216,617 kW), followed by biomass (131,836 kW), wind (83,114 kW) and solar (1146 kW), with low participation fossil fuel (143 kW) [29].

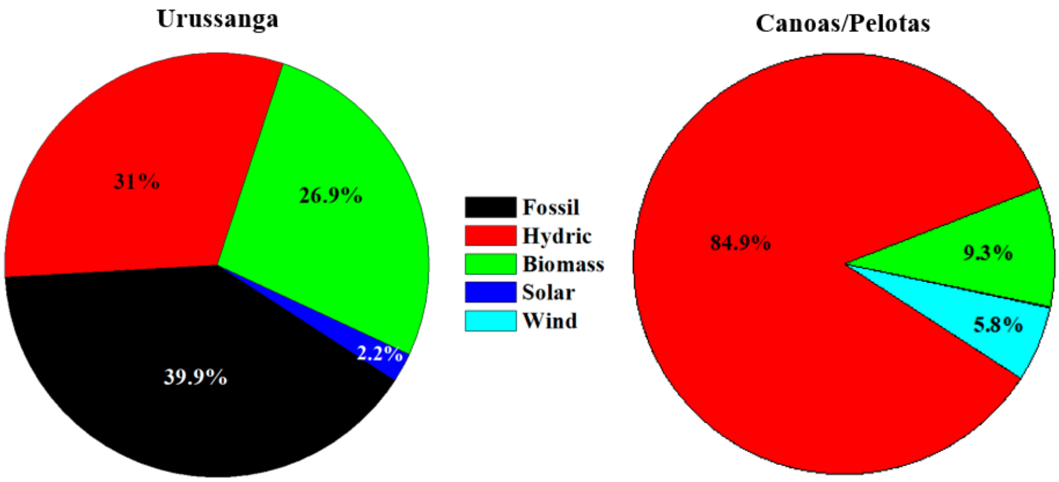


Figure 4. Installed power electricity by source (source: authors' illustration based on [29]).

It appears that the Canoas/Pelotas basin has a total installed capacity (1,431,567 kW) much higher than that of Urussanga (14,244 kW). Data from the National Electric Energy Agency [29] indicate that the Canoas/Pelotas basin also has a greater number of electrical generation enterprises in operation, totaling 55, compared to Urussanga, with a total of 24 enterprises. The hydric sector is much more representative of the Canoas/Pelotas basin, with 40 enterprises (72% of the total), when compared to Urussanga with 7 (29% of the total). The representation of this sector is also greater than in the state of Santa Catarina, which hydropower represents 58% of the total of all electrical energy enterprises. In turn, the fossil source is the most significant in the Urussanga basin (13 enterprises) when compared to the Canoas/Pelotas basin (1 enterprise). Furthermore, wind energy has the presence of five projects in the Canoas/Pelotas basin, being absent in Urussanga. From these data, it can be inferred that the Canoas/Pelotas basin expresses greater energy security in terms of installed capacity, with an emphasis on renewable sources. In the Urussanga basin, energy security is potentially lower and still has a significant dependence on fossil sources, including coal. Therefore, it is necessary to promote the increase in installed capacity and electrical energy in the region, with an emphasis on projects using clean and renewable sources.

3.3. Food Production Data

The annual food production data from agriculture (2022/2023 harvest) and horticulture (2016) in the two basins are presented in Figure 5. In the Urussanga River basin, a total of 487,170 tons of food was produced from agriculture. The main products were corn (50.4%), rice (12.4%) and cassava (11.9%). In horticulture, production was 3828 tons, with cabbage (19%), strawberries (17.4%), lettuce (16%) and carrots (13.4%) being the main products. In the Canoas/Pelotas basin, agricultural production was 2,272,847 tons, with the main products being soybeans (36%), corn (24.4%) and apples (23.2%). In horticulture, production was 17,567 tons, with the main products being carrots (34.4%), cabbage (29.2%) and beetroot (11.5%) [24,30].

