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Analysis of Indicator Dynamics in Agricultural Sustainability using Neutrosophic Cognitive Maps

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Abstract. Agricultural sustainability is a complex system influenced by interconnected environmental, economic, and sociocultural factors, whose relationships are often marked by uncertainty. This study addresses the interdependence of these factors using Neutrosophic Cognitive Maps (NCMs), a methodology capable of modeling causality in complex systems by incorporating degrees of truth, falsity, and indeterminacy. Twelve key indicators across the three dimensions of sustainability were selected, and an NCM was constructed based on expert criteria to visualize and analyze their dynamic interactions. Centrality analysis, following a de-neutrosophication process, revealed that sociocultural indicators, specifically the well-being of the agricultural community (X12) and the preservation of traditional knowledge (X11), along with economic resilience to shocks (X8), possess the greatest influence within the system. Findings underscore the strong interconnection between dimensions, highlighting, for example, the positive influence of traditional knowledge on biodiversity (X1) and the tension between productivity (X5) and natural resources (X2, X3) if not managed sustainably. The research demonstrates the utility of NCMs for capturing the complexity and uncertainty inherent in agricultural sustainability and offers a basis for developing more integrated and adaptive strategies and policies, recognizing the fundamental role of sociocultural dynamics and economic resilience.

Keywords: Agricultural Sustainability, Neutrosophic Cognitive Maps (NCM), Sustainability Indicators, Centrality Analysis, Sociocultural Factors, Economic Resilience, Uncertainty Modeling, Complex Systems

1. Introduction

Sustainability in agriculture is one of the essential features of human existence and the world to come. Yet many factors are amiss, and a new outlook is needed. This study intends to assess the effects of farm environmental, economic, and sociocultural indicators via neutrosophic cognitive mapping. The significance of the study is that without positive considerations of food production, naturalistic resources, and socioeconomic well-being [1]. Already, with climate change and population dynamics rendering information inaccessible at times, agricultural systems could fail. The value of the new contribution is that without this assessment from these perspectives, farms are not likely to sustain operation for the foreseeable future.

Agriculture has evolved from basic familiar practices to highly intensive agriculture based on technological advancements and financial profit. However, changes in agriculture have created significant challenges for the environment—soil erosion, quality loss, and decreased biodiversity. At the same time, economic inequalities and socio-culturally driven challenges like rural depopulation hinder opportunities for sustainability. Thus, in the last few decades, multidisciplinary research has increasingly been important to try to bring together the sustainability triad [2].

Thus, despite extensive research achievements concerning the sustainability triad, a significant gap exists. How can one project uncertainties in a model based on agricultural results? Most of the studies in literature either take one component into account or fail to integrate them without accounting for dimension uncertainties; therefore, the politician/farmer's understanding of how they all depend upon one another or how they differ is lacking [3-6]. Thus, there is a significant gap in research: how can the relationships be determined?

In summary, the complexity of agricultural sustainability arises from the non-linear and interdependent relationships among environmental, economic, and socio-cultural factors, which complicate the development of predictive models. This study addresses these challenges by employing neutrosophic cognitive maps, which utilize neutrosophic logic to represent blurred, uncertain, and causative relationships among variables, thereby providing a more comprehensive understanding of sustainable agricultural systems. The research aims to construct these maps to visualize and evaluate the interdependence of determinants, identify common patterns for improved practices, and establish a transferable scientific methodology applicable to other multidisciplinary sustainability contexts. This approach not only advances the discourse on sustainable agriculture and food security but also responds to the growing need for integrative solutions that reflect the empirical realities of a complex world.

2. Preliminaries

2.1. Neutrosophic cognitive maps.

Neutrosophic Cognitive Maps (NCMs), is an innovative methodology that integrates the principles of neutrosophic logic, have emerged as a promising solution to many practical problems. NCMs allow for modeling situations that include degrees of truth, falsity, and indeterminacy, offering a more faithful and nuanced representation of reality [8]. The concept of NCMs is based on neutrosophic set theory, developed by Florentin Smarandache, which extends classical logic to handle uncertainty, ambiguity, and paradox. This theory introduces a third neutral value (N) in addition to the traditional truth (T) and falsity (F) values, allowing for a more flexible and adaptive representation of information. NCMs apply these principles to the field of cognitive maps, allowing for a graphical and analytical representation of causal and the dynamics of complex systems [9-10].

