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Assessing the Degree of Sustainability in Extractive Reserves in the Amazon Biome Using the Fuzzy Logic Tool for Decision Making

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Abstract: The Extractive Reserve (RESEX) was designed to protect rubber tapping communities and their livelihoods, thus guaranteeing environmental health. This study was carried out between 2021 and 2023 and aimed to propose a methodology based on the fuzzy logic method to assess the degree of sustainability in RESEXs in the state of Amazonas, Brazil. For this assessment, 10 indicators were used, represented through input variables in the fuzzy inference systems represented by the Environmental Subsystem (ES), Economic Subsystem (ECS), Social Subsystem (SS), and Institutional Subsystem (IS), with performances that converged so that the Sustainability System in the RESEX (SRE) system reached a performance value of 30.0, on a scale of 0 to 100, which translates into low sustainability in these spaces in the state of Amazonas. The methodology's ability to represent the main phenomena that impact sustainability in the RESEX studied through linguistic variables and weight them in their complexities, as well as inferring a set of decision rules that reflect the knowledge of experts and which aim to quantitatively contextualise sustainability under uncertainty and imprecision in these areas, makes it a viable instrument to be applied and used by managers and decision-makers in the management of these spaces.

Keywords: protected territories; state of Amazonas; environmental health; social justice; sustainable development

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1. Introduction

The Amazon rainforest plays a vital role in climate patterns, ecosystems, hydrological cycling, carbon storage, biodiversity [1], and the source of resources that form the basis of subsistence for the people who inhabit the interior of the forest [2]. Of this forest, however, ~20% has already been cut down, and another 17% is being degraded by human intervention [3], while in Brazil, the Amazon has already lost 18% of its original forest [4]. In this region, Conservation Units (CUs) represent efficient containment barriers to advance agricultural frontiers and to mitigate climate change [5]. These CUs represent 28.6% (1,204,430 km^2) [6] of the territory of the Amazon biome, which covers 58.8% of the national territory [7].

In this region, there are 77 (151,895 km^2) located Extractive Reserves (RESEXs) out of the 95 (156,217 km^2) existing throughout Brazil, representing 6.12% of all Conservation Units (CUs) in the National System of Conservation Units (NSCU) [8]. The establishment of RESEXs in the Amazon is the result of a land policy aimed at resolving land conflicts in this region [9,10]. These conflicts intensified during the National Integration Plan (NIP—1971 and 1974) and the First and Second National Economic and Social Development Plans (NESDP—1972 and 1979) of the federal government, based on a development model that is indifferent to local socio-environmental conditions and negatively impact the way of life of forest peoples and their relationship with nature [11].

The RESEX was conceived by rubber tappers in the state of Acre, in the Brazilian Amazon, and differs from other protected areas because of its emphasis on human beings, who are assigned the task of promoting conservation [12]. It represents one of the main strategies for sustainable development in tropical forests, with a model that consists of protecting rubber tapper communities, their forests, and their livelihoods, thus ensuring that deforestation is contained and biodiversity is conserved [13].

The first RESEX in the Amazon was created in the early 1990s under Presidential Decree 98.897/1990 [14], based on the National Environmental Policy (NEP) [15], which established these areas as territorial spaces of ecological and social interest. At the international level, RESEXs were recognised in 1994 with the creation of Category VI protected areas by the International Union for Conservation of Nature (IUCN). This category was established almost exclusively for these areas in the Amazon [16].

With the creation of the NSCU, RESEXs became part of the Sustainable Use (SU) category group of CUs, which aims to reconcile nature conservation with the sustainable use of part of the natural resources. On the other hand, the Integral Protection (IP) category is more restrictive and aims to preserve nature, allowing only indirect use of its natural resources. The territory of CU in the SU group represents 74.0% of these in the NSCU [8] and seeks to reconcile nature conservation with the presence of traditional populations and their modes of social and subsistence reproduction through procedures that guarantee the sustainable use of natural resources [17].

Despite the establishment of RESEXs in the Amazon assuming different perspectives, such as guaranteeing the right to land, the use of natural resources, and the continued reproduction of the way of life of the traditional populations and communities that inhabit these territories [18,19]; serving as an instrument for combating poverty [20] and the rural exodus [21]; and stimulating income generation [22], it reconciles the interests of conservation with those of social development [23–26]. This conservation is guaranteed, above all, by the traditional practices of local populations in working with and managing nature, which counteract current production systems [27]. However, the sustainability of the model has been hindered by the lack of public policies for social development [28–30], the expansion of economic activities not foreseen in the NSCU by local populations, such as cattle ranching [31,32], uncertainties of the extractive plant economy [33–35], among others.

These challenges have taken on new contours in the face of the effects of climate change in recent decades. All over the world, climate change has led to a reduction in the amount of arable land; reduced harvests and economic yields; food shortages for ethnic minority groups [36]; loss of biodiversity; impacts on agriculture, forestry, fishing, livelihoods, and culture; loss of property and economic income; the occurrence of diseases and food insecurity; among others [37]. Studies of 56 RESEXs in the Amazon show that over the next 30 years, climate change will affect the geographical distribution of 18 native species used by local populations and reduce the natural distribution of 11 species, and 9 of these species are expected to disappear from some RESEXs. In four RESEXs, there will be a total loss of species, and in 21 RESEXs, one or more native species will disappear [5]. In the Parnaíba delta RESEX, climate change has led to the expansion of mangrove areas, suppression of native vegetation, ecological dominance of plant species, and impacts on fauna and local communities [38]. In the Amazon, deforestation and wildfires are the main drivers of changes in climate, land use, loss of biodiversity, suppression of vegetation cover, alterations to the hydrological regime, among others [39].

This region is also impacted by climate variability caused by anomalies in the surface temperature of the tropical oceans of the Tropical Pacific, such as El Niño or La Niña, and of the Tropical Atlantic, as well as other diffuse climatic events that cause atypical flooding or long periods of drought [40,41]. In 2023, the combination of anthropogenic actions and climatic events (El Niño) caused one of the longest droughts in the history of this region, with some of its areas registering a warming of 3 °C above the global average, causing rivers to dry up, communities to become isolated, wild species to become extinct, and forest fires to intensify [42]. In the state of Amazonas, located in the respective region, this drought was the longest in the last 100 years, with consequences in both cities and rural areas [43], and which follows a global trend, showing that 2023 was the hottest year ever recorded on the planet since 1850, with an average global temperature of 14.98 °C [44].

In CUs, methods that promote sustainability assessment can make decisions more democratic and transparent, promote a better understanding of reality and predict impacts on the environment and society [45]. Due to its multidimensional and multiscale nature, this assessment requires adapted methodologies and continuous monitoring [46], particularly in an uncertain and dynamic context such as that of the Amazon region [47].

From this perspective, this study aimed to propose a methodology based on the fuzzy logic method for assessing the degree of sustainability in Extractive Reserves in the state of Amazonas in the Amazon Biome. Fuzzy logic has been suitable for application in complex modelling systems or under uncertainty [48]. It has the ability to represent subjective issues and qualitative reasoning, and variables can be stated linguistically and translated into numerical values. In fuzzy logic, exact reasoning corresponds to a limit case of approximate reasoning, which is interpreted as a process of composing nebulous relationships [49].

The flexible approach of fuzzy logic has made this method a viable alternative for use in different applications [50–52], such as in attempts to assess sustainability [46] in coastal marine areas [53], coordinate anthropogenic activities on the environment in protected wetlands [54], evaluate nature conservation in a biosphere reserve [55], monitor social and ecological support capacities in protected areas [56], verify potential areas for establishing a scientific nature reserve [57], verify sustainability in a state park [45], among others. The proposed methodology may be suitable for modelling and evaluating sustainability under uncertainty and imprecision in the RESEXs investigated and a tool capable of helping managers and decision-makers in managing and promoting development.

2. Materials and Methods

2.1. Study Area

The state of Amazonas concentrates 60.0% of the public forests in the Legal Amazon [58], which is made up of nine Brazilian states in the northern region. These areas are largely located in federal, state, and municipal CU territories, which account for 30.21% of its territory, covering an area of 472,000 km^2 [59]. The state is home to 13 RESEXs, 4 of which belong to the state government and 9 to the federal government, where ~4687 families live. These families are remnants of rubber tappers who migrated from the Northeast Region of Brazil to the Amazon between 1870 and 1912 during the golden period of this economic activity at the end of the 19th century.

The natural resources in these RESEXs (Figure 1) are of fundamental importance for the subsistence of families in these spaces, as well as for other families in communities located in their surroundings. In the Lago Capanã Grande RESEX, for example, the use of its natural resources is carried out by ~350 families, including those registered in Settlement Projects, Indigenous Lands, and in other CUs, according to the local Chico Mendes Institute for Biodiversity Conservation (CMIBC) office. Likewise, in the Guariba RESEX, although there are no human populations living in its territory, there are 38 extractive families registered at the local Amazonas State Secretariat for the Environment (ASSE) office in the municipality of Apuí, authorized to access the natural resources of this RESEX.

In the respective state, RESEX areas cover 45,586 km^2, equivalent to 15.0% of the territory of Sustainable Use CU and 8.5% of Full Protection CU [59]; 30.01% of these areas are located in the Amazon and 29.18% of these areas in the whole of Brazil.

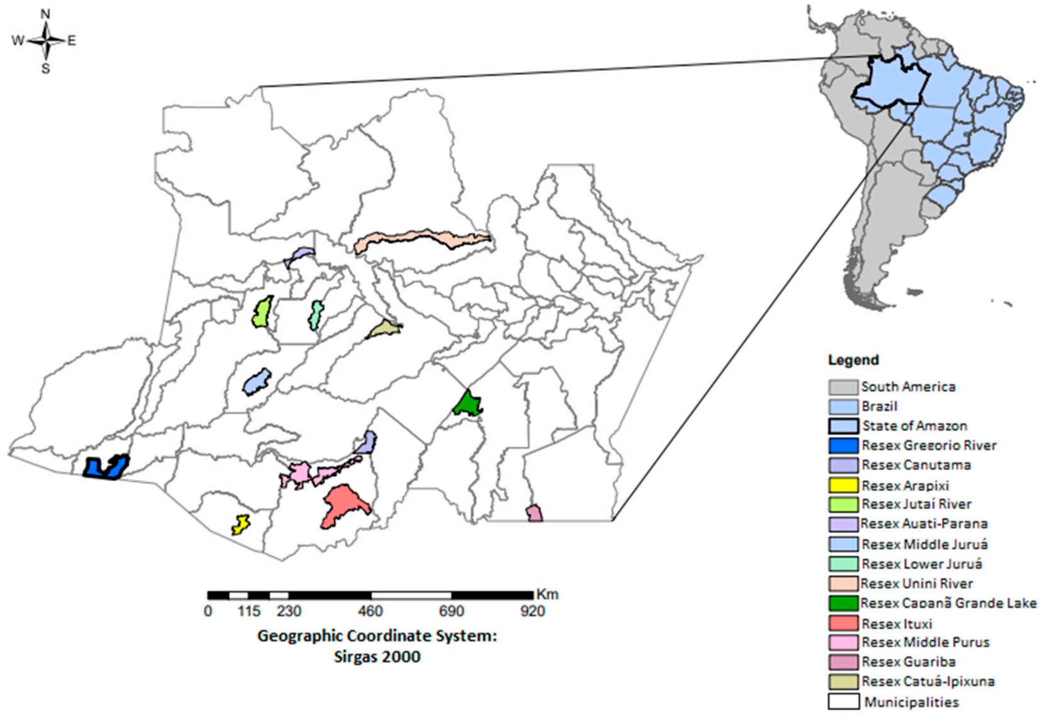

Figure 1. Map of the Extractive Reserves located in the state of Amazonas, in the Amazon biome, Brazil (Source: Authors; Map created with QGIS v.3.18 software and IBGE 2022 Cartographic base).