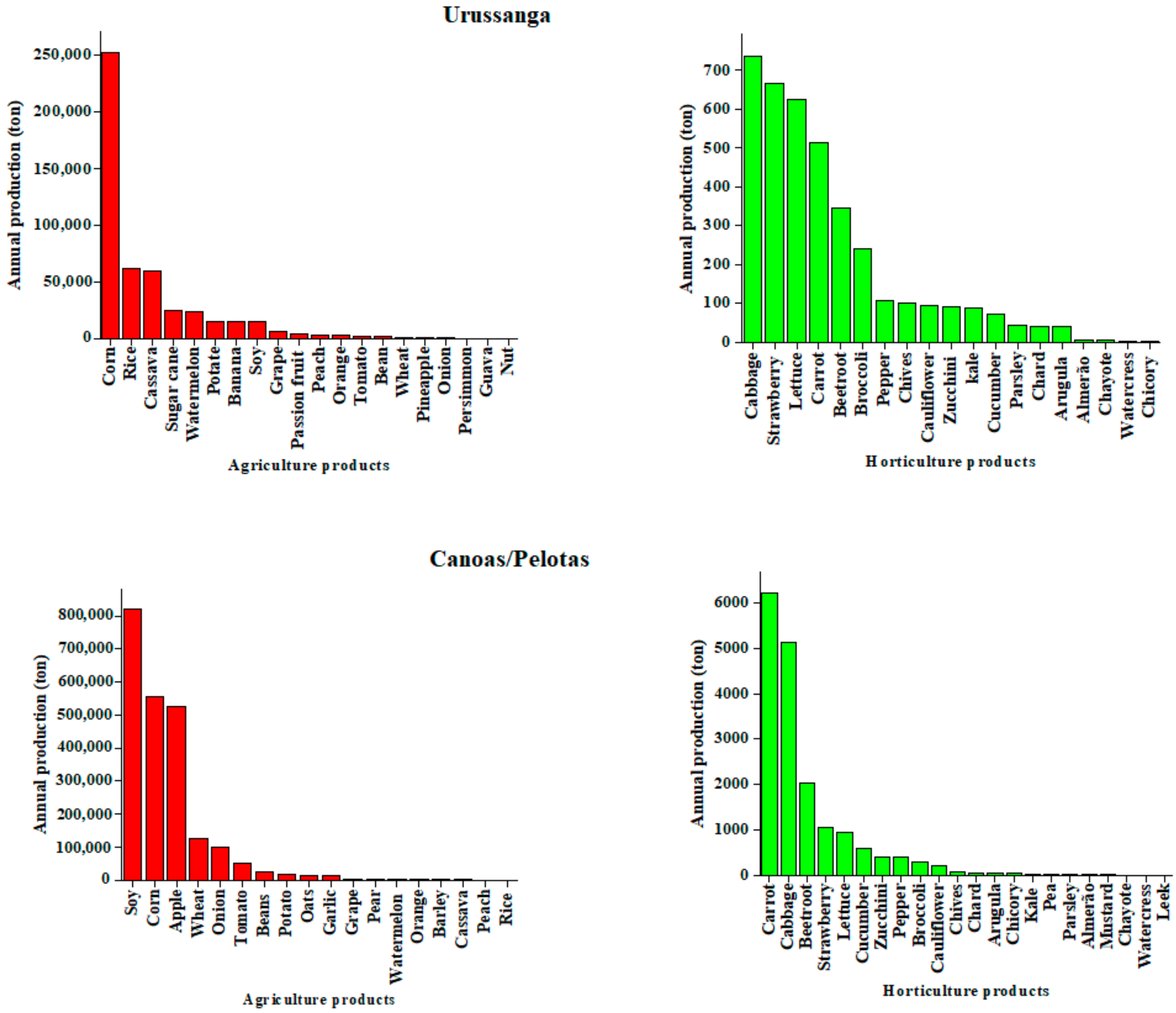


Figure 5. Agricultural (2022/2023 harvest) and horticulture (2016) production in the Urussanga and Canoas/Pelotas basins (Source: Authors' illustration based on [24,30]).

Livestock data (Table 2) demonstrate that chicken and egg production are the most significant in both basins. It is noteworthy that the production of pigs; cattle; fish and livestock products (milk, honey and eggs) is greater in the Pelotas/Canoas basin [24].

Table 2. Livestock products in the Urussanga and Canoas/Pelotas basins.

Products	Urussanga	Canoas/Pelotas
Chicken (unit)	13,848,927	12,471,196
Pig (unit)	81,742	610,874
Cattle (unit)	16,671	76,873
Fish (ton)	1045	2815
Milk (liter)	13,724,000	141,097,000
Honey (kg)	303,774	1,256,675
Chicken egg (unit)	55,860,000	183,948,000
Quail egg (unit)	78,504,000	32,256,000

(Source: [24]).

The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted. Agriculture and livestock data reveal production very concentrated in grains (corn, soy and rice) and chicken and its products in both basins. It is also noteworthy that many of these products aim to supply the export market. According to Santa Catarina Agricultural Observatory, of the total 7,197,706 tons of products exported in the state in 2024, chickens and pigs and their derivatives represented around 33%, and soybeans, corn, rice and their derivatives reached around 22% [22]. It must be taken into account that the state still has around 11% of the population with some category of food insecurity [31]. Therefore, it is necessary to diversify the food chain, as well as access to food in sufficient quality and quantity to meet the demands of the population, without harming the domestic and foreign markets.