In this study, neutrosophic cognitive maps will be used, so we explain them below.

Definition 1: Let X be a universe of discourse. [11] A Neutrosophic Set (NS) is characterized by three membership functions, $u_A(x), r_A(x), v_A(x) : X \rightarrow]^-0,1^+[$, which satisfy the condition $^-0 \leq \inf u_A(x) + \inf r_A(x) + \inf v_A(x) \leq \sup u_A(x) + \sup r_A(x) + \sup v_A(x) \leq 3^+$ for all $x \in X$. $u_A(x)$, $r_A(x)$ and $v_A(x)$ are the truthfulness, indeterminacy and falsity membership functions of x in A, respectively, and their images are standard or non-standard subsets of $]^-0,1^+[$.

Definition 2[11]: Let X be a universe of discourse. A single-valued neutrosophic set (SVNS) A in X is a set of the form :

$$A = \{ \langle x, u_A(x), r_A(x), v_A(x) \rangle : x \in X\} \quad (1)$$

Where $u_A, r_A, v_A : X \rightarrow [0,1]$, satisfies the condition $0 \leq u_A(x) + r_A(x) + v_A(x) \leq 3$ for all $x \in X$. $u_A(x)$, $r_A(x)$ and $v_A(x)$ are the truthiness, indeterminacy and falsity membership functions of x in A, respectively. For convenience, a single-valued neutrosophic number (SVNN) will be expressed as A = (a, b, c), where $a, b, c \in [0,1]$ and satisfies $0 \leq a + b + c \leq 3$.

Other important definitions are related to graphs [11-

Definition 3[12-19] : A *neutrosophic graph* contains at least one indeterminate edge, represented by dotted lines

Definition 4 : A *neutrosophic directed graph* is a directed graph that contains at least one indeterminate edge, which is represented by dotted lines [18] .

Definition 5: A *neutrosophic cognitive map* (NCM) is a neutrosophic directed graph, whose nodes represent concepts and whose edges represent causal relationships between edges [19] .

If there are k vertices C_1, C_2,…, C_k, each can be represented by a vector (x_1, x_2,…, x_k) where xi ∈ {0,1, I} depending on the state of vertex C_i at a specific time or situation:

- $x_i = 1$: Vertex C_i is in an activated state .
- $x_i = 0$: Vertex C_i is in disabled state .
- $x_i = I$: The state of vertex C_i is undetermined .

Definition 6 : An NCM that has edges with weights in {−1, 0, 1, I} is called *a simple neutrosophic cognitive map* [20] .

Connections between vertices: a directed edge from C_m to C_n is called a connection and represents causality from C_m to C_n.

Associate weights to each vertex: Each vertex in the NCM is associated with a weight within the set { 0 , 1, -1, I} . The edge weight $C_m C_n$, denoted as α_{mn}, indicates the influence of C_m on C_n and can be:

- $\alpha_{mn} = 0$: Cm does not affect C_n.

- $\alpha_{mn} = >0$: An increase (decrease) in C_m results in an increase (decrease) in C_n.

- $\alpha_{mn} = < 0$: An increase (decrease) in C_m results in a decrease (increase) in C_n.

- $\alpha_{mn} = I$: The effect of C_m on C_n is undetermined .

Definition 7: If C_1, C_2,…, C_k are the vertices of an NCM . The neutrosophic matrix N(E) is defined as N(E) = α_{mn}), where α_{mn} denotes the weight of the directed edge $C_m C_n$, with $\alpha_{mn} \in$ [-1,0,1, I] . N (E) is called *the neutrosophic adjacency matrix* of the NCM .

Definition 8: Let C_1, C_2,…, C_k be the vertices of an NCM . Let A = (a_1, a_2,…, a_k), where a m ∈ {-1, 0, 1, I} . A is called *the neutrosophic instantaneous state vector* and means an on-off-indeterminate state position of the vertex at a given instant .

- $a_m = 0$ if C_m is disabled (has no effect),

- $a_m = 1$ if C_m is activated (has effect),

- $a_m = I$ if C_m is indeterminate (its effect cannot be determined) .