2.2. Methodological Approach

This study took place between 2021 and 2023, with information on the RESEX being gathered through field and documentary research. For the field research, visits were made to the offices of the ASSE and the CMIBC, located in the inner regions of the state of Amazonas. These visits took place after these institutions had issued authorisations for access to information. During the visits, information was collected in files passed on by managers (13) responsible for RESEX governance regarding cattle herds, land regularization, production activities, public policies, and the number of employees who work in the management and supervision of RESEX.

The information on the Guariba RESEX was limited to the rate of deforestation, threats to biodiversity and natural resources used by extraction families outside the RESEX. It is part of the Apuí State Mosaic of Conservation Units (ASMCU), which integrates the management of nine State Conservation Units of different types. Through documentary research, information was collected on deforestation (2010–2022) in the respective RESEX and in the state of Amazonas by consulting the platform of the Project for Monitoring Deforestation in the Legal Amazon by Satellite of the National Institute for Space Research—PRODES–INPE [60,61].

The information on the cattle herd in the state of Amazonas was obtained by accessing the platform of the Brazilian Institute of Geography and Statistics [62]. With regard to accessing information on cattle herds in municipalities in the respective state, this was obtained during on-site visits to the Amazonas State Agricultural and Forestry Defence Agency (AFDA), which is linked to the State Secretariat for Rural Production (SSRP). This information was compared with information on cattle herds obtained from local ASSE and CMIBC offices. The information on cattle herds in the Lower Juruá RESEX was obtained in the field [63], as it was more up to date than the information provided by CMIBC.

The information on financial resources earmarked for RESEX management was taken from the 2021 Management Report of the National Fund for Biodiversity Conservation—NFBC [64], while the information on the Management Plan (Federal) or Environmental Management Plan (State) and Deliberative Councils was taken from the Ministry of the

Environment portal [65] and the ASSE [66], where information on federal and state CUs in the state of Amazonas is available under the Conservation Unit tab.

2.3. Data and Methods

2.3.1. Modelling the Sustainability System Using Fuzzy Logic

To design the methodology for assessing sustainability in RESEX, 10 indicators were adopted covering the environmental, economic, social, and institutional dimensions. These dimensions came to represent the primary dimensions of sustainable development during Rio 92, within the framework of the Agenda 21 Commission on Sustainable Development (CSD), and a reference to the development of sustainability indicators [67–69], which are among the main strategies used to assess sustainability [70,71].

The indicators used by the methodology are represented through input variables in the fuzzy inference systems represented by the following subsystems, Environmental (ES): IES1 + IES2 + IES3; Economic (ECS): IECS1 + IECS2; Social (SS): ISS1 + ISS2; and Institutional (IS): IIS1 + IIS2 + IIS3, the results of which underpinned the evaluation of the RESEX Sustainability System (SRE) via Equation (1) as follows:

$$\text{SRE} = (\text{ES} + \text{ECS} + \text{SS} + \text{IS}) \tag{1}$$

The respective assessment was based on the fuzzy inference process approach. This was achieved by (i) defining the indicators for the sustainability subsystems, (ii) outlining the fuzzy inference process, and (iii) experimenting with the methodology (Table 1).

Table 1. Modelling stage for assessing sustainability in RESEX (Source: Authors).

Steps	Description
Sustainability Indicators	Conservation of forest cover (IES1) Cattle herd (IES2) Land regularisation (IES3) Productive activities (IECS1) Incentive programmes (IECS2) Infrastructure (ISS1) Sanitation (ISS2) Financial resources (IIS1) Management Plan (IIS2) Total area per server (IIS3)
Fuzzy Inference System	Fuzzy system development Development of inference rules Simulation in MatLab software version R2013a
Methodology Experiment	Compilation of the indicator regression algorithms, analysing and discussing the results

The indicators were designed using the fuzzy inference process to assess sustainability in RESEX in the state of Amazonas. The choice of indicators was based on their relevance in the scientific debate on sustainability in RESEX, on the legal instruments (Table 2) that guide the creation and management of these spaces and those that guarantee the rights of traditional populations and communities in Brazil, and on the information available on these territories in the respective state.

Table 2. Legal aspects of the indicators used to assess sustainability in RESEX in the state of Amazonas (Source: Authors).

Indicators	Legal Instruments
Conservation of forest cover (IES1)	Federal Law No.9.985/2000 (art. 18); Federal Decree No. 4.339/2002; Federal Law No. 12.651/2012 (art. 12); Federal Constitution (art. 255–§ 1°) [72–75]

Table 2. *Cont.*

Indicators	Legal Instruments
Cattle herd (IES2)	Federal Law No. 9.985/2000 (art. 18°) [72]
Land regularisation (IES3)	Federal Law No. 9.985/2000 (art. 18°); State Law No. 3.135/2007 (XIII); Normative Instruction No. 03/2007 [72,76,77]
Productive activities (IECS1)	Federal Law No. 9.985/2000 (art. 5°–VI, art. 18°); Federal Law No. 10.831/2003 (art. 2°); Joint Normative Instruction No. 17/2009. (art. 10) [72,78,79]
Incentive programmes (IECS2)	Federal Law No. 9.985/2000 (art. 5°); Federal Decree No. 6.040/2007 (art. 3°–XVII; Federal Decree No. 9.334/2018 (art. 2º, 3º) [72,80,81]
Infrastructure (ISS1)	Federal Constitution (art. 5°, 23°–IX, 187°–VII, 196°); Federal Decree No. 6.040/2007 (art. 1°–III, V); Federal Decree No. 9.334/2018 (art. 2°, 3°); Federal Law No. 9.394/1996 (art. 1°–§ 2°, art. 21°–I); Federal Law No. 12.796/2013 (art. 4°, 5°) [75,80–83]
Sanitation (ISS2)	Federal Decree No. 9.334/2018 (art. 2°, 3°); Federal Law No. 11.445/2007 (art. 2°–III, V) [81,84]
Financial resources (IIS1)	Federal Law No. 9.985/2000; Federal Decree No. 4.339/2002 [72,73]
Management plan (IIS2)	Federal Law No. 9.985/2000 (art. 2°–XVII, 27– § 3°) [72]
Total area per server (IIS3)	Federal Law No. 9.985/2000; Federal Decree No. 4.339/2002 [72,73]

2.3.2. Fuzzy Inference Process

Fuzzy logic is based on the theory of fuzzy sets, which is a qualitative computational method that describes imprecision or partial truth and focuses on the degree of pertinence of the set. Its theoretical foundations were first publicised in 1965 by Lotfi Asker Zadeh, who, eight years later, introduced fuzzy control, based on the concept of linguistic variables and IF–THEN rules, from the formulation of human knowledge inference [52]. Logical reasoning or fuzzy inference follows three distinct and interconnected stages (Figure 2), which are Fuzzification, Inference, and Defuzzification.

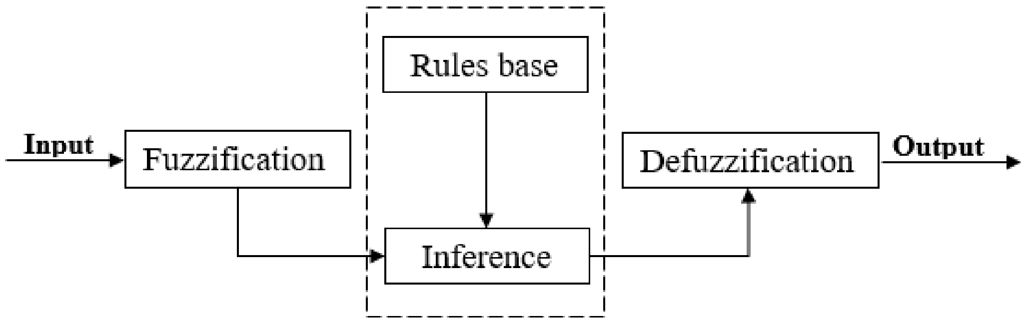

Figure 2. Fuzzy inference process (Source: Authors).

In the Fuzzification stage, the inputs of the linguistic variables were defined with their respective terms, numerical reference intervals (metrics), and linguistic values, as well as the pertinence functions responsible for gradually mapping the degree of adherence into sets of rules, ranging from 0 (total exclusion) to 1 (total inclusion), with the pertinence factor assuming any value of this interval in the set. The choice of this function represents the first stage in the representation of fuzzy sets, the choice of which depends on issues such as the modelling of the problem and computational performance [85].

A total of ten inputs were made for the ES, ECS, SS, and IS in the fuzzy system's pertinence functions. These inputs varied between two and three in the respective subsystems, with one output for each, while for the SRE system, four inputs and one output were produced, resulting in a total of fourteen inputs and five outputs in the fuzzy inference system. The representations of the numerical ranges of the inputs varied in percentage (%), arithmetic mean, units (Un), financial values (BRL), time (year), and square kilometres (km^2). With the linguistic values representing the analysis variables varying in "Very Low", "Low", "Medium", "High", and "Very High". The pertinence functions used to map these inputs were trapezoidal and triangular (Figure 3), which were implemented using MatLab software version R2013a.