3.4. Land Data

Land occupation data demonstrate that, of the total area of the two basins (22,900 km^2), forest represents the largest occupation (19,700 km^2), followed by agriculture (2500 km^2). The urbanized area, bodies of water and exposed soil resulting from mineral extraction total an area of approximately 675 km^2 [21,27]. When comparing the percentage of occupation between the two basins (Figure 6), the forest also stands out. It appears that agriculture, urbanization and exposed soil are more representative in the Urussanga basin (29% of total) in comparison to Canoas/Pelotas (12%). The area of forest and water bodies is greater in the Canoas/Pelotas basin.

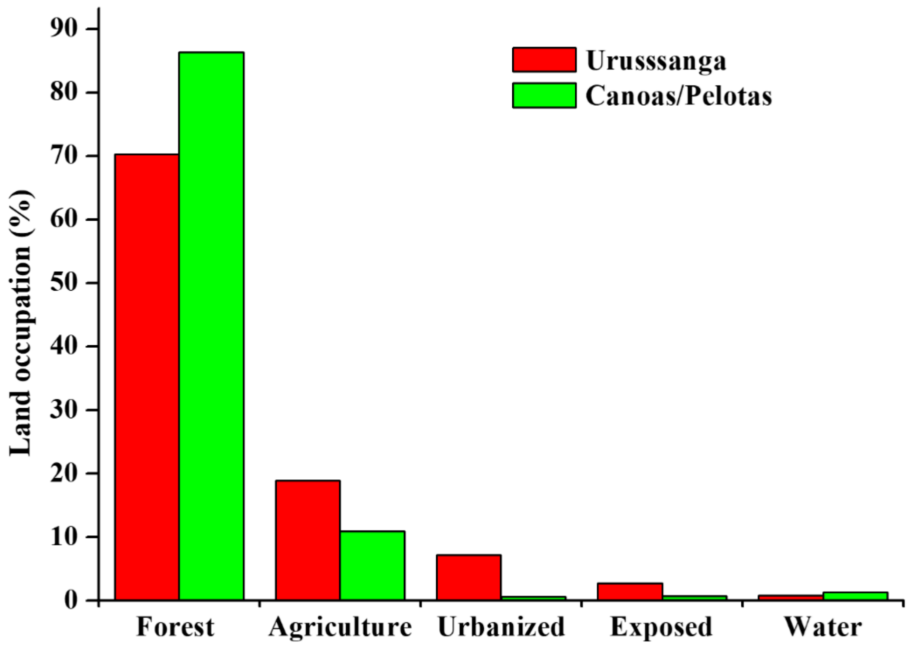


Figure 6. Land occupation in the Urussanga and Canoas/Pelotas basins (Source: Authors' illustration based on [21,27]).

Therefore, the data show greater anthropogenic action in the Urussanga basin, including coal activity, which must be taken into consideration in urban planning policies and equity in different land occupations and uses.

3.5. Coal Mining and Its Environmental Impacts

Several economic activities are developed in the Urussanga River basin, including the coal industry. The most recent data indicate that 1,453,019 tons of Run of Mine (ROM) coal and 556,404 tons of saleable energy coal were produced in the region in 2022. The main consumer sectors were thermoelectric (97.8%), mining (0.68%), ceramic (0.35%), coke (0.16%) and others (0.97%) [32]. However, it is worth noting that around 60% of the extracted ROM coal is discarded as waste with no great commercial value, which consists of sedimentary rocks, pyrite nodules and ash [26]. Other products from coal processing are coke, coal dust with a high volatile content, ground coal, dry fine coal and fluxing minerals. They are used in the steel, ceramics, glass, petrochemical, paper and pulp and food industries, among others. The processing of waste generates products that serve the market of foundries, sulfuric acid producers and the chemical industry in general. Afforestation and reforestation activities, plant-strengthening products and animal nutrition have also been developed by the coal industry [32]. Although coal mining contributes to the socioeconomic development of the region, the activity has caused several negative impacts on the environment and health, as well as accidents and deaths of workers. Due to these and other impacts, the region was classified as a “critical pollution area” by Decree No. 85206 on 25 September 1980 [33]. Table 3 describes studies of environmental impacts of coal mining conducted in the Urussanga River basin. The main pollutants from mining are acid effluents and waste improperly deposited in abandoned mines.

Table 3. Environmental impacts of coal mining in the Urussanga River basin.