Definition 9: Let C_1, C_2,…, C_k be the vertices of an NCM . Let be $\overrightarrow{C_1C_2}, \overrightarrow{C_2C_3}, \overrightarrow{C_3C_4}, \dots, \overrightarrow{C_mC_n}$ the edges of the NCM, then the edges constitute a *directed cycle* .

- The NCM is said to be *cyclical* if it has a directed cycle. It is said to be *acyclic* if you do not have any directed cycles

Definition 10: An NCM that contains cycles is said to have *feedback*. When there is feedback in the NCM it is said to be a *dynamical system*.

Definition 11: Leave $\overrightarrow{C_1C_2}, \overrightarrow{C_2C_3}, \overrightarrow{C_3C_4}, \ldots, \overrightarrow{C_{k-1}C_k}$ be a cycle. when C_m is activated and its causality flows over the edges of the cycle and then is the cause of C_m itself, then the dynamical system is circulating. This is valid for every vertex C_m with m = 1, 2, …, k. The equilibrium state of this dynamical system is called *hidden pattern*.

Definition 12: If the equilibrium state of a dynamical system is a single state, then it is called a *fixed point*. An example of a fixed point is when a dynamical system starts being triggered by C_1. If the NCM is assumed to be set to C_1 and C_k, meaning that the state remains as (1, 0 ,…, 0, 1), then this neutrosophic state vector is called a fixed point.

Definition 13: If the NCM establishes a neutrosophic state vector that repeats in the form:

$$A_1 \rightarrow A_2 \rightarrow \cdots \rightarrow A_m \rightarrow A_1 \quad (2)$$

Then this sequence is called a *limit cycle*.

3. Material and Methods

This study employs Neutrosophic Cognitive Maps (NCM), an advanced methodology that integrates neutrosophic logic to model complex systems characterized by uncertainty and ambiguity [20]. In NCMs, nodes represent specific concepts—in this case, agricultural sustainability indicators—and directed edges represent causal relationships between these indicators.

The distinctive feature of NCMs is their representation of three fundamental types of causal relationships:

- Positive relationships: An increase/decrease in one indicator causes an increase/decrease in another.
- Negative relationships: An increase/decrease in one indicator causes a decrease/increase in another.
- Indeterminate relationships (I): The influence of one indicator on another cannot be determined with certainty.

This methodology is particularly valuable in contexts such as agricultural sustainability, where interactions among environmental, economic, and sociocultural factors are often ambiguous or uncertain.

Selection of Indicators

To build the NCM, critical indicators covering three key dimensions of agricultural sustainability were selected (Figure 1)

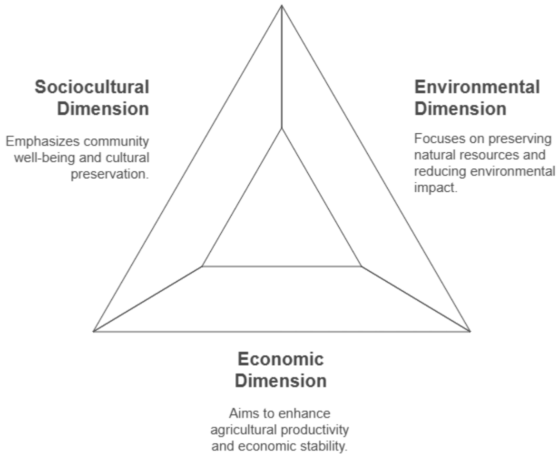

Figure 1: Integrated Framework for Sustainable Agriculture

To build the NCM, critical indicators covering three key dimensions of agricultural sustainability were selected (Table 1).

Table 1. Criteria and Description of Indicators

Dimension	Indicator	Description
Environmental	X_1: Biodiversity and ecosystem services	Assesses biological diversity and ecosystem services (pollination, pest control, nutrient cycling) essential for agricultural resilience.
Environmental	X_2: Soil quality and conservation	Measures the physical, chemical, and biological status of soil, and the practices promoting its conservation against erosion and degradation.
Environmental	X_3: Water resource management	Analyzes access, availability, and efficient management of water for sustainable agricultural production.
Environmental	X_4: Greenhouse gas emissions	Evaluates the contribution of agricultural practices to carbon emissions and their impact on climate change.