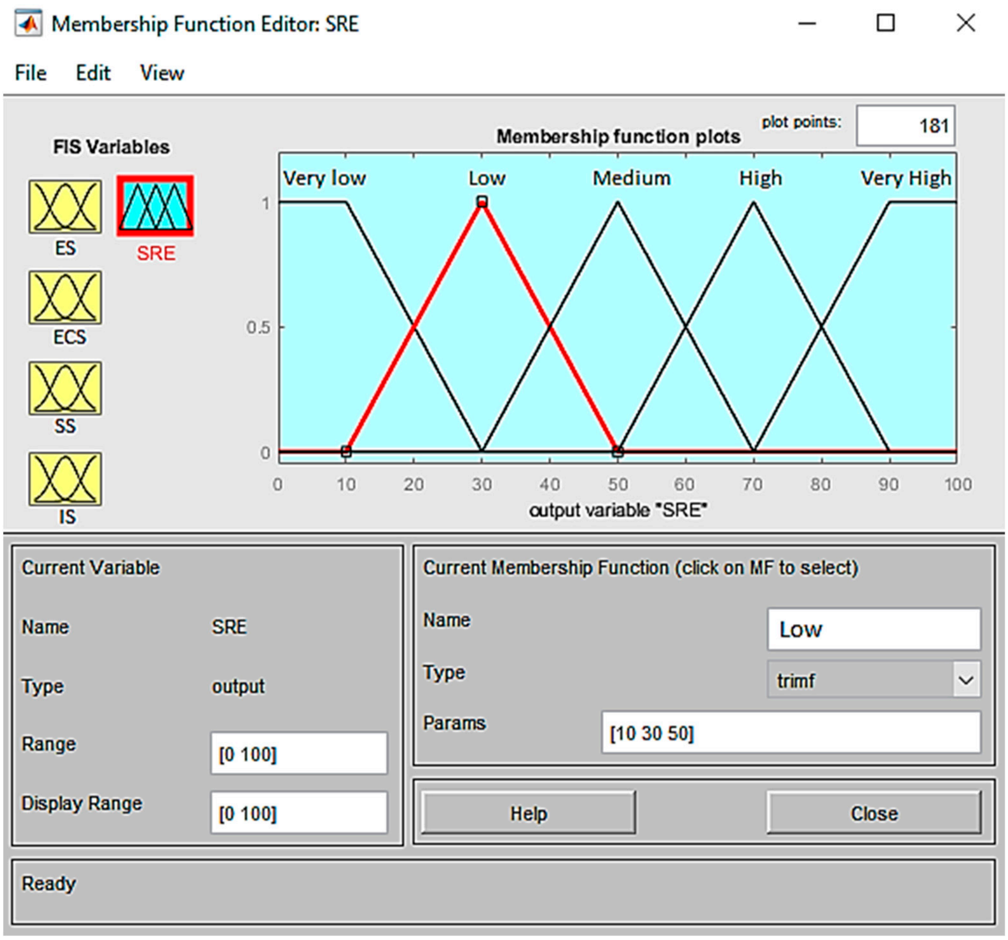

Figure 3. Representation of the input (ES, ECS, SS, IS) and output (SRE) variables in the Fuzzification stage of the SRE system. In the centre, a graph shows the trapezoidal and triangular pertinence functions, with the *y*-axis representing the degree of pertinence and the *x*-axis the numerical interval (Source: Authors).

These functions define the degree of pertinence of an input in one or more fuzzy sets, which can be understood as qualitative groups defined by their pertinence functions and identified through linguistic variables [86]. To assess environmental, economic, social, and institutional sustainability, ten input variables and four output variables were declared (Table 3).

Table 3. Characteristics of the variables by type (input and output) and subsystems in the pertinence functions in the fuzzy system (Source: Authors).

Subsystem	Type of Variables	Variable	Numeric Range	Numeric Range
ES	Input	IES1—Conservation of Forest Cover (%km^2) IES2—Cattle Herd (AU/ha) IES3—Land Regularisation (%km^2)	0–100 0–2 0–100	Low, Medium, High
	Output	ES—Environmental Subsystem	0–100	Low, Medium, High

Table 3. *Cont.*

Subsystem	Type of Variables	Variable	Numeric Range	Numeric Range
ECS	Input	IECS1—Productive Activities IECS2—Incentive Programmes	0–10 0–10	Low, Medium, High
	Output	ECS—Economic Subsystem	0–100	Low, Medium, High
SS	Input	ISS1—Infrastructure ISS2—Sanitation	0–100	Very Low, Low, Medium, High
	Output	SS—Social Subsystem	0–100	Very Low, Low, Medium, High
IS	Input	IIS1—Financial Resources (BRL/km^2) IIS2—Management Plan IIS3—Human Resources (Qty/km^2)	0–150 0–20 0–200	Very Low, Low, Medium, High
	Output	IS—Institutional Subsystem	0–100	Very Low, Low, Medium, High
SRE	Input	ES—Environmental Subsystem ECS—Economic Subsystem SS—Social Subsystem IS—Institutional Subsystem	0–100	Very Low, Low, Medium, High
	Output	SRE—Sustainability in RESEX	0–100	Very Low, Low, Medium, High, Very High

For each variable used in the fuzzy analysis, the following conditions were considered for Brazil:

(a) IES1—In order to preserve the biodiversity of a biome or ecosystem, it is necessary to preserve at least 30 percent of the area of the rural property [87,88]. In a forest property in the Amazon, the Brazilian Forest Code allows the loss of up to 20 percent of the vegetation cover. However, indicators of vegetation cover integrity alone may not reflect the viability of terrestrial biotas, given the effects of habitat loss, species extinction and degradation, among other non-linear disturbances [89]. As this is a CU, IES1 considers the integrity of vegetation cover in RESEX for performance purposes based on the accumulated deforestation between 2010 and 2022.

(b) IES2—Extensive cattle ranching represents the main threat to vegetation cover in the Amazon [90–92] and in RESEX areas [31,93]. Despite the NSCU restriction on the breeding of large animals in Conservation Units, in the RESEX investigated, the policy on cattle activity takes on a distinct characteristic in their Management Plans. For performance purposes, IES2 considered the lowest stocking animal unit per hectare (AU/ha) in the RESEX. In the state of Amazonas in 2006, this rate ranged from 0.51 to 0.76 AU/ha [94], while, in Brazil, it was 0.92 AU/ha, according to the 2017 Agricultural Census [95].

(c) IES3—In the Amazon, the loss of vegetation cover is mainly concentrated in areas with ambiguous or undefined land ownership [96], which are more susceptible to misappropriation and environmental crimes [58]. In RESEX, these areas also contribute to intensifying territorial conflicts [97]. For performance purposes, this variable considered the percentage of RESEX areas regularised by the state.

(d) IECS1—In RESEX, the economic concentration on a few products and the lack of public policies aimed at this sector contribute to the unfeasibility of this economy, despite the fact that there are several native species capable of improving the quality of life of local populations, with ecological balance and social justice [98,99]. Even if the income from a particular species is reduced, this can be offset by the diversification of other species that are harvested and sold in a sustainable way [100]. In this way, as more productive activities are developed in RESEX, better performances will be attributed to this variable.

(e) IECS2—Brazilian public policies aimed at extractivist, riverine, and indigenous populations have been inefficient in recent decades [101], even serving to induce deforestation in protected areas [102]. In the RESEX, the number of programmes aimed at promoting productive activities is of fundamental importance for the enhancement of this economy and the well-being of the families that practice them. For the purposes of performance, IECS2 considered the supply of these programmes in RESEX.

(f) ISS1—The absence of public social development policies in RESEX is the main cause of poverty among their populations [28,103]. As these are essential services, ISS1 considered, for performance purposes, the universalisation of infrastructure services offered to families in the RESEX (Education—Basic Education, Early Childhood Education, Primary Education, and Secondary Education; Health—health centres and emergency medical services; electricity—via the public grid, renewable or mixed energy system, communication system—fixed, mobile, or mixed telephony and internet access).

(g) ISS2—The assessment of this variable takes the same approach as ISS1, i.e., it considers, for performance purposes, the universalisation of access to basic sanitation services (mains water, sewage system, and rubbish collection services) by families in the RESEX. These services are essential for social well-being and environmental health, as they involve sanitation issues and the possibility of soil and river contamination. Due to the geographical isolation of the RESEX, the practice of incinerating or burying household rubbish by families was considered to be a rubbish collection service.

(h) IIS1—Brazilian investment in protected areas is one of the lowest (BRL 4.43 per 0.01 km^2) compared to countries such as Canada (BRL 53.33), Australia (BRL 55.1), South Africa (BRL 67.09), among others [104]. IIS1 was based on financial transfers from the NFBC [64] between November 2014 and September 2021, earmarked for the management and inspection of RESEX, correlating the distribution of these amounts to the areas (km^2) of the RESEX.

(i) IIS2—The Management Plan is a compulsory instrument from the fifth year of the establishment of a CU, according to the NSCU. In 2010, in the Amazon region, 70.0% of management plans had not been started or completed [105]. In 2018, only 55.0% of federal CU had a Management Plan, with this absence being more pronounced in RESEX (73.0%) and federal Natural Monuments—Monas (100%) [106]. As this is a fundamental instrument in the management and territorial planning of CU, IIS2 considers the shortest time taken to approve the RESEX Management Plan for performance purposes.

(j) IIS3—The evaluation of this variable is similar to that of IIS1, i.e., it considers the total area of the RESEX (km^2) per server for management and inspection purposes. In Brazil, the total protected area per employee is 186 km^2, much higher than in countries such as South Africa (11.76 km^2), the United States (21.25 km^2), New Zealand (23.52 km^2), Argentina (24 km^2), Costa Rica (26.78 km^2), Canada (52.57 km^2), and Australia (71.04 km^2) [104]. Thus, the smaller the total area of RESEX per server, the better the assessment of this variable.

In the fuzzy system inference stage, the data were aggregated to produce the indicators. This aggregation took place in two stages using fuzzy modelling. The first stage was to obtain the sustainability results of the ES, ECS, SS, and IS, and the second stage was to obtain the result of the SRE system, based on the results of the respective subsystems. These two stages are called the first- and second-order input modelling of the fuzzy system [107]. A total of 260 propositions were defined using "IF and THEN" rules (Figure 4). These rules were examined in parallel using an algorithm responsible for the computational treatment of sets of rules, which reflect the knowledge of the experts and the representation of a scenario capable of leading to the determination of the degree of sustainability in RESEX in the state of Amazonas. This stage can be understood as a metric that uses fuzzy logic to map the relationship between input and output variables [108].

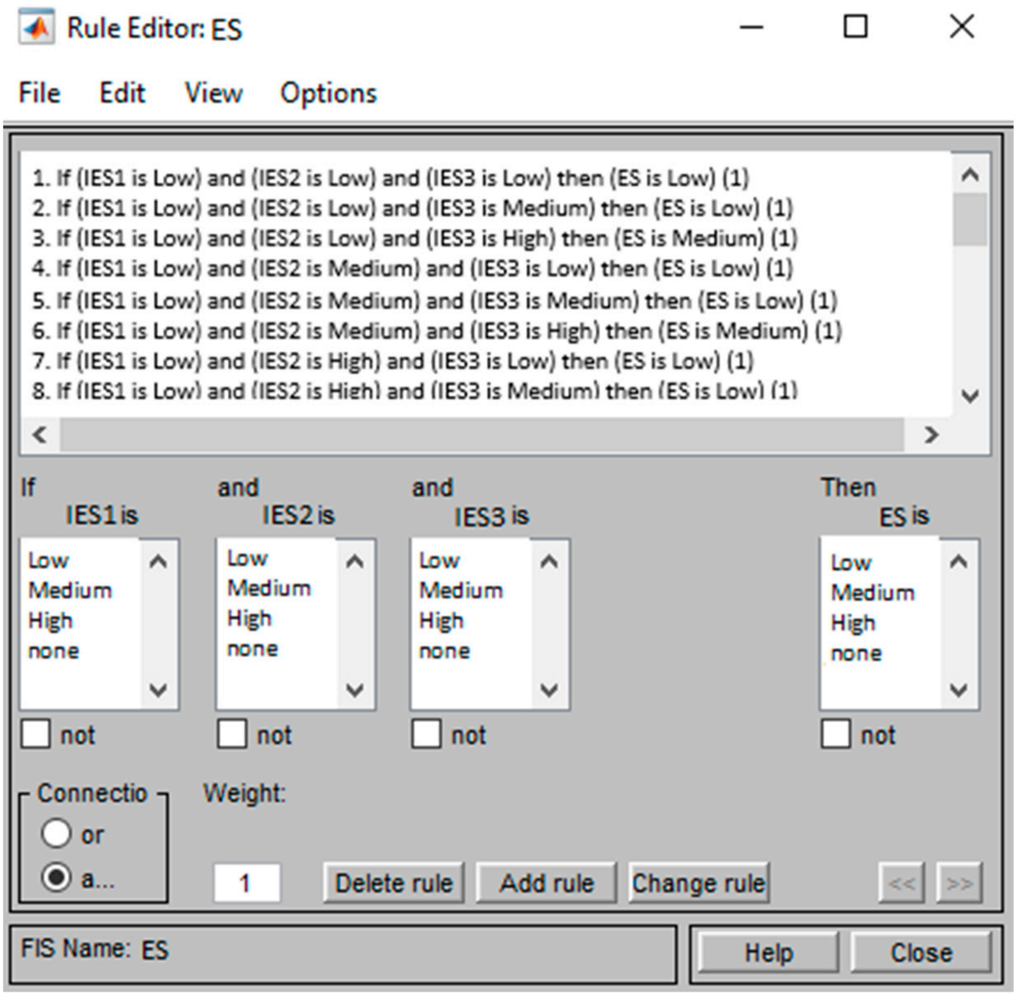

Figure 4. Definition of the ES inference rules in the MatLab software toolbox version R2013a (Source: Authors).