Environmental Impacts	Reference
. Depletion of several fishing resources near the mouth of the Urussanga River, including fish of the species *Pomatomus saltatrix* and *Mugil liza*. . Perception by the population of a 90% reduction in the diversity of species of fishing resources in the estuarine environment of the basin. . Impacts associated with coal mining effluents.	[15]
. Contamination of sediments collected in the basin estuary by the metals Iron (76,100 mg·L^{-1}) and Manganese (115 mg·L^{-1}). . Contamination associated with pollutant loads from coal mining, with emphasis on acid mine drainage.	[34]
. Water samples collected in the estuarine region of the Urussanga River with high acidity (pH between 4.0 and 6.0) and significant concentration of Iron (5.32 mg·L^{-1}), Aluminum (6.2 mg·L^{-1}), Manganese (0.61 mg·L^{-1}) and Zinc (0.1 mg·L^{-1}) . Contamination associated with pollutant loads from coal mining	[20]
. Forecast of unsustainable demands for water in quantity and quality in the basin, suggesting the urgent need for continuous management interventions, accompanied by large investments. . Prognosis resulting from predatory economic activities, including coal mining.	[22]
. Contamination of aquifers by iron and sulfate metals in regions with abandoned coal mine tailings deposits.	[35]
. Anthropogenic transformation of the basin area due to different activities, including coal mining, with the following results: slightly degraded basin area (39.47%); area with regular degradation (23.12%); degraded area (27.15%); very degraded area (9.02%)	[36]
. Contamination of the basin’s aquifers by metals and acidity (pH < 5) resulting from coal mining. . Percentage of aquifer area with high vulnerability to contamination = 38.53%	[37]

Figure 7 presents images of environmental impacts of coal mining in water resources contaminated by acid mine drainage and degradation of the biotic and abiotic environment due to inadequate waste disposal in the Urussanga basin.

Figure 7. Images of environmental impacts of coal mining in the Urussanga basin: (**A**) contamination of rivers by acid mine drainage, (**B**) confluence of a river polluted by mining (red arrow) with an unpolluted river (green arrow) and (**C**) degradation of the biotic and abiotic environment due to inadequate waste disposal (Source: Authors’ photo).

The impacts of mining in environments have also been reported in the coal region close to the Urussanga River basin. Silva and collaborators identified the presence of sulfate and metals in sediments collected along the Tubarão River, south of Santa Catarina. Metal concentration (mg·kg^{-1}) ranges were 2206–164.693 for Fe; 547–60.494 for Al; 207–1120 for Na; 51–3365 for K; 24–209 for Mg; 37–145 for Ba; 29–84 for Zn; 14–30 for B; 4–22 for Sr; 3–88 for Mn; 0.3–4.3 for Co; 0.001–15 for Cr; 4–10 for Li; 0.4–23 for Cu; 1–3.9 and 4.7 for Se and Sn, respectively; 0.5, 6, 57 and 113 for Ni, Pb and Ti, respectively; 0.005–0.3, 1, 9, 25 and 43 for Ag, W, Mo, As and V, respectively. According to the results, the sediment drainages were mainly composed of quartz and iron oxides (hematite, goethite and magnetite) and also were identified as rutile and different aluminum–silicates such as amazonite, kaolinite or microcline. Calcite and some sulphates (gypsum, calcium hemihydrate and barite) were occasionally detected in the drainages of certain areas studied. It has been suggested that these contaminants come from acid mine drainage generated in coal mining activities [38]. Duarte and collaborators found estuarine sediments in the Santa Catarina coal region contaminated with dangerous elements (silicates, sulfides, sulfates, carbonates, oxides and hydroxides) present in nanoparticle structures. Elements such as sulfur-based compounds (0.08–4.63%); Se (1.8–7.8 mg/L); Na (0.01–0.19%); K (<0.01–1.43%); Li (61.6 mg/L); Rb (81.2 mg/L); Cs (14.5 mg/L); Ca (<0.01–0.32%); Mg (0.01–0.33%); Sr, Be, and Ba (63.8 mg/L, 8.6 mg/L, and 270.2 mg/L, respectively); Fe (2.60–44.68%); Mn (16.1 ppm–132.4 ppm); Cd, Cr, Ni, Pb, Zn, W, Zr, Hf, Mo, V, and Ti in the range of <0.8 mg/L, 8.4–59.5 mg/L, 1.8–12.4 mg/L, 0.9–97.2 mg/L, 0.8–83.3 mg/L, 0.8–10.8 mg/L, 1.6–251.5 mg/L, 0.8–4.6 mg/L, <0.8–16.0 mg/L, 21.9–123.3 mg/L and 28.9–5671.3 mg/L, respectively; Sn (<0.8; mg/L–5.4 mg/L) and Ga (0.8 mg/L–24.2 mg/L). It was also suggested that the contaminants came from acid drainage. Qualitative analysis of soluble nano-minerals containing toxic elements (Cr, Hf, Hg, Mo, Ni, Se, Pb, Th, U, Zr and others) from the combustion of coal mining waste was detected in the coal region of Santa Catarina [39]. It was considered that these materials could compromise the quality of soils and river sediments, as well as surface and underground waters surrounding these areas [40]. In another study, a high presence of potential toxic elements was found in agricultural soils located in the vicinity of a coal-fired thermoelectric plant in south of the state of Santa Catarina. The ranges of values (mg·kg^{-1}) found for the main elements were As (15–0.10), Fe (68,700–550), Mn (1240–16), Ti (1010–3.00), Pb (61–3.0), V (225–2.5) and Zn (280–12) [41]. Vallejuelo and collaborators found the presence of dangerous elements in coal cleaning waste from abandoned mines located in an area of coal activity in Santa Catarina, which pose risks and environmental issues in these regions. The main elements found and their respective ranges (mg·Kg^{-1}) were As (5–25); Cd (0.5–1.0); Cr (45–60); Cu (20–30); Ni (10–25); Pb (45–100) and Zn (50–200) [42]. Therefore, it appears that mining and its contaminants, in addition to causing damage to biota, cause impacts on water and soil resources. This can compromise quality, quantity and their different uses, including the water source of energy and food production. Therefore, recovery strategies for the impacted environment and improvements in the production process are necessary to prevent damage caused by coal mining.