Dimension	Indicator	Description
Economic	X_5: Agricultural productivity and performance	Measures production efficiency in terms of crop yields and agricultural profitability.
Economic	X_6: Income diversification	Analyzes the existence of multiple sources of rural income to reduce economic vulnerability.
Economic	X_7: Market access	Assesses the ease for producers to market their products and obtain fair prices.
Economic	X_8: Economic resilience to shocks	Measures the capacity of the agricultural system to withstand disturbances like economic crises, climate events, or health emergencies.
Sociocultural	X_9: Food sovereignty and nutrition	Evaluates the community's ability to ensure sufficient, safe, and culturally appropriate food.
Sociocultural	X_{10}: Equity and social inclusion	Analyzes the degree of equity in access to resources, opportunities, and benefits among different social groups.
Sociocultural	X_{11}: Preservation of traditional knowledge	Measures the conservation and intergenerational transmission of agricultural traditional knowledge adapted to the local context.
Sociocultural	X_{12}: Well-being of the agricultural community	Assesses living conditions (health, education, housing, satisfaction) of farmers and their central role in sustainability.

These indicators were defined through a literature review and expert consultations in agricultural sustainability.

Construction of the Neutrosophic Cognitive Map

The NCM was constructed by identifying and defining causal relationships among the twelve indicators described above. Interactions were visually represented and subsequently formalized into an adjacency matrix, assigning neutrosophic values based on expert criteria:

$W = [w_{ij}]$ where w_{ij} represents the weight of the directed edge $X_i \rightarrow X_j$, with:

- $w_{ij} > 0$: indicating a positive causal relationship,
- $w_{ij} < 0$: indicating a negative causal relationship,
- $w_{ij} = 0$: indicating no connection between nodes,
- $w_{ij} = I$: indicating an indeterminate causal relationship.

Centrality Analysis

Centrality measures were calculated from the adjacency matrix to evaluate the relative importance of each indicator within the agricultural sustainability system. These measures include:

- **Out-degree (od):** Sum of outgoing connections, indicating the direct influence of a factor on others.
- **In-degree (id):** Sum of incoming connections, showing how much a factor is influenced by others.
- **Total degree (td):** Total sum of all connections, representing the overall relevance of a factor within the system.

De-neutrosophication Process

To facilitate interpretation and analysis of the results, a de-neutrosophication process was performed by replacing the indeterminacy parameter (I) with a conventional value of 0.5. This step provided more defined values for clearly interpreting influences and dynamics among indicators.

This method ensures a comprehensive and realistic assessment of complex agricultural sustainability systems by explicitly accounting for uncertainty and nonlinear relationships inherent in the studied context.

4. Results

An NCM was developed to represent the causal connections between the 12 identified agricultural sustainability indicators. This process involved defining the interactions between these factors and visualizing them in a neutrosophic cognitive map, as shown in Figure 2.