In the Defuzzification stage, MatLab software version R2013a was used to compile the indicator aggregation algorithms. In this stage, the region resulting from the inference stage was translated into numerical values, turning qualitative information into quantitative. Standard Mamdeni type inference operators (Min–Max) were used, with Defuzzification by centre of gravity (centroid). These operators are among the most widely used methods in this process [109]. The first provides an action on the average value of all the individual control actions, with the pertinence functions assuming a maximum value between 0 and 1, while in the second method, the numerical control action is calculated from the centre of gravity of the global control action arrangements. Finally, the results achieved were compiled to reach a final conclusion on the performance of the SRE. To this end, the performance of the sustainability indicators and their effects on the sustainability performance of the ES, ECS, SS, and IS were analysed, as well as the ability of the proposed methodology to promote realistic sustainability scenarios under uncertainty in RESEX in the state of Amazonas.

3. Results and Discussion

3.1. Environmental Sustainability

The sustainability of the Environmental Subsystem (ES) in the fuzzy inference process produced an output considered high in the Defuzzification stage, with sustainability reaching a performance level of 80.8 (Figure 5). This result is consistent with the low loss of vegetation cover in the RESEX, which, between 2010 and 2022, was equivalent to 0.16% (77.16 km^2) of their territories, guaranteeing an integrity of 99.9% of the vegetation cover, according to the IES1. In addition to a low cattle herd in these territories, which currently stands at 1114 head and represents an AU/ha of 0.02, according to IES2, and the land regularisation of RESEX almost in its entirety, which corresponds to 96.2% of their areas, as shown by IES3.

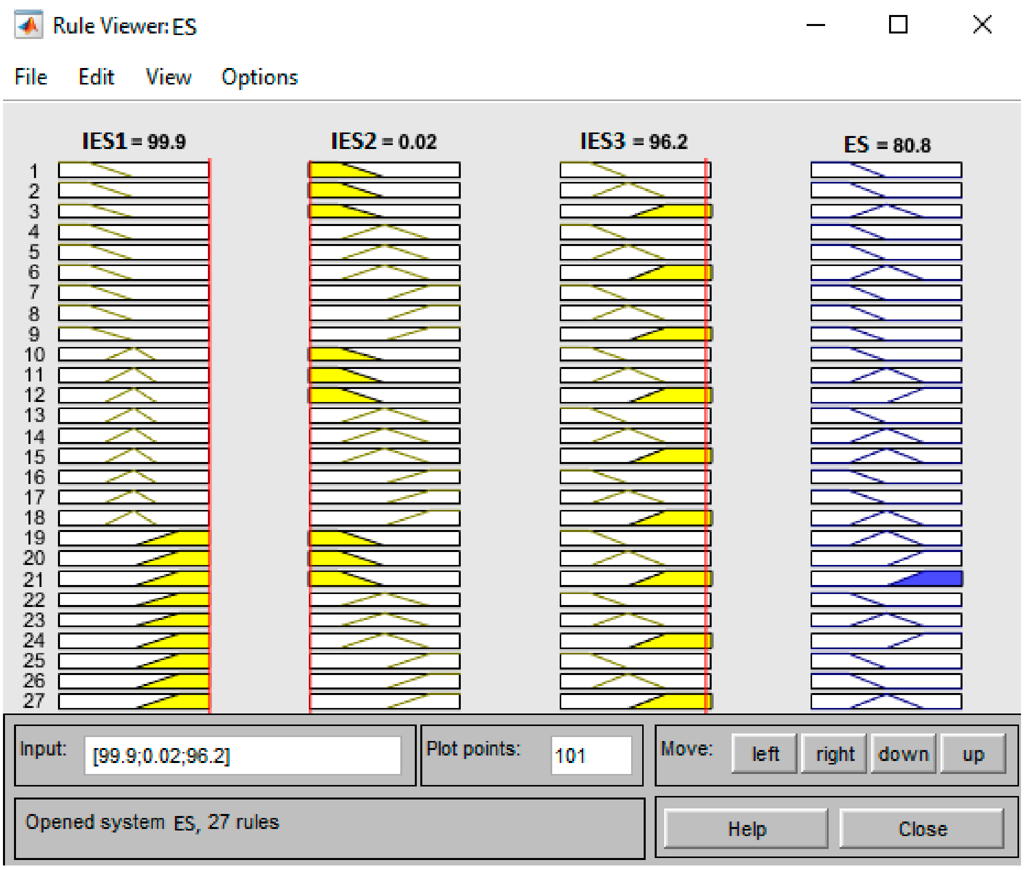

Figure 5. Fuzzy inference of the Environmental Subsystem (Source: Authors).

Protected areas inhabited by human populations have been shown to be more effective in conserving biodiversity, and traditional peoples and communities in these areas play a critical role in global biodiversity conservation objectives, despite the fact that these populations are present in less than 15 percent of the planet's forests [110].

3.2. Economic Sustainability

The sustainability of the Economic Subsystem (ECS) (Figure 6) resulted in the Defuzzification stage in an output with a performance grade of 20.1, which reflects the low sustainability of the ECS.

This performance is related to the concentration of the extractive economy in RESEX, with an average of only 4.02 products, according to IECS1, and the low supply of public policies for this sector, with an average of 0.84 per RESEX, as represented by IECS2.

In these areas, the production of Brazil nuts (*Bertholletia excelsa* Humb. & Bonpl.), managed fishing, particularly that of the pirarucu (*Arapaima gigas* Schinz, 1822), and the production of manioc flour (*Manihot esculenta* Crantz) stand out as the main productive activities. This concentration contributes to the economic unviability of extractive activities and the economic empowerment of local populations. This economy in the RESEX is also affected by the absence or poor quality of policies for this sector, despite the fact that nine support programmes for productive activities have been identified in these RESEX, which are not evenly distributed among them. In the Amazon, with the decline of the extractive economy comes the expansion of the agricultural frontier, the emergence of new economic alternatives, an increase in population density, the emergence of substitute products [34], among others.

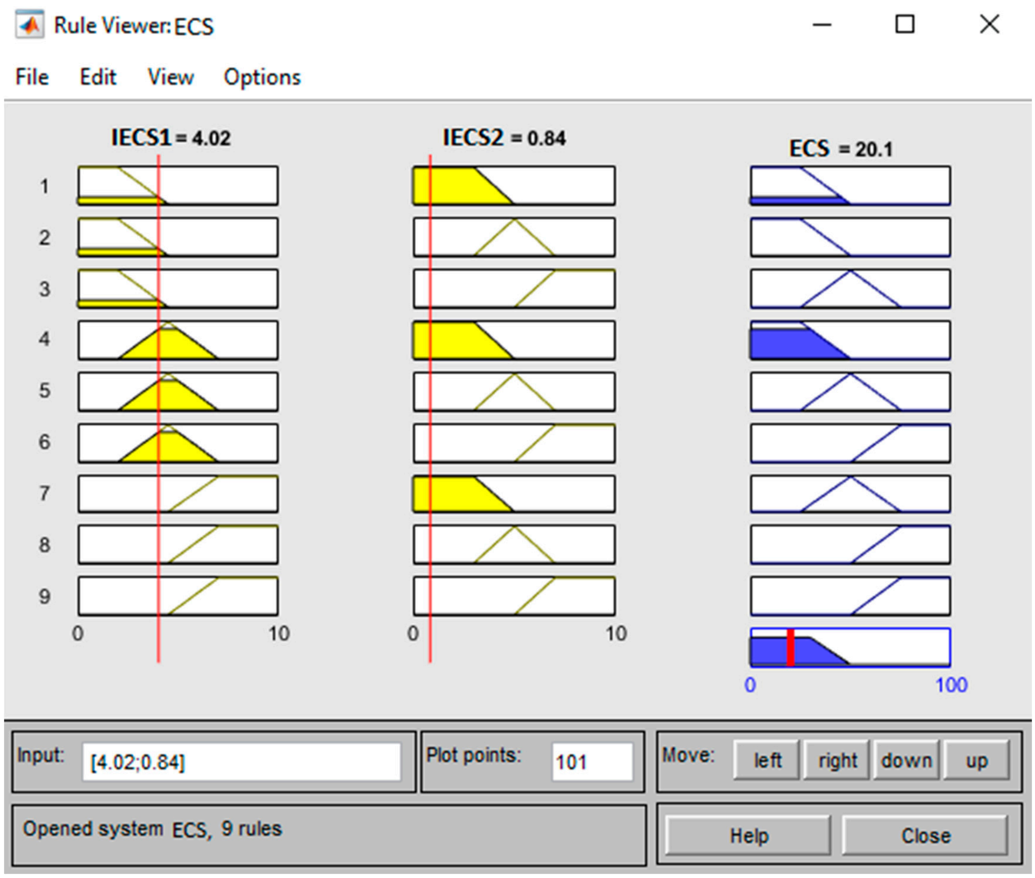

Figure 6. Fuzzy inference of the Economic Subsystem (Source: Authors).

3.3. Social Sustainability

The sustainability of the Social Subsystem (SS) showed a low performance value (17.0) in the Defuzzification stage (Figure 7). This result is consistent with the absence or low quality of public social development policies made available to families in RESEX, such as those that promote access for these families to infrastructure and communication services, as well as basic sanitation, represented by ISS1 and ISS2, with a performance that was 11.3 and 11.3, respectively.