3.6. WELF Nexus Approach

In this section, the WELF nexus approach was applied to compare the water, energy, food and land subsystems in an integrated way in the two study areas, considering indicators focused on reliability, robustness and equilibrium. Based on the results, it can be analyzed how coal mining can affect them individually and the WELF system as a whole. Figure 8 presents the results of the indicators evaluated in the WELF system, which were standardized and normalized in intervals from 0.0 to 1.0 by Equation (1). In relation to water, the data indicate a higher per capita consumption in the Canoas/Pelotas basin, which index assumed a value of 0.73, when compared with the Urussanga River basin (0.19). This result indicates greater efficiency in the distribution and production of water resources in the Pelotas/Canoas basin, which provides more robustness, with less susceptibility of the WELF system to external disturbances. Regarding water consumption per cultivated area, the results were similar in both basins (Canoas/Pelotas = 0.0; Urussanga = 0.0002). This profile can characterize a degree of efficient coordination between the water–land subsystem in the two basins, which provides greater balance between them and less susceptibility to competition and internal conflicts. Data on installed electricity per capita reveal significantly higher values in the Canoas/Pelotas River basin (1.0) compared to the Urussanga River basin (0.01), which also gives greater robustness to the WELF system in terms of production and distribution of the energy resource, reflecting lower impacts on externalities. The results of agricultural production per unit area indicate more significant values in the Urussanga River basin (1.0) compared to the Canoas/Pelotas basin (0.26). This demonstrates a greater abundance of the food resources in the system, which provides greater reliability and adequate guarantee for the sustainable development of the WELF system. In turn, the per capita agricultural production indicator assumed much higher values in the Canoas/Pelotas basin (1.0) compared to the Urussanga River basin (0.22), also revealing greater efficiency in food production, giving greater robustness to the system and less propensity for impacts from external factors. Finally, the data indicate the presence of areas degraded by coal mining in the Urussanga River basin (1.0), which are absent in the Canoas/Pelotas basin (0.0). This indicator suggests a deterioration in reliability, robustness and balance in the WELF systems, since degrading causes a compromise of the abundance, production, distribution and the degree of coordination of all its subsystems, with consequent susceptibility to competition, internal and external conflicts and disturbances. Overall, the Urussanga River basin exhibits a comparative advantage in agricultural production, particularly in terms of high productivity per unit area. However, it is also characterized by an extensive land area affected by coal mining. In contrast, the Canoas/Pelotas basin demonstrates advantages in per capita water consumption, electricity power infrastructure and agricultural production, while the land area impacted by coal mining remains relatively limited.

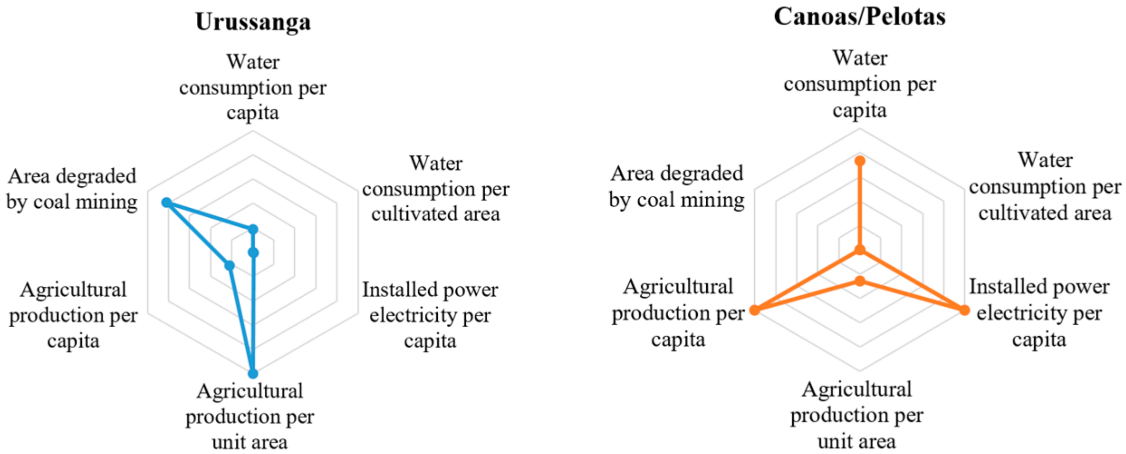


Figure 8. Radar chart of the WELF system evaluation indicators (Source: Authors' illustration).