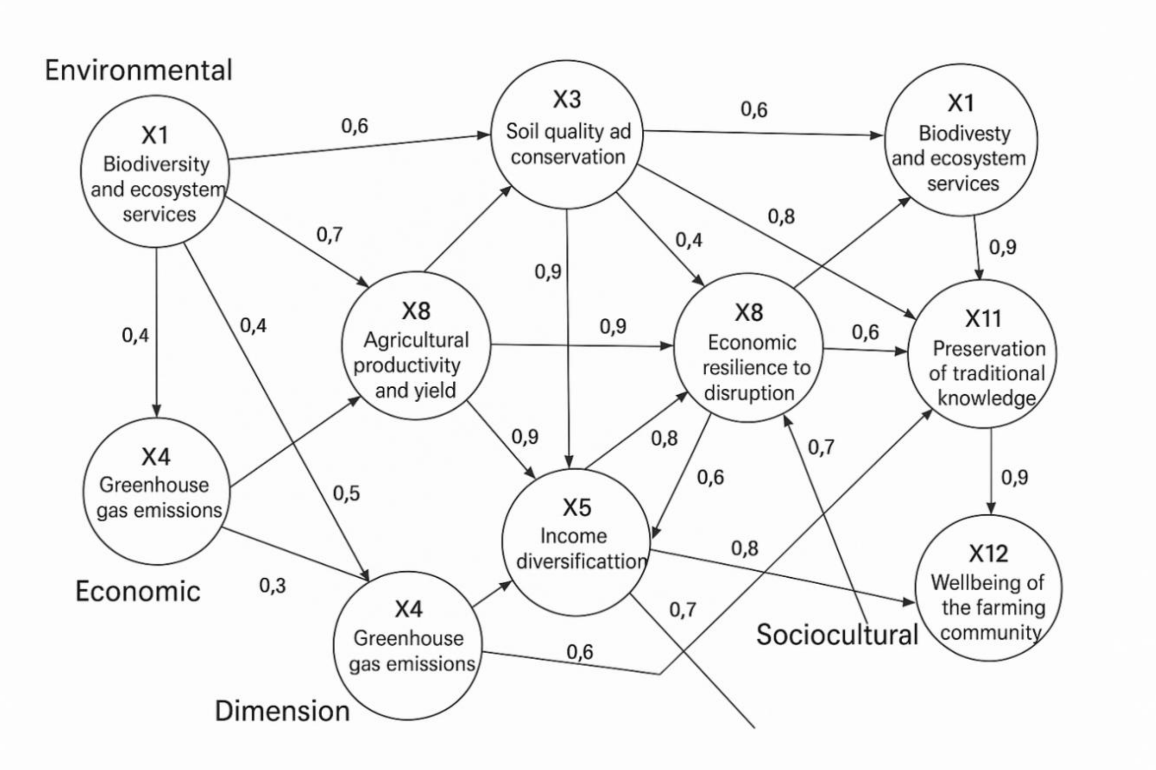

Figure 2: Neutrosophic cognitive map between indicators of agricultural sustainability.

The adjacent matrix obtained, based on the neutrosophic values provided by sustainable agriculture specialists, is detailed in Table 2.

Table 2: Adjacency matrix of agricultural sustainability indicators

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}
X_1	0	0.8	0.6	0.7	0.5	0.3	0	0.4	0.2	I	0.5	0.3
X_2	0.7	0	0.8	0.4	0.9	0.2	0	0.5	0.3	0	0.2	0.1
X_3	0.5	0.7	0	0.3	0.8	0.4	0	0.7	0.6	0.2	0.3	0.4
X_4	-0.7	-0.3	-0.2	0	-0.1	0	0	-0.6	0	0	0	-0.3
X_5	I	-0.4	-0.5	-0.3	0	0.7	0.8	0.6	0.9	0.4	0	0.5
X_6	0.3	0.2	0	0.1	0.4	0	0.5	0.9	0.3	0.6	0.4	0.7
X_7	0	0	0	0.2	0.7	0.8	0	0.7	0.4	0.5	0.2	0.6
X_8	0.4	0.5	0.4	0.3	0.6	0.7	0.5	0	0.6	0.5	0.3	0.7
X_9	0.3	0.2	0.3	0	0.3	0.4	0.5	0.4	0	0.8	0.7	0.9
X_{10}	0.4	0.3	0.3	0.1	0.4	0.6	0.7	0.5	0.7	0	0.8	0.9
X_{11}	0.9	0.8	0.7	0.4	0.3	0.5	0.2	0.5	0.6	0.7	0	0.6
X_{12}	0.5	0.4	0.5	0.2	0.3	0.5	0.4	0.6	0.8	0.9	0.7	0

Centrality Analysis

Based on the adjacency matrix, centrality measures were calculated for each indicator, providing a quantitative analysis of their relative relevance within the agricultural sustainability system.

Table 3: Centrality analysis of the indicators

Indicator	od (vi)	id(vi)	td (vi)
X_1	4.3+I	3.0+I	7.3+2I
X_2	4.1	3.6	7.7
X_3	4.9	3.9	8.8
X_4	-2.2	3.0	0.8
X_5	3.4+I	5.7	9.1+I
X_6	4.4	5.1	9.5
X_7	4.1	3.6	7.7
X_8	5.5	5.5	11.0
X_9	4.5	5.4	9.9
X_{10}	5.7	4.6	10.3
X_{11}	6.2	4.1	10.3
X_{12}	5.0	6.0	11.0

Deneutrosophication process was performed, replacing the indeterminacy parameter I with a value of 0.5, which allowed for obtaining more defined and precise values.