In percentage terms, the results presented by ISS1 and ISS2 represent the 528 families in the Middle Juruá RESEX who access these services, unlike what happens in the other RESEXs investigated. In this RESEX, public policies have played an important role in promoting environmental health and quality of life for families. It has a number of programmes stemming from public–private partnerships and organised civil society, making it the only RESEX in the state of Amazonas to offer distance learning higher education, which is the result of a partnership with the Federal University of Amazonas (UFAM). Public policies become efficient in RESEX when they ensure adequate livelihoods for their populations, with high financial incomes, access to health services and education, among others [111,112]. In protected areas, guaranteeing adequate livelihoods for the local populations and those around them is a fundamental requirement for forest conservation [113].

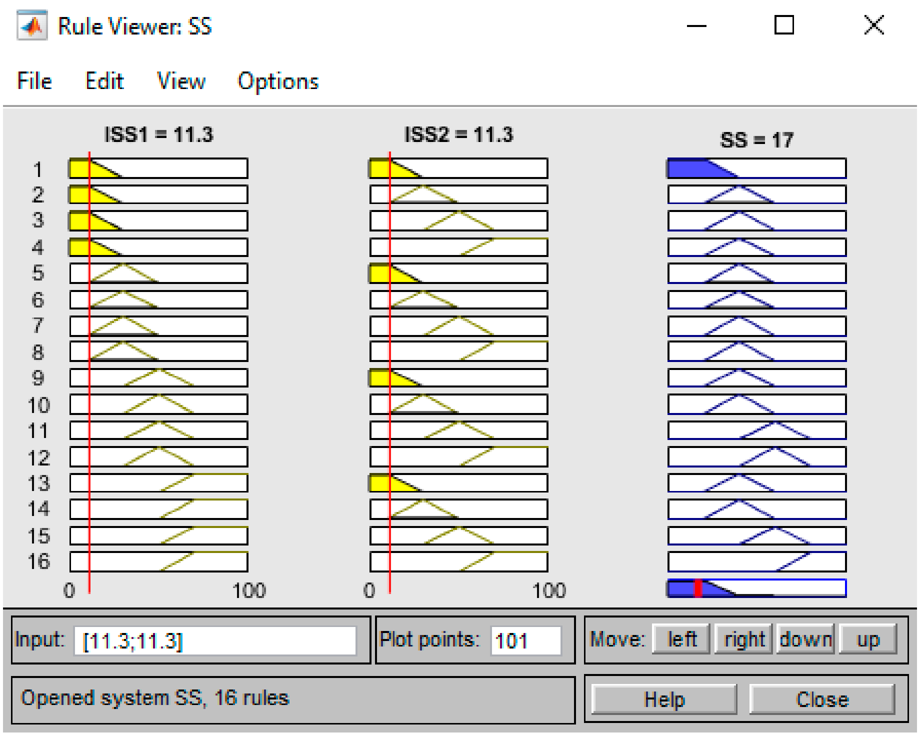

Figure 7. Fuzzy inference of the Social Subsystem (Source: Authors).

3.4. Institutional Sustainability

The sustainability result produced in the output at the Defuzzification stage for the Institutional Subsystem (IS) was 40.0 (Figure 8). Although this performance was higher than the sustainability performance of the ECS and SS, it is still considered a low level of performance. It is related to the low financial investments in recent years aimed at managing and supervising RESEX. These investments, between 2014 and 2021, totalled BRL 13,621,404, equivalent to BRL 42.7/km^2/year, represented by the IIS1. Although this figure exceeds the national average for investment in the Conservation Units in Brazil and that of countries like Argentina (BRL 21.37), Costa Rica (BRL 32.29), and Mexico (BRL 39.71), it is still lower than that of countries like New Zealand (BRL 110.39) and the United States (BRL 156.12) [104].

The low sustainability performance of the IS was also influenced by the time it takes to approve management plans, which currently takes 8.7 years, as indicated by the IIS2, exceeding the mandatory period of five years from the creation of the CU, as determined by the NSCU. The Management Plan is a fundamental instrument in the management of protected areas, through which the way in which humans occupy the space and appropriate the natural resources is standardised. This guarantees sustainable management with less impact on local ecosystems [16]. In addition, there is the low number of civil servants responsible for managing and supervising RESEX, which have 46 civil servants for these functions, equivalent to one civil servant for every 991 km^2, according to IIS3, even exceeding the national average of one civil servant for 186 km^2 [104].

The ES indicators were the best performers, contributing to this subsystem's high performance in the Defuzzification stage, showing the high environmental health in RESEX and the importance that traditional populations in these areas play in forest conservation. In contrast, the low performance of the ECS, SS, and IS indicators contributed to these subsystems showing a low level of performance in the Defuzzification stage. These designs resulted in the SRE system achieving a performance value of 30.0 (Figure 9), on a scale of 0 to 100, which demonstrates low sustainability in the RESEX investigated.

Figure 8. Fuzzy inference of the Institutional Subsystem (Source: Authors).

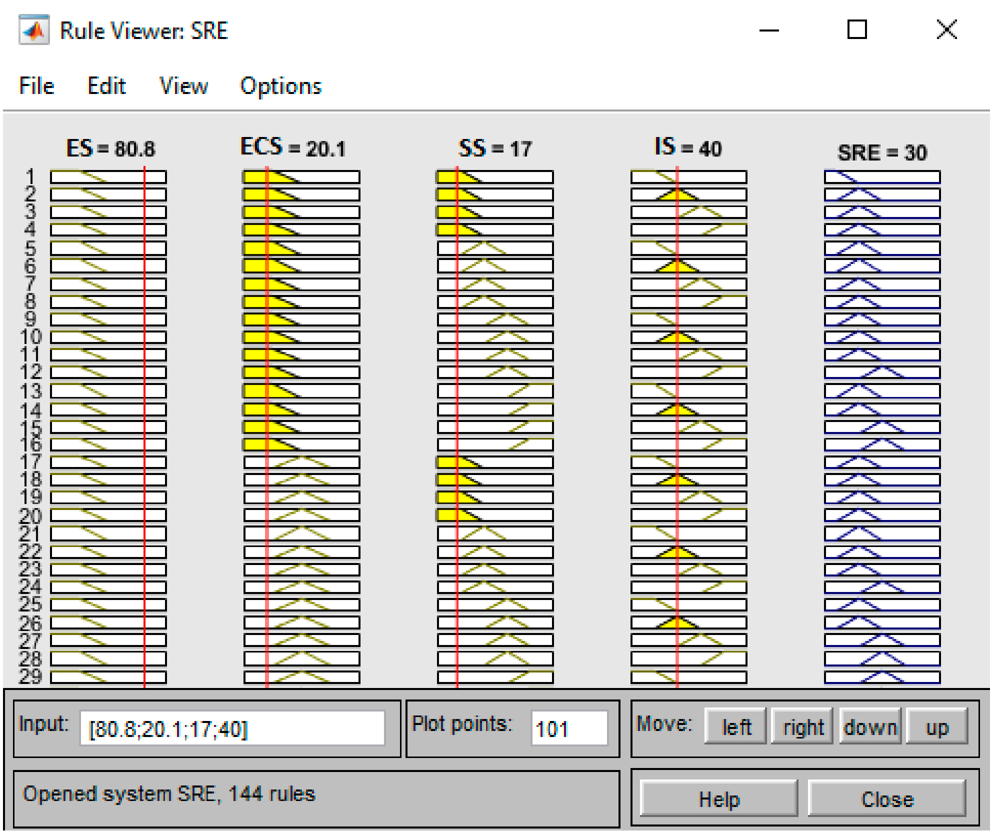

Figure 9. Fuzzy inference of the SRE system (Source: Authors).

The ability of the proposed methodology using the fuzzy logic method to quantitatively represent the degree of sustainability of the ES, ECS, SS, and IS dimensions and how these performances affect the degree of the SRE system, has enabled the modelling of sustainability under uncertainty and imprecision in RESEX in the state of Amazonas, as well as a better understanding of the human–nature relationship in these territories. It has highlighted the main phenomena that impact the degree of sustainability in RESEX, such as the absence or low quality of public social development policies, and these policies are aimed at promoting extractive activities and incipient financial and personnel investments for management and inspection, which limit the actions envisaged in the management plans with regard to promoting social development in these spaces, where the discrepancy between environmental health and social well-being has been evident. Protected areas that allow sustainable extractive activities, despite being effective in containing deforestation, are less effective in reducing poverty [114]. The reality of the RESEX investigated is also experienced by other RESEXs located in the Amazon region, where the lack of an alliance between environmental conservation and social development has led to socio-environmental erosion [28] and organisational deterioration [115]. Despite this situation, the RESEXs investigated have fulfilled one of their fundamental objectives, which is the conservation of biodiversity, and this translates into a low loss of vegetation cover in their territories, guaranteed above all by the traditional way of life of the local populations in working with and managing nature. This reinforces the idea of these areas acting as barriers to contain deforestation in the Amazon [25,27,116]. In particular, in the state of Amazonas, where deforestation between 2014 and 2022 showed a significant increase, resulting in the suppression of 12,493 km^2 of forest, making it the second most deforested state in the Amazon region between 2021 and 2022, behind only the state of Pará [61].

Using the proposed methodology, the phenomena that impact the sustainability of RESEX were represented using linguistic variables and weighted in terms of their complexity, and inferences were made using a set of decision rules, which quantitatively contextualise sustainability under uncertainty and imprecision in RESEX. Fuzzy logic offers suitable methods and is easy to implement [46], which makes it a viable alternative for modelling sustainability in complex systems such as socio-environmental systems [117–119]. Modelling these systems is an expensive process because most of the tools used for formal modelling are deterministic and precise [50]. This is the situation with indicator systems, which tend not to measure sustainability in a systemic way; in many cases, place greater emphasis on the human factor [120]; and, like stochastic methods, are not suitable for modelling scenarios under uncertainty [50,56].

The above-mentioned characteristics attribute important aspects to the methodology and its ability to contextualise sustainability under uncertainty and imprecision in RESEX, as well as an instrument capable of helping managers and decision-makers formulate public policies that meet local social demands, capable of promoting the ecological and social character of RESEX, their identities as sustainable use conservation units, resilience to the effects of climate change and sustainable development in these areas. This methodology can also make the sustainability assessment process more democratic, in which decision rules can be drawn up and reflect the knowledge of specialists involved in the management of these areas such as local managers, community representatives, field technicians, and others, making it possible to include new variables and parameters in addition to those used in this study, thus promoting realistic sustainability scenarios in these spaces.

4. Conclusions

The methodology proposed for evaluating the degree of sustainability in RESEX showed that, although these areas are environmentally healthy, as demonstrated by the ES, sustainability in these areas has been made unfeasible by the absence or low quality of public policies for social development and these policies aimed at promoting extractivist activity, as well as by the low financial and personnel investments for management and inspection, which limits the actions provided for in the Management Plans, such as those aimed at promoting social development, leading to the low performance of the ECS, SS, and IS. This is reflected in the low performance value (30.0) of the SRE system, in a numerical range varying between 0 and 100, indicating low sustainability in the RESEX in the state of Amazonas. There is a clear discrepancy between environmental health and social well-being, which is the main obstacle to consolidating the RESEX model.