3.7. Shannon Diversity Index

Figure 9 presents the results of the Shannon index used to evaluate the diversity of water consumption by sector, energy sources and different agricultural products, as well as land occupation. It appears that the Canoas/Pelotas basin presents a higher level of diversity in terms of water consumption by the sectors evaluated (agriculture, industry, human, aquaculture and animal). The lower diversity in the Urussanga River basin may be associated with a more concentrated consumption in the agricultural and industrial sectors, including coal mining, which represents around 79%. It should also be noted that, in this basin, irrigated rice cultivation is one of the main products, which requires a significant amount of water resources. In relation to the diversity of electrical energy sources, it is observed that the Urussanga River basin has a much higher rate. In this basin, there are sources of fossil, water and biomass origin, which participation percentages are similar to each other, in addition to the presence of solar and wind sources, with lower representation. On the other hand, in the Canoas/Pelotas basin, the water source is very significant, with less representation of the biomass and solar source, with fossil and solar sources being practically absent. This implies a lower diversity of electrical sources in the region.

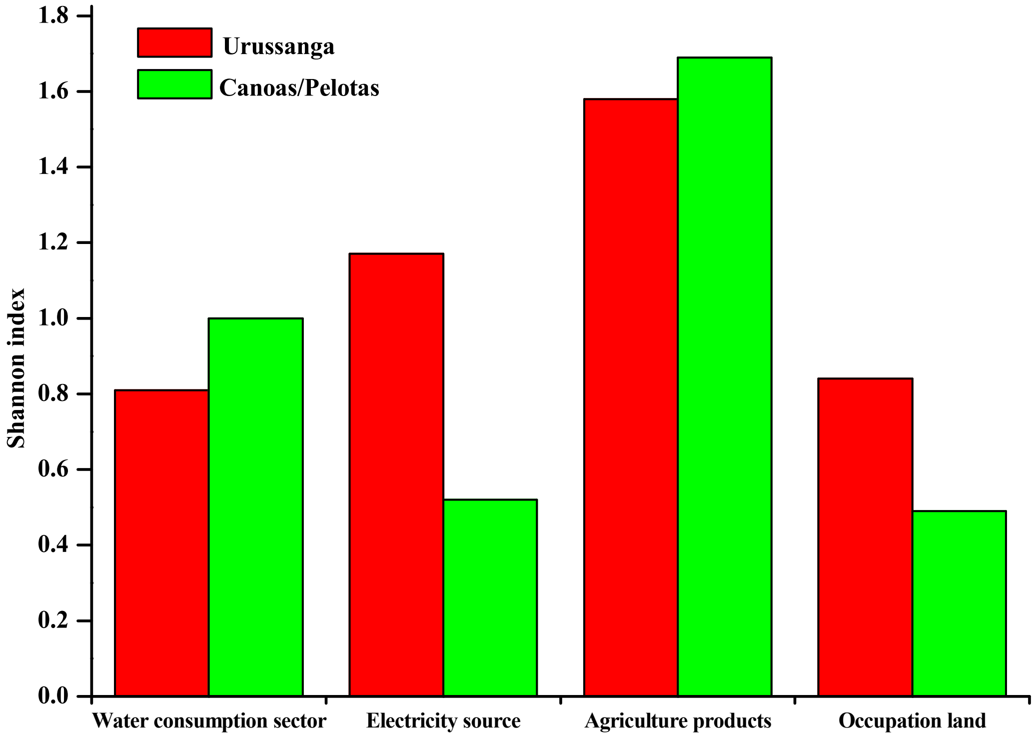


Figure 9. Shannon index of diversity indicators (Source: Authors' illustration).

When comparing the diversity of agricultural products, the results demonstrate higher index values in the Canoas/Pelotas basin. In this region, there is a better distribution of production between the main products (soy, corn and apples). In turn, in the Urussanga River basin, corn production is very significant compared to other products, providing a lower diversity index. In relation to land occupation, the Urussanga River basin presents higher diversity values. Although, in this basin, the majority is occupied by forest, there is a better distribution of occupation by agriculture, urbanized areas and exposed areas. In the Canoas/Pelotas basin, basically, the occupation is by forest and agriculture, with a low share of urbanized, exposed areas and water bodies, which contributes to the lower level of diversity.

4. Implications Based on the Results

Based on the results of the WEFE indicators and diversity indices, it is possible to establish some important reflections on the impacts of coal activity on the WEFE system and its subsystems.