Table 4: Deneutrosophicated centrality ordered from highest to lowest

Indicator	Description	Deneutrosophicated Centrality
X_{12}	Well-being of the agricultural community	11.0
X_8	Economic resilience to shocks	11.0
X_{11}	Preservation of traditional knowledge	10.3
X_{10}	Equity and social inclusion	10.3
X_9	Food sovereignty and nutrition	9.9
X_5	Agricultural productivity and performance	9.6
X_6	Income diversification	9.5
X_3	Water resource management	8.8
X_7	Market access	7.7
X_2	Soil quality and conservation	7.7
X_1	Biodiversity and ecosystem services	8.3
X_4	Greenhouse gas emissions	0.8

Analysis of Agricultural Sustainability Indicators

Sociocultural Dimension: The Fundamental Pillars

The results of the centrality analysis reveal that sociocultural indicators, particularly the well-being of the farming community (X_{12}) and the preservation of traditional knowledge (X_{11}), have a predominant influence on the agricultural sustainability system, with the highest centrality scores.

The well-being of the farming community emerges as a critical factor with the highest centrality (11.0), suggesting that farmers' living conditions, health, and satisfaction are fundamental to the system's sustainability. This indicator shows strong connections with both input and output factors, indicating that it not only influences other aspects of sustainability but is also influenced by them, creating a positive feedback loop when properly managed.

The preservation of traditional knowledge (X_{11}) also demonstrates a high centrality (10.3), highlighting the importance of ancestral knowledge and traditional practices in sustainable agriculture. This result highlights that knowledge accumulated over generations on local varieties, adapted cultivation techniques and natural resource management constitutes an invaluable asset for sustainability, especially in a context of climate change and biodiversity loss.

Social equity and inclusion (X_{10}) share the same level of centrality as traditional knowledge, reflecting how fair social structures and equitable benefit distribution are crucial to maintaining long-term sustainable agricultural systems. This indicator shows strong connections with community well-being and food sovereignty.

Economic Dimension: The Engine of Resilience

In the economic dimension, resilience to shocks (X_8) stands out as the most central indicator (11.0), equaling the importance of community well-being. This underlines how the capacity of agricultural systems to absorb shocks, adapt and reorganize in the face of external changes (climate, market or political) is fundamental for long-term sustainability.

Income diversification (X_6) and agricultural productivity (X_5) also show high centrality scores, indicating that economic viability remains an essential pillar of agricultural sustainability. Diversification acts as a risk management strategy, while productivity ensures the returns needed for food security and profitability.

Access to markets (X_7), although with a lower centrality (7.7), remains an important factor influencing both the economic and social dimensions, facilitating the marketing of agricultural products and contributing to the economic stability of rural communities.

Environmental Dimension: Natural Resources as a Base

Among the environmental indicators, water resource management (X_3) shows the greatest centrality (8.8), reflecting the critical importance of water for sustainable agricultural production. This result highlights how efficient and responsible water management not only directly impacts productivity, but also soil quality and biodiversity.

Biodiversity and ecosystem services (X_1) and soil quality and conservation (X_2) have similar centralities (8.3 and 7.7 respectively), indicating their fundamental role as the basis of sustainable agricultural systems.

Biodiversity provides essential services such as pollination, pest control and nutrient recycling, while soil health determines long-term fertility and productivity.

Surprisingly, greenhouse gas emissions (X_4) show the lowest centrality (0.8), with multiple negative connections. This suggests that, although this indicator is important from a global climate change perspective, in the local context of sustainable agricultural systems, other factors exert a more direct and immediate influence on overall sustainability.

Interconnections between Dimensions

The analysis of the adjacency matrix reveals numerous interconnections between the three dimensions of sustainability, demonstrating that they cannot be considered in isolation:

- Water resource management (environmental) positively influences agricultural productivity (economic) and food sovereignty (sociocultural).
- Traditional (sociocultural) knowledge has a significant impact on biodiversity and soil (environmental) conservation.
- Economic resilience (economic) strengthens community well-being (sociocultural) and contributes to more sustainable resource management practices (environmental).

These interconnections confirm the systemic nature of agricultural sustainability and the need to adopt comprehensive approaches that simultaneously address all three dimensions.

Recommendations

The Neutrosophic Cognitive Mapping analysis has allowed us to identify the most influential indicators of agricultural sustainability and understand their complex interrelationships. The results highlight the central importance of sociocultural factors such as community well-being and traditional knowledge, along with economic resilience and the proper management of natural resources, especially water[21].