The methodology used is sensitive to the main phenomena that impact on the sustainability of RESEX represented by linguistic variables, allowing sustainability to be quantitatively contextualised under uncertainty and imprecision in RESEX. The proposed methodology can be useful for RESEX managers and decision-makers, as well as for identifying and monitoring the main phenomena that impact sustainability, as well as helping to formulate and implement public policies that meet the demands of local society, making better use of the resources earmarked for management and promoting a more democratic process in assessing sustainability, among other things. This will ensure greater empowerment of these spaces in the Amazon region since they play an important role in containing deforestation caused mainly by cattle ranching and extensive agriculture in this region, guaranteed mainly by the way local people work and manage nature.

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Institutional Review Board Statement: This study was conducted in accordance with the guidelines of the Declaration of Helsinki. The procedures adopted in this study for gathering information, which was based on field and documentary research, dispensed with invasive methods in dealing with human beings and, as such, ethical approval for this study was waived.

Informed Consent Statement: As these are Federal and State Extractive Reserves, prior to gathering the information, the Authorisation for Activities for Scientific Purposes (No. 84260–1, dated 31 August 2022) and the Project Authorisation Term (No. 029/2022–DEMUC/ASSE, dated 4 July 2022) were issued by the Amazonas State Secretariat for the Environment (ASSE/AM) on the Ministry of the Environment (ME) portal, in the National Biodiversity Information and Authorisation System (NBIS).

Data Availability Statement: The data presented in this study can be made available upon request to the corresponding author. Other data, results, and publications related to this manuscript can be accessed through the electronic addresses available in this manuscript.

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References

1. Mu, Y.; Jones, C. An observational analysis of precipitation and deforestation age in the Brazilian Legal Amazon. *Atmos. Res.* **2022**, *271*, 106122. [CrossRef]
2. Viana, V.; Torres, E.; Val, A.; Salviati, V. Soluções para o desenvolvimento sustentável da Amazônia. *Ciência Cult.* **2014**, *66*, 25–29. [CrossRef]
3. Hirschberger, P. *Forests Ablaze: Causes and Effects of Global Forest Fires*; WWF: Berlim, Germany, 2016.
4. Costa, C. Amazônia: O que Ameaça a Floresta em Cada um de Seus 9 Países? 2020. Available online: https://www.bbc.com/portuguese/brasil-51377232 (accessed on 9 October 2023).
5. Evangelista-Vale, J.C.; Weihs, M.; José-Silva, L.; Arruda, R.; Sander, N.L.; Gomides, S.C.; Machado, T.M.; Pires-Oliveira, J.C.; Barros-Rosa, L.; Castuera-Oliveira, L.; et al. Climate change may affect the future of extractivism in the Brazilian Amazon. *Biolog. Conser.* **2021**, *257*, 109093. [CrossRef]
6. CNUC, Cadastro Nacional de Unidades de Conservação. Unidades de Conservação por Bioma. 2020. Available online: https://www.gov.br/mma/pt-br/assuntos/areas-protegidas/plataforma-cnuc-1/CNUC_FEV20C_Bio.pdf (accessed on 21 September 2023).

7. Viana, V. Health Climate Justice and Deforestation in the Amazon. In *Health of People, Health of Planet and Our Responsibility: Climate Change, Air Pollution and Health*; Al-Delaimy, W., Ramanathan, V., Sánchez Sorondo, M., Eds.; Springer Nature: Vatican City, Italy, 2020. Available online: https://link.springer.com/book/10.1007/978-3-030-31125-4 (accessed on 14 November 2023).
8. CNUC, Cadastro Nacional de Unidades de Conservação. Tabela Consolidada das Unidades de Conservação. 2020. Available online: https://antigo.mma.gov.br/images/arquivo/80229/CNUC_FEV20%20-%20B_Cat.pdf (accessed on 21 September 2023).
9. Maciel, R.C.G.; Cavalcanti, F.C.S.; Souza, E.F.; Oliveira, O.F.; Cavalcante Filho, P.G. The "Chico Mendes" extractive reserve and land governance in the Amazon: Some lessons from the two last decades. *J. Environ. Manag.* **2018**, *223*, 403–408. [CrossRef] [PubMed]
10. Pereira, G.P.; Fenelon, A.N.; Oliveira, M.L.R. Perspectivas e desafios na criação de uma Reserva Extrativista. Marinha. *Rev. Agronegócio Meio Ambiente* **2019**, *12*, 1291–1316. [CrossRef]
11. Nascimento, T.P.; Nascimento, J.R. Participação social nos processos de criação e gestão da Reserva Extrativista Marinha de Tracuateua-PA, Brasil. *Novos Cad. NAEA* **2020**, *23*, 129–154. [CrossRef]
12. Murrieta, J.R.; Rueda, R.P. *Reservas Extrativistas*; Suíça e Cambridge, Reino Unido, UICN: Gland, Switzerland, 1995.
13. Vadjunec, J.M.; Rocheleau, D. Beyond forest cover: Land use and biodiversity in rubber trail forests of the Chico Mendes Extractive Reserve. *Ecol. Soc.* **2009**, *14*, 29. [CrossRef]
14. Brasil. *Decreto n° 98.897, de 30 de Janeiro de 1990. Diário Oficial [da] República Federativa do Brasil, Brasília, 31 de Janeiro de 1990*; DOU: Brasília, Brazil, 1990.
15. Brasil. *Lei n° 7.804, de 18 de Julho de 1989. Diário Oficial [da] República Federativa do Brasil, Brasília, 20 de Julho de 1989*; DOU: Brasília, Brazil, 1989.
16. Wadt, L.H.O.; Kainer, K.A.; Staudhammer, C.L.; Serrano, R.O.P. Sustainable forest use in Brazilian extractive reserves: Natural regeneration of Brazil nut in exploited populations. *Biolog. Conser.* **2008**, *141*, 332–346. [CrossRef]
17. Espínola, R.S.; Castro, V.M. Ecoturismo e gestão participativa em Áreas Protegidas: O caso da Floresta Nacional do Tapajós (PA). *Rev. Bras. Ecot.* **2012**, *5*, 281–296. [CrossRef]
18. Rocha, T.T.; Tavares-Martins, A.C.C.; Lucas, F.C.A. Traditional populations in environmentally protected areas: An ethnobotanical study in the Soure Marine Extractive Reserve of Brazil. *Boletín Lat. Car. Plantas Medic. Arom.* **2017**, *16*, 410–427.
19. Wallace, R.H.; Gomes, C.V.A.; Cooper, N.A. The Chico Mendes Extractive Reserve: Trajectories of agro-extractive development in Amazonia. *Desenvolv. Meio Ambiente* **2018**, *48*, 184–213. [CrossRef]
20. Lima, D.M.; Peralta, N. Programas de transferência de renda em duas Unidades de Conservação na Amazônia brasileira e Sustentabilidade. *Novos Cad. NAEA* **2016**, *19*, 43–67. [CrossRef]
21. Fearnside, P.M. Extractive reserves in Brazilian Amazonia. *BioScience* **1989**, *39*, 387–393. [CrossRef]
22. Goeschl, T.; Igliori, D.C. Property rights for biodiversity conservation and development: Extractive reserves in the Brazilian Amazon. *Dev. Chang.* **2006**, *37*, 427–451. [CrossRef]
23. Allegretti, M.H. Política de uso dos recursos naturais renováveis: A Amazônia e o extrativismo. *Rev. Admin. Pública* **1992**, *26*, 145–162.
24. Nobre, D.M.; Alarcon, D.T.; Cinti, A.; Schiavettie, A. Governance of the Cassurubá Extractive Reserve, Bahia State, Brazil: An analysis of strengths and weaknesses to inform policy. *Mar. Policy* **2017**, *77*, 44–55. [CrossRef]
25. Fearnside, P.M.; Nogueira, E.M.; Yanai, A.M. Maintaining carbon stocks in extractive reserves in Brazilian Amazonia. *Desenvolv. Meio Ambiente* **2018**, *48*, 446–476. [CrossRef]
26. Cavalcante Filho, P.G.; Maciel, R.C.G.; Oliveira, F.O.; Hundertmarck, C.L.C.; Silva, Í.H.B.; Almeida, M. Dinâmica inovativa e investimento na Reserva Extrativista Chico Mendes. *Braz. J. Dev.* **2019**, *5*, 13358–13382. [CrossRef]
27. Almeida, M.W.B.; Allegretti, M.H.; Postigo, A. O legado de Chico Mendes: Êxitos e entraves das Reservas Extrativistas. *Desenvolv. Meio Ambiente* **2018**, *48*, 25–55.
28. Freitas, J.S.; Rivas, A.F. Unidades de Conservação Promovem Pobreza e Estimulam Agressão à Natureza na Amazônia. *Rev. Gestão Soc. Amb.* **2014**, *8*, 18–34.
29. Silva, J.B.; Simonian, L.T.L. População tradicional, Reservas Extrativistas e racionalidade estatal na Amazônia brasileira. *Desenvolv. Meio Ambiente* **2015**, *33*, 163–175. [CrossRef]
30. Freitas, J.S.; Mathis, A.; Caldas, M.M.; Homma, A.K.O.; Farias Filho, M.C.; Rivas, A.A.F.; Santos, K.M. Socio-environmental success or failure of Extractive Reserves in the Amazon? *Res. Soc. Dev.* **2021**, *10*, 11610514631. [CrossRef]
31. Spínola, J.N.; Carneiro Filho, A. Criação de gado em Reservas Extrativistas: Ameaça ou necessidade? O caso da Reserva Extrativista tapajós-Arapiuns, Pará, Brasil. *Desenvolv. Meio Ambiente* **2019**, *51*, 224–246. [CrossRef]
32. Assunção, J.; Mobarak, A.M.; Lipscomb, M.; Szerman, D. Agricultural Productivity and Deforestation in Brazil. 2016. Available online: https://www.climatepolicyinitiative.org/wp-content/uploads/2017/06/Agricultural-Productivity-and-Deforestation-in-Brazil-CPI.pdf (accessed on 17 July 2022).
33. Silva, A.G.; Silva, F.C.; Yamada, T. Reprodução social de populações tradicionais e pecuária na Reserva Extrativista Chico Mendes: Reflexões a partir dos projetos de vida de jovens extrativistas. *Desenvolv. Meio Ambiente* **2019**, *52*, 235–260. [CrossRef]
34. Homma, A.K.O. Amazônia: Manter a floresta em pé ou plantar? *Rev. Econ. Agronegócio* **2020**, *18*, 1–17. [CrossRef]
35. Franco, A.O.; Sahr, C.L.L. De modelo ideal de gestão territorial à realidade atual: As disfuncionalidades na reserva extrativista chico mendes (ACRE/BRASIL). *RAEGA O Espaço Geogr. Análise* **2022**, *54*, 37–58.