In relation to the water subsystem, the data revealed that, in the Urussanga River basin, the availability of water resources is more limited, in addition to presenting a lower diversity index in terms of the consumption sector (H = 0.81), compared to the Canoas/Pelotas basin (H = 1.0). The results of the WEFE indicators also demonstrate less robustness to the system, which indicates less efficiency in the supply and distribution of this resource, with consequent susceptibility to external disturbances. Among the disturbances, it is worth highlighting the contamination of water bodies by potentially toxic and harmful effluents generated in the coal industry. It is considered that these aspects have implications for the connections between water and other subsystems. The compromise in the quality and quantity of water resources caused by the coal industry may limit its use for the production of thermal and electrical energy from water sources. In the production of biofuels (e.g., bioethanol, biogas and biohydrogen), there is also a need to use water. Furthermore, this element is necessary in the process of extracting and processing energy coal and in the treatment of its waste.

The food subsystem can also be affected due to the impact of mining on water. As described, among the main economic sectors of the Urussanga River basin are agriculture, horticulture, livestock and their products and fish farms. In all these activities, there is a need for water for irrigation, fish cultivation, animal watering and food processing. In this way, the region's food chain may suffer negative consequences with the compromise of the supply of water resources. The land subsystem can also be impacted, since water plays an important role in maintaining humidity and transporting nutrients to the soil, giving it greater fertility and food productivity.

In relation to the energy subsystem, despite the Urussanga River basin presenting higher levels of diversity by source (H = 1.17) compared to the Canoas/Pelotas basin (H = 0.52), statistical data demonstrated that the region is very dependent on fossil sources (40% of total). The WEFE indicator also demonstrated less robustness of the system in the basin due to a low installed electricity capacity per capita. This reveals fragility in the supply and distribution of this resource, with a consequent propensity for the influence of external factors, including dependence on mineral coal. It is known that energy is essential to the balance of the WEFE system and its connections. This subsystem is necessary for the extraction and distribution of water to the different consumption sectors. The water treatment and waste process also involve energy use. The production, processing and transportation of food and preparation for consumption require thermal and electrical energy. The soil preparation and soil correction mechanisms for food production also require energy. The energy sector itself depends on this resource for the energy generation and distribution process. Therefore, a lower supply of this subsystem, combined with a large dependence on coal, can worsen the impacts of mining on the WEFE system as a whole.

Regarding the food and land subsystems, statistical data indicated that, in the Urussanga River basin, there is a great concentration in grain production (corn = 50% of total production) and with a focus on the external market. A lower diversity index was also found in terms of the variety of agricultural products (H = 1.58) compared to the Canoas/Pelotas basin (H = 1.69). Furthermore, the per capita agricultural production indicator assumed a much lower value, which reveals less robustness of the system in terms of production efficiency. When analyzing the land subsystem, a higher index of land cover diversity was found in the Urussanga River basin (H = 0.84) compared to the Canoas/Pelotas basin (H = 0.49). However, the data demonstrate greater anthropogenic intervention in the region (agriculture and urbanized = 26% of total), including exposed soil (3%) as a result of mining activities, such as coal extraction. As already described in the literature, the soil also suffers impacts from coal mining in the region, mainly due to inadequate deposits of its tailings, in addition to the contamination of dangerous elements. As a result, there may be limitations in agricultural production or the danger of contamination of its products, with a consequent worsening of the region's food security situation. It is worth noting that land plays a role in draining water to surface water bodies, as well as storing it in aquifers. In this way, contaminated soil can also carry harmful elements to these water bodies and compromise their different uses. Another relevant aspect is that affected soil compromises its use in the production of energy crops (e.g., sugar cane and corn), as well as its use as a water reservoir in hydroelectric plants and the installation of photovoltaic and wind farms. This may affect the alternative diversity of energy sources in the basin.

The implications of the coal industry for part of these systems have also been described in the literature. Highlighted here is the work carried out by Simpson and collaborators in the province of Mpumalanga (South Africa) [16]. The region has large expanses of high-production agricultural land and a strong presence of several operating and abandoned mines. The authors assessed that the contamination of water resources and arable land by mining impacts the availability and quality of water for the coal industry, agriculture and energy production. They also consider that dependence on coal for energy generation—which, in turn, requires land for the development of mines—threatens food security through the search for energy security based on this fossil source. They warn that poor governance and deficiencies in the regulation of coal activity also contribute to the worsening of the situation.

Brazilian legislation requires prior environmental licensing for the construction, installation, expansion, modification and operation of coal mining projects. Among the requirements contained in the licensing is the need to prepare a diagnosis of the site where the activity will be implemented, with data on water resources, soil, air quality, fauna and flora, as well as socioeconomic aspects. It is also necessary to issue a technical and legal opinion on the adoption of measures and strategies for the preservation and recovery of areas degraded by mining [43]. Therefore, the studies carried out in this research can contribute to the effectiveness of environmental regulation in coal-based regions.