Relationships between variables studied

The study shows multiple bidirectional relationships between sustainability indicators:

1. **Synergy between traditional knowledge and biodiversity:** Traditional knowledge shows a strong positive influence (0.9) on biodiversity, while biodiversity contributes moderately (0.5) to the preservation of knowledge, creating a virtuous cycle.
2. **Tension between productivity and natural resources:** Agricultural productivity shows negative relationships with soil quality (-0.4) and water management (-0.5) when intensified without sustainable considerations, revealing potential compromises.
3. **Mutual reinforcement between social equity and community well-being** : These indicators show strong positive reciprocal relationships (0.9 in both directions), indicating how they enhance each other.
4. **Indeterminate effects in complex systems:** The relationship between biodiversity and productivity shows indeterminacy (I), reflecting the contextual complexity of this interaction that can vary according to specific conditions.
5. **Interdependence between dimensions:** The matrix reveals numerous connections between indicators of different dimensions, confirming that agricultural sustainability requires an

integrated approach that simultaneously considers environmental, economic and sociocultural aspects.

Recommendations to Improve Agricultural Sustainability

Based on the results of the NCM analysis, the following recommendations are proposed:

1. **Strengthen biocultural knowledge systems:** Implement programs that value, document, and promote the intergenerational transmission of traditional agricultural knowledge, complementing it with appropriate scientific innovations.
2. **Develop comprehensive rural welfare policies:** Create policy frameworks that simultaneously address quality of life in rural areas, including access to basic services, education, health, and diversified economic opportunities.
3. **Promote productive diversification:** Encourage diverse agricultural systems that integrate multiple crops, livestock, and non-agricultural activities, increasing economic and ecological resilience to shocks.
4. **Implement adaptive water management strategies:** Develop water management systems that combine traditional conservation knowledge with modern efficiency technologies, considering climate change scenarios.
5. **Create participatory governance platforms:** Establish decision-making mechanisms that equitably integrate all actors in the agri-food system, with an emphasis on the inclusion of women, youth, and marginalized groups.
6. **Design contextualized sustainability indicators:** Develop monitoring systems that incorporate the uncertainty and complexity inherent in agricultural systems, adapted to specific socio-ecological contexts.
7. **Promote inclusive and fair markets:** Strengthen short value chains and local markets that guarantee fair prices for producers and access to nutritious food for consumers.
8. **Promote regenerative practices**: Promote agroecological approaches that restore soil health, increase functional biodiversity, and reduce greenhouse gas emissions.

The effective implementation of these recommendations requires a systemic approach that recognizes the interdependencies between dimensions and factors of sustainability. Neutrosophic Cognitive Maps have proven to be a valuable tool for understanding these complex interrelationships and can continue to be used to monitor and evaluate interventions in agricultural systems, capturing the inherent indeterminacy and dynamism of these socioecological systems.

5. Conclusions

This study applied Neutrosophic Cognitive Maps (NCMs) to unravel the complex causal relationships among key indicators of agricultural sustainability across its environmental, economic, and sociocultural dimensions. The results reaffirm the systemic nature of sustainability, demonstrating that no single dimension operates in isolation.

Centrality analysis identified sociocultural factors – the well-being of the agricultural community (X12) and the preservation of traditional knowledge (X11) – and economic resilience (X8) as the most influential nodes in the system. This underscores the critical importance of investing in the human and social capital of rural communities and strengthening their adaptive capacity to external shocks for achieving lasting sustainability. Water resource management (X3) emerged as the most central environmental factor, highlighting agriculture's dependence on this resource.

Significant interdependencies were confirmed, such as the synergy between traditional knowledge and biodiversity (X1), and the potential tension between intensifying productivity (X5) and conserving resources like soil (X2) and water (X3). The NCM methodology proved valuable for modeling these interactions, including indeterminate relationships (I), reflecting the inherent uncertainty in socio-ecological systems.

Although the study has limitations, such as reliance on contextualized data and potential subjectivity in indicator selection, it provides a robust basis for decision-making. Recommendations focus on strengthening biocultural knowledge systems, promoting productive and economic diversification, implementing adaptive water management, and fostering participatory governance. NCMs can continue to be used as a tool for monitoring and evaluating interventions, guiding farmers and policymakers toward more resilient and equitable agricultural systems. This research not only contributes to understanding the dynamics of agricultural sustainability but also validates a promising methodological approach for studying other complex systems.

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