36. Van Huynh, C.; Le, Q.N.P.; Nguyen, M.T.H.; Tran, P.T.; Nguyen, T.Q.; Pham, T.G.; Nguyen, L.H.K.; Nguyen, L.T.D.; Trinh, H.N. Indigenous knowledge in relation to climate change: Adaptation practices used by the Xo Dang people of central Vietnam. *Heliyon* **2020**, *6*, e05656. [CrossRef]
37. IPCC. Painel Intergovernamental sobre Mudança do Clima. *Mudança do Clima 2023: Relatório Síntese*; IPCC: Genebra, Switzerland, 2023.
38. Farias, G.A.M. Evidências do Efeito do Aquecimento Global Sobre a Reserva Extrativista Marinha (RESEX) do Delta do Parnaíba (PI). Master's Thesis, Universidade Estadual do Oeste do Paraná, UNIOESTE, Toledo, Brazil, 2022.
39. Silva, R.M.; Lopes, A.G.; Santos, C.A.G. Deforestation and fires in the Brazilian Amazon from 2001 to 2020: Impacts on rainfall variability and land surface temperature. *J. Environ. Manag.* **2023**, *326*, 116664. [CrossRef] [PubMed]
40. Marengo, J.A.; Souza Junior, C. *Mudanças Climáticas: Impactos e Cenários Para a Amazônia*; Alana: São Paulo, Brazil, 2018.
41. Builes-Jaramillo, A.; Valencia, J.; Salas, H.D. The influence of the El Niño-Southern Oscillation phase transitions over the northern South America hydroclimate. *Atmos. Res.* **2023**, *290*, 106786. [CrossRef]
42. Butler, R.A. The Year in Rainforests: 2023. Available online: https://news.mongabay.com/2023/12/the-year-in-rainforests-2023/ (accessed on 27 December 2023).
43. Pereira, J.; Bispo, F. O Clima no Futuro Será de Extremos, Mas não é o fim, diz Cientista José Marengo. Available online: https://infoamazonia.org/2023/12/01/o-clima-no-futuro-sera-de-extremos-mas-nao-e-o-fim-diz-cientista-jose-marengo/ (accessed on 27 December 2023).
44. Copernicus Climate Change Service. Copernicus: 2023 in the Hottest Year on Record, with Global Temperatures Close to the 1.5 °C Limit. *Disponível em.* Available online: https://climate.copernicus.eu/copernicus-2023-hottest-year-record#:~:text=Global%20surface%20air%20temperature%20highlights:&text=2023%20marks%20the%20first%20time,than%202%C2%B0C%20warmer (accessed on 13 January 2024).
45. Campos Filho, P. Método Para apoio à Decisão na Verificação da Sustentabilidade de uma Unidade de Conservação, Usando Lógica Fuzzy. Ph.D. Thesis, Universidade Federal de Santa Catarina, UFSC, Florianópolis, Brazil, 2004.
46. Santos, S.A.; Lima, H.P.; Massruhá, S.M.F.S.; Abreu, U.G.P.; Tomás, W.M.; Salis, S.M.; Cardoso, E.L.; Oliveira, M.D.; Soares, M.T.S.; Santos Júnior, A.; et al. A fuzzy logic-based tool to assess beef cattle ranching sustainability in complex environmental systems. *J. Environ. Manag.* **2017**, *198*, 95–106. [CrossRef]
47. Vieira, I.C.G. Abordagens e desafios no uso de indicadores de sustentabilidade no contexto amazônico. *Ciência Cult.* **2019**, *71*, 46–50. [CrossRef]
48. Mcneill, F.M.; Thro, E. *Fuzzy Logic: A Practical Approach*; Academic Press: London, UK, 2014.
49. Gomide, F.A.C.; Gudwin, R.R. Modelagem, controle, sistemas e lógica Fuzzy. *SBA Contr. Autom.* **1994**, *4*, 97–115.
50. Zimmermann, H.J. Fuzzy set theory. *Wiley Interd. Rev. Comp. Statis.* **2010**, *2*, 317–332. [CrossRef]
51. Singh, H.; Gupta, M.M.; Meitzler, T.; Hou, Z.; Garg, K.K.; Solo, A.M.G.; Zadeh, L.A. Real-life applications of fuzzy logic. *Adv. Fuzzy Syst.* **2013**, *2013*, 581879. [CrossRef]
52. Vairal, K.L.; Kulkarni, S.D.; Basotia, V. Fuzzy logic and its applications in some area: A mini review. *J. Eng. Sci.* **2020**, *11*, 85–96.
53. Sun, X.; Zhang, L.; Lu, S.; Tan, X.; Chen, K.; Zhao, S.; Huang, R. A new model for evaluating sustainable utilization of coastline integrating economic output and ecological impact: A case study of coastal areas in Beibu Gulf, China. *J. Clean. Prod.* **2020**, *271*, 122423. [CrossRef]
54. Zeng, X.T.; Huang, G.H.; Yang, X.L.; Wang, X.; Fu, H.; Li, Y.P.; Li, Z. A developed fuzzy-stochastic optimization for coordinating human activity and eco-environmental protection in a regional wetland ecosystem under uncertainties. *Ecol. Eng.* **2016**, *97*, 207–230. [CrossRef]
55. Lü, Y.; Chen, L.; Fu, B.; Liu, S. A framework for evaluating the effectiveness of protected areas: The case of Wolong Biosphere Reserve. *Landsc. Urban Plan.* **2003**, *63*, 213–223. [CrossRef]
56. Prato, T. Fuzzy adaptive management of social and ecological carrying capacities for protected areas. *J. Environ. Manag.* **2009**, *90*, 2551–2557. [CrossRef]
57. Stoms, D.M.; Mcdonald, J.M.; Davis, F. W Fuzzy assessment of land suitability for scientific research reserves. *Environ. Manag.* **2002**, *29*, 545–558. [CrossRef]
58. FAS, Fundação Amazônia Sustentável. FAS de Olho nas Políticas Públicas Socioambientais–n° 01/2020: Nota Técnica Sobre o Projeto de Lei n° 2.633/2020. 2020. Available online: https://fas-amazonia.org/novosite/wp-content/uploads/2022/02/psi-posicionamento-pl-2633-2020-fas-v10.pdf (accessed on 5 September 2022).
59. FAS, Fundação Amazônia Sustentável. *Unidades de Conservação do Amazonas: Histórico, Presente e Futuro*, 1st ed.; Fundação Amazônia Sustentável: Manaus, Brazil, 2020.
60. PRODES–INPE; Projeto de Monitoramento do Desmatamento na Amazônia Legal por Satélite–Instituto Nacional de Pesquisas Espaciais. Incrementos de Desmatamento–Amazônia–Unidades de Conservação. Available online: http://terrabrasilis.dpi.inpe.br/app/dashboard/deforestation/biomes/amazon/increments (accessed on 12 April 2023).
61. PRODES–INPE; Projeto de Monitoramento do Desmatamento na Amazônia Legal por Satélite–Instituto Nacional de Pesquisas Espaciais. Incremento de Desmatamento–Amazônia–Estados. Available online: http://terrabrasilis.dpi.inpe.br/app/dashboard/deforestation/biomes/legal_amazon/increments (accessed on 14 December 2023).
62. IBGE, Instituto Brasileiro de Geografia e Estatística. Pesquisa da Pecuária Municipal. Available online: https://sidra.ibge.gov.br/pesquisa/ppm/quadros/brasil/2020 (accessed on 17 May 2023).

63. Bessa, D.M. Ciclo do Carbono na Floresta Amazônica: Percepções Ambientais de Moradores da Reserva Extrativista do Baixo Juruá, Amazônia Ocidental, Brasil. Master's Thesis, Universidade Federal do Amazonas, UFAM, Manaus, Brazil, 2019.
64. Brasil–FUNBIO; Fundo Brasileiro Para a Biodiversidade. Relatório L–Finanças Específicas do Fundo de Transição Para os Doadores. 2021. Available online: http://arpa.mma.gov.br/wp-content/uploads/2022/01/Programa-ARPA-Relatorio-L-Outubro-2021-Retificado.pdf (accessed on 11 October 2022).
65. Brasil–MMA; Ministério do Meio Ambiente. Todas as Unidades de Conservação. Available online: https://www.gov.br/icmbio/pt-br/assuntos/biodiversidade/todas-as-unidades-de-conservacao (accessed on 27 August 2022).
66. SEMA, Secretaria de Estado do Meio Ambiente do Estado do Amazonas. Unidades de Conservação. Available online: https://meioambiente.am.gov.br/unidade-de-conservacao/ (accessed on 23 November 2022).
67. Holden, E.; Linnerud, K.; Banister, D. Sustainable development: Our common future revisited. *Glob. Environ. Chang.* **2014**, *26*, 130–139. [CrossRef]
68. IBGE, Instituto Brasileiro de Geografia e Estatística. *Indicadores de Desenvolvimento Sustentável*; IBGE: Rio de Janeiro, Brazil, 2015.
69. Teles, C.D.; Dutra, C.C.; Ribeiro, J.L.D.; Guimarães, L.B.M. Uma proposta para avaliação da sustentabilidade socioambiental utilizando suporte analítico e gráfico. *Production* **2016**, *26*, 417–429. [CrossRef]
70. Nilashi, M.; Rupani, P.F.; Rupani, M.M.; Kamyab, H.; Shao, W.; Ahmadi, H.; Rashid, T.A.; Aljojo, N. Measuring sustainability through ecological sustainability and human sustainability: A machine learning approach. *J. Clean. Prod.* **2019**, *240*, 118162. [CrossRef]
71. Feil, A.A.; Schreiber, D. Sustentabilidade e desenvolvimento sustentável: Desvendando as sobreposições e alcances de seus significados. *Cad. Ebape. Br.* **2017**, *14*, 667–681. [CrossRef]
72. Brasil. *Lei n° 9.985, de 18 de Julho de 2000. Diário Oficial [da] República Federativa do Brasil, 19 de Julho de 2000*; DOU: Brasília, Brazil, 2000.
73. Brasil. *Decreto n° 4.339, de 22 de Agosto de 2002. Diário Oficial [da] República Federativa do Brasil, Brasília, 23 de Agosto de 2002*; DOU: Brasília, Brazil, 2002.
74. Brasil. *Lei n° 12.651, de 25 de Maio de 2012. Diário Oficial [da] República Federativa do Brasil, Brasília, 28 de Maio de 2012*; DOU: Brasília, Brazil, 2012.
75. Brasil. *Constituição da República Federativa do Brasil: Texto Constitucional Promulgado em 5 de Outubro de 1988, com as Alterações Determinadas Pelas Emendas Constitucionais de Revisão nos 1 a 6/94, pelas Emendas Constitucionais n° 1/92 a 91/2016 e pelo Decreto Legislativo n° 186/2008*; Senado Federal, Coordenação de Edições Técnicas: Brasília, Brazil, 2016.
76. Amazonas. *Lei n° 3.135, de 05 de Junho de 2007; Diário Oficial do Estado do Amazonas, Manaus, 5 de Junho de 2007*; DOE: Manaus, Brazil, 2007.
77. Brasil–ICMBIO; Instituto Chico Mendes de Conservação da Biodiversidade. *Instrução Normativa n° 03, de 18 de Setembro de 2007*; DOU: Brasília, Brazil, 2007.
78. Brasil. *Lei n° 10.831, de 23 de Dezembro de 2003. Diário Oficial [da] República Federativa do Brasil, Brasília, 24 de Dezembro de 2003*; DOU: Brasília, Brazil, 2003.
79. Brasil–MAPA–MMA; Ministro de Estado da Agricultura, Pecuária e Abastecimento e Ministro de Estado do Meio Ambiente. *Instrução Normativa Conjunta n° 17, de 28 de Maio de 2009. Diário Oficial [da] República Federativa do Brasil, Brasília, 29 de Maio de 2009*; DOU: Brasília, Brazil, 2009.
80. Brasil. *Decreto n° 6.040, de 7 de Fevereiro de 2007. Diário Oficial [da] República Federativa do Brasil, Brasília, 8 de Fevereiro de 2007*; DOU: Brasília, Brazil, 2007.
81. Brasil. *Decreto n° 9.334, de 5 de Abril de 2018. Diário Oficial [da] República Federativa do Brasil, Brasília, 6 de Abril e 2018*; DOU: Brasília, Brazil, 2018.
82. Brasil. *Lei n° 9.394, de 20 de Dezembro de 1996. Diário Oficial [da] República Federativa do Brasil, 23 de Dezembro de 1996*; DOU: Brasília, Brazil, 1996.
83. Brasil. *Lei n° 12.796, de 4 de Abril de 2013. Diário Oficial [da] República Federativa do Brasil, Brasília, 5 de Abril de 2013*; DOU: Brasília, Brazil, 2013.
84. Brasil. *Lei n° 11.445, de 5 de Janeiro de 2007. Diário Oficial [da] República Federativa do Brasil, Brasília, 8 de Janeiro de 2007*; DOU: Brasília, Brazil, 2007.
85. Marro, A.A.; Souza, A.M.C.; Cavalcante, E.R.S.; Bezerra, G.S.; Nunes, R.O. *Lógica Fuzzy: Conceitos e Aplicações*; Universidade Federal do Rio Grande do Norte (UFRN): Natal, Brazil, 2010.
86. Nardez, N.N.; Gonçalves, R.M.; Soares, C.R.; Krueger, C.P. Classificação fuzzy da vulnerabilidade aos processos costeiros em Pontal do Paraná, Brasil. *Pesqui. Geociências* **2016**, *43*, 169–181. [CrossRef]
87. Amorim, A.S.; Araújo, M.F.F.; Cândido, G.A. Uso do Barômetro da Sustentabilidade para avaliação de um Município localizado em Região Semiárida do Nordeste Brasileiro. *Desenvolv. Questão* **2014**, *12*, 189–217. [CrossRef]
88. Kronemberger, D.M.P.; Clevelario Junior, J.; Nascimento, J.A.S.; Collares, J.E.R.; Silva, L.C.D. Desenvolvimento sustentável no Brasil: Uma análise a partir da aplicação do barômetro da sustentabilidade. *Soc. Nat.* **2008**, *20*, 25–50. [CrossRef]
89. Peres, C.A. Conservation in sustainable-use tropical forest reserves. *Conser. Biol.* **2011**, *25*, 1124–1129. [CrossRef] [PubMed]