The diagnosis and evaluation of the different subsystems in the Urussanga basin described here reveal the need to propose alternatives for the prevention and mitigation of the effects of mining. For the coal industry, plans can be proposed for the recovery of degraded areas; the use of coal extraction and processing technologies that minimize environmental damage; more efficient systems for the treatment, deposition and reuse of waste and the valorization of its by-products in other industrial sectors. For the water subsystem, strategies can be suggested to improve the distribution of surface resources between the different sectors, as well as the sustainable exploitation of aquifer reserves, with the definition of their priority uses. In relation to energy, the need to diversify its sources, focusing on clean and renewable sources, must be taken into account. The region under study has the potential to generate thermal and electrical energy from agricultural, livestock and urban waste. Among the alternatives, there are the use of rice husks in thermal plants, generation of biomethane from poultry and swine waste and food waste and bioethanol production with cassava residues. The installation of small hydroelectric plants along water sources is another viable alternative. Solar incidence in the region also favors the installation of photovoltaic systems in homes and commercial, industrial and public sector buildings. Wind farms can be installed on land degraded by coal mining. Furthermore, offshore wind potential can be explored in the coastal region of the basin. In relation to the food system, public policies can be created to encourage the diversification of agricultural products that serve the domestic market and favor access to food, especially for the most vulnerable people. In turn, planning territorial space through the establishment of residential, commercial, industrial and agricultural cultivation areas can favor improvements in the occupation and use of land. It is understood that these strategies will make an important contribution to WELF systems in regions with coal activity.

5. Conclusions

This study proposed to describe how coal mining can affect the connections of the water–energy–land–food (WELF) nexus system, focusing on reliability, robustness, equilibrium and diversity indicators. To this end, comparative studies were carried out between a region with coal activity (Urussanga River basin) and another area without mining (Canoas/Pelotas basin), both located in the state of Santa Catarina, Brazil. Statistical data indicate that agriculture is the sector with the highest water consumption (45–52%) in both basins. The energy source of fossil origin is more representative in the Urussanga River basin (40%), while, in the Canoas/Pelotas Basin, water energy prevails (85%). Food production in both basins is mainly represented by agricultural subsidies (corn = 50%, Urussanga; soybeans = 36%, Canoas/Pelotas) and livestock, with values exceeding 12 million units of pigs and chickens. Different types of soil occur in both regions, and their occupation is mainly by forests (70–85%). The WELF system indicators showed that the Urussanga basin presents less robustness in the subsystems of per capita water consumption (0.19), installed electrical capacity (0.01) and per capita agricultural production (0.22) compared to Canoas/Pelotas at 0.73, 1.0 and 1.0, respectively. The Shannon index results also indicated that the Urussanga basin presented less diversity in the water consumption sector (H = 0.81) and in the variety of agricultural products (H = 1.58) compared to Canoas/Pelotas (H = 1.0; H = 1.69, respectively).Therefore, the results revealed that the Urussanga River basin is more susceptible to external disturbances, including the negative impacts of coal mining. Although coal activity is important for the socioeconomic development of the region, it has been revealed that it has caused several environmental damages, with emphasis on the contamination of its water and land resources for metals, oxides and acidity (pH < 5). It is considered that these impacts have implications for the different systems and their connections, with consequences for the global WELF system. These include limiting the use of water for energy purposes and soil food production, with a consequent worsening of energy and food security. In this context, policies and plans must be aimed at preventing and mitigating these effects and promoting a better connection between the evaluated subsystems. Finally, this research was relevant and innovative, as it allowed a more integrated study of the elements of water, energy, food and land and how coal-based regions can cause internal and external disturbances of the WELF system.

This work has some limitations, such as a lack of availability of more up-to-date statistical data on water resources and land use in the Urussanga River basin, primary data and few studies focused on the indicators of mining impacts in the region and qualitative and quantitative analyses of the risk perception among the population affected by mining. This information would allow for a more representative and realistic comparison between the two study regions.

For future investigations, on-site research may be proposed on the impacts of the coal sector in the Urussanga River basin; a comparative analysis between the basin under study and other adjacent coal regions; the application of other WELF system evaluation indicators; the collection of risk perception information from the community, public and private actors and the evaluation of future scenarios on the impact of mining on the WELF system.

Author Contributions: Conceptualization, R.G. and N.M.; methodology, R.G. and N.M.; software, R.G. and N.M.; validation, R.G. and N.M.; formal analysis, R.G. and N.M.; investigation, R.G. and N.M.; resources, R.G. and N.M.; data curation, R.G. and N.M.; writing—original draft preparation, R.G. and N.M.; writing—review and editing, R.G. and N.M.; visualization, R.G. and N.M.; supervision, N.M.; project administration, R.G. and N.M.; funding acquisition, N.M. and R.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Dataset is available on request from the authors.

Conflicts of Interest: The authors declare no conflicts of interest.

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