90. Pinillos, D.; Poccard-Chapuis, R.; Bianchi, F.J.J.A.; Corbeels, M.; Timler, C.J.; Tittonell, P.; Ballester, M.V.R.; Schulte, R.P. Landholders' perceptions on legal reserves and agricultural intensification: Diversity and implications for forest conservation in the eastern Brazilian Amazon. *For. Policy Econ.* **2021**, *129*, 102504. [CrossRef]
91. Potenza, R.F.; Quintana, G.O.; Cardoso, A.M.; Tsai, D.S.; Cremer, M.S.; Silva, F.B.; Carvalho, K.; Coluna, I.; Shimbo, J.; Silva, C.; et al. Análise das Emissões Brasileiras de Gases de Efeito Estufa e suas Implicações Para as Metas Climáticas do Brasil 1970–2020. 2021. Available online: http://seeg.eco.br/ (accessed on 18 November 2022).
92. West, T.A.P.; Fearnside, P.M. Brazil's conservation reform and the reduction of deforestation in Amazonia. *Land Use Policy* **2021**, *100*, 105072. [CrossRef]
93. Freitas, J.S.; Mathis, A.; Farias Filho, M.C.; Homma, A.K.O.; Silva, D.C.C. Reservas Extrativistas na Amazônia: Modelo de conservação ambiental e desenvolvimento social? *GEOgraphia* **2017**, *19*, 150–160. [CrossRef]
94. Valentim, J.F.; Andrade, C.M.S. Tendências e perspectivas da pecuária bovina na Amazônia Brasileira. *Amazon. Cienc. Desenvolv.* **2009**, *4*, 9–32.
95. IBGE, Instituto Brasileiro de Geografia e Estatística. *Censo Agropecuário 2017: Características Gerais das Produções Agropecuária e Extrativista, Segundo a Cor ou Raça do Produtor e Recortes Territoriais Específicos*; IBGE: Rio de Janeiro, Brazil, 2022; Volume 9.
96. Brito, B.; Almeida, J.; Gomes, P.; Salomão, R. *10 Fatos Essenciais Sobre Regularização Fundiária na Amazônia Legal*; Imazon: Belém, Brazil, 2021.
97. Arnaud, M.J.C.; Cleps Junior, J. Conflitos Socioterritoriais em unidades de conservação: A RESEX "Verde para Sempre", em Porto de Moz (Pará). *Campo.-Terr. Revista. Geog. Agr.* **2021**, *16*, 482–510.
98. Teixeira, T.H.; Nottingham, M.C.; Ferreira Neto, J.A.; Estrela, L.M.B.; Santos, B.V.S.; Figueredo, N.A. A diversidade produtiva em Reservas Extrativistas na Amazônia: Entre a invisibilidade e a multifuncionalidade. *Desenvolv. Meio Ambiente* **2018**, *48*, 164–183. [CrossRef]
99. Oliveira Júnior, C.J.F.; Voigtel, S.D.S.; Nicolau, S.A.; Aragaki, S. Sociobiodiversidade e agricultura familiar em Joanópolis, SP, Brasil: Potencial econômico da flora local. *Hoehnea* **2018**, *45*, 40–54. [CrossRef]
100. Moegenburg, S.M.; Levey, D.J. Prospects for conserving biodiversity in Amazonian extractive reserves. *Ecol. Lett.* **2002**, *5*, 320–324. [CrossRef]
101. Simonian, L.T.L. Políticas públicas e participação social nas Reservas Extrativistas amazônicas: Entre avanços, limitações e possibilidades. *Desenvolv. Meio Ambiente* **2018**, *48*, 118–139. [CrossRef]
102. Arraes, R.A.; Mariano, F.Z.; Simonassi, A.G. Causas do desmatamento no Brasil e seu ordenamento no contexto mundial. *Rev. Econ. Soc. Rural* **2012**, *50*, 119–140. [CrossRef]
103. Negret, J.F. Flexibilização do capital na Reserva Extrativista Chico Mendes e seu entorno: O cronômetro entrou na floresta. *Soc. Nat.* **2010**, *22*, 373–390. [CrossRef]
104. Medeiros, R.; Young, C.E.F.; Pavese, H.B.; Araújo, F.F.S. *Contribuição das Unidades de Conservação Para a Economia Nacional*; UNEP–WCMC: Brasília, Brazil, 2011.
105. Veríssimo, A.; Rolla, A.; Vedoveto, M.; Futada, S.M. *Áreas Protegidas na Amazônia Brasileira: Avanços e Desafios*; Imazon: Belém, Brazil; Instituto Socioambiental: São Paulo, Brazil, 2011.
106. Barros, L.S.C.; Leuzinger, M.D. Planos de Manejo: Panorama, desafios e perspectivas. *Cad. Prog. Pós-Grad. Direito/UFRGS* **2018**, *13*, 281–303.
107. Quinhoneiro, F.H.F. Desenvolvimento de Metodologia de Análise de Indicadores de Sustentabilidade como Ferramenta Para Tomada de Decisão Utilizando Lógica Fuzzy. Master's Thesis, Instituto de Pesquisas Energéticas e Nucleares, Universidade de São Paulo, USP, São Paulo, Brazil, 2015.
108. Farias, M.S. Realimentação de Estados Baseada em Regras Fuzzy Tipo-2 para Servocontrole de Sistemas Não Lineares. Ph.D. Thesis, Universidade Federal do Rio Grande do Norte, UFRN, Natal, Brazil, 2019.
109. Nogueira, E.L.; Nascimento, M.H.R. Inventory control applying sales demand prevision based on fuzzy inference system. *Itegam-Jetia* **2017**, *3*, 31–36. [CrossRef]
110. Bandiaky-Badji, S.; Lovera, S.; Márquez, G.Y.H.; Leiva, F.J.A.; Robinson, C.J.; Smith, M.A.; Currey, K.; Ross, H.; Agrawal, A.; White, A. Indigenous stewardship for habitat protection. *One Earth* **2023**, *6*, 68–72. [CrossRef]
111. Azevedo, E.M. A efetividade das Reservas Extrativistas no estado do Acre. *Cientif. Multid. J.* **2022**, *9*, 1–21. [CrossRef]
112. Freitas, J.S.; Farias Filho, M.C.; Homma, A.K.O.; Mathis, A. Reservas extrativistas sem extrativismo: Uma tendência em curso na Amazônia? *Rev. Gestão Soc. Ambient* **2018**, *12*, 56–72. [CrossRef]
113. Schwartzman, S.; Nepstad, D.; Moreira, A. Arguing tropical forest conservation: People versus parks. *Conser. Biol.* **2000**, *14*, 1370–1374. [CrossRef]
114. Miranda, J.J.; Corral, L.; Blackman, A.; Asner, G.; Lima, E. Effects of protected areas on forest cover change and local communities: Evidence from the Peruvian Amazon. *World Dev.* **2016**, *78*, 288–307. [CrossRef]
115. Haddad, R.D.; Haddad, M.D.; Melo, C.M.; Madi, R.R.; Coleho, A.S. Análise social, econômica e histórica das reservas extrativistas da Amazônia: Lutas e trajetórias. *Espac. Abierto Cuad. Venez. Soc.* **2019**, *28*, 93–110.
116. Lopes, R.V.P.; Garro, F.L.T.; Leite, J.C. Extractive reserves in the Brazilian Amazon region: Dilemma between environmental health and the well-being of traditional populations. *Rerev. Ibero-Amer. Ciên. Ambiente* **2022**, *13*, 165–180.
117. Andriantiatsaholiniaina, L.A.; Kouikoglou, V.S.; Phillis, Y.A. Evaluating strategies for sustainable development: Fuzzy logic reasoning and sensitivity analysis. *Ecol. Econ.* **2004**, *48*, 149–172. [CrossRef]

118. Pislaru, M.; Trandabat, A.; Avasilcai, S. Environmental assessment for sustainability determination based on fuzzy logic model. In *2nd International Conference on Environmental Science and Technology*; IACSIT Press: Singapore, 2011; Volume 6.
119. Prato, T. Fuzzy Adaptive Management of Coupled Natural and Human Systems. *Dev. Environ. Mod.* **2016**, *28*, 211–225.
120. Eustachio, J.H.P.P.; Caldana, A.C.F.; Liboni, L.B.; Martinelli, D.P. Systemic indicator of sustainable development: Proposal and application of a framework. *J. Clean. Prod.* **2019**, *241*, 118383. [CrossRef]

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