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Composite Sustainability Indicator for the Conservation of Ashigua Páramo: Integration of Neutrosophic Logic and the PROMETHEE TODIM Method

Patricio Clavijo Cevallos[1]

[1] Technical University of Cotopaxi, Cotopaxi. Ecuador. E-mail: manuel.clavijo@utc.edu.ec

Abstract. The project was conducted in the Ashigua páramo, Mulaló, Latacunga, Cotopaxi province. Its objective was to develop a composite environmental sustainability indicator for the conservation of the páramo. Neutrosophic logic and the PROMETHEE TODIM method were used to select and evaluate sub-indicators in a context of uncertain and complex environmental data. Neutrosophic logic facilitated the management of ambiguities and contradictions in the data. The findings highlighted the relevance of sub-indicators linked to carbon storage and ecological productivity. Indicators of regulatory compliance and sustainable management were evaluated, emphasizing the importance of adjusting environmental policies to regulations and social expectations. This study introduced a novel methodological approach to environmental assessment, providing valuable insights for policy development and effective management of natural resources and ecosystems.

Keywords: composite indicator, neutrosophic indicator, neutrosophic TODIM, PROMETHEE, environmental sustainability, Ecuador.

1 Introduction

In Ecuador, páramo ecosystems cover approximately 1,260,000 hectares, which represents 5% of the national territory. These ecosystems, characterized by their semi-humid and cold nature, extend almost continuously along the Andes Mountain Range, exceeding the current or potential limits of the forest [1]. Fourteen of the country's thirty-five protected areas include páramos, in addition to other conserved areas such as protective forests and private reserves. Páramos provide vital ecosystem services, such as hydrological regulation and the capture of atmospheric carbon, which are essential for both local communities and society in general, contributing to the control of global warming and the sustained provision of high-quality water. [2]

However, these ecosystems face significant threats due to the expansion of the agricultural frontier, grazing, climate change, unregulated tourism, and extreme sports, which compromise the integrity of the sensitive soils in these areas [3]. Despite the potential productivity of the páramos and their inclusion in various protection categories, inadequate management, especially in the province of Cotopaxi, can lead to irreversible environmental deterioration due to the fragility of their soils.

The páramos of the Cotopaxi province in Ecuador comprise approximately 105,000 hectares, representing 8% of the national páramos. Within this region, the parish of Mulaló stands out for its rich biodiversity and cultural heritage, hosting Andean ecosystems, forests, lakes, rivers, and cliffs. Nevertheless, it is observed that conservation strategies in these páramos are insufficient.

In the field of environmental policies, the incorporation of environmental variables is crucial. This process involves the creation and application of environmental sustainability indicators, developed by various entities and community organizations. These indicators are fundamental for assessing the interaction between human activities and the environment, providing clear and understandable data on the current state and environmental trends. [4]

Environmental sustainability indicators not only reflect the impact of productive practices on ecosystems but also calculate the environmental responsibility and sustainability of individuals, organizations, and communities [5]. This tool is indispensable for discerning how human activities affect the planet and for guiding policies that promote a balance between human development and environmental conservation.

Sustainable Development Indicators (SDIs) constitute an integral system of metrics that facilitate the assessment of progress towards sustainable development in various geographies. These indicators function as essential practical tools in the design and evaluation of public policies, improving informed decision-making and fostering citizen participation, essential for guiding countries toward more sustainable practices. [6]

Furthermore, SDIs allow quantifying corporate commitment to the environment and society. It is widely recognized in environmental sciences that humanity consumes the planet's resources at an unsustainable pace, increasing global environmental damage. If adequate control measures are not implemented, this deterioration continues to escalate. Therefore, it is critical to analyze and measure human activities to manage and potentially reduce their environmental impact. [7]

Globally, some environmental indicators are designed to be universally applied, while others are specifically developed to measure the quality of ecosystems in particular locations. In the context of Ecuador, for example, the creation of indicators is underway through the Unified National Information System (SUIN), led by the Ministry of the Environment. Currently, although national environmental indicators are limited, they represent a crucial step towards more robust environmental management and greater ecological responsibility.

Environmental indicators are fundamental tools for articulating sustainability goals, being essential both at the sectoral and comprehensive levels. Their value lies in their ability to be formulated in unique and specific social, administrative, and territorial contexts [8]. These indicators, when carefully selected and related to variables to be evaluated, provide crucial information for an optimal interpretation of sustainability, desired by local managers. Additionally, they can be considered as scientifically configured variables that condense a social interest in the environment, thus facilitating their inclusion in the decision-making process. [9]

This research project is vital to ensure the protection and conservation of fragile ecosystems, such as the páramos, contributing to the well-being of the community. The development of a system of specific indicators will allow for the proper management of these ecosystems, especially in the Ashigua páramo of the Mulaló parish, whose inhabitants will be the main beneficiaries. Through this system, it will be possible to assess and act on the collected data, improving the conservation of these vital areas.

The limited environmental awareness of the inhabitants about the use of natural resources can lead to excessive exploitation, compromising the capacity of ecosystems to meet human needs. In this context, generating environmental development indicators is key to promoting sustainable development and effectively addressing local environmental issues. Additionally, soil compaction, a result of agricultural activities and human settlements, reduces vegetation cover and accelerates soil erosion, threatening the integrity of the páramos and their ability to sustain life.

The insufficient environmental awareness and the profound lack of knowledge among the population about the significance of ecosystems, along with a deficient understanding of the environmental regulations that govern the management of these, contribute significantly to their deterioration. Factors such as the expansion of the agricultural and livestock frontier, the burning of grasslands, and deforestation.

2. Preliminaries

2.1 Neutrosophic Theory

The implementation of Single-Valued Neutrosophic Sets (SVNS) constitutes a significant advancement in the domains of set theory and logic, providing a robust framework for the precise representation of ambiguity and uncertainty. These SVNS are essential for detailing the truth, indeterminacy, and falsity associated with elements within a set. This capability makes them valuable tools for multiple fields, including decision-making in contexts of uncertainty, artificial intelligence, and information management.

Within the framework of SVNS, let's consider X as a space that contains points or objects, with generic elements in X denoted by x. A Single-Valued Neutrosophic Set A in X is defined by three characteristic functions: the truth-membership function $T_A(x)$, the indeterminacy-membership function $I_A(x)$, and the falsity-membership function $F_A(x)$. Therefore, an SVNS A can be formally expressed as $A = \{x, T_{A(x)}, I_{A(x)}, F_{A(x)x} \in X\}$, where $T_{A(x)}, I_{A(x)}, F_{A(x)} \in [0,1]$ for each point x in X. In this way, the sum of $T_{A(x)}, I_{A(x)}$, and $F_{A(x)}$ meets the condition $0 \leq T_{A(x)} + I_{A(x)} + F_{A(x)} \leq 3$. [15]

This formalism allows each element x in the space X to be evaluated under these three metrics, thereby facilitating a more nuanced and detailed understanding of its state in terms of truth, falseness, and indeterminacy. This approach not only enriches traditional set theory with an additional dimension of analysis but also optimizes decision-making and analysis processes in complex and dynamic environments.

The modeling of membership functions in the range [0,1] in SVNS provides greater flexibility and precision in the analysis of contexts where uncertainty is a predominant factor. This interval ensures that the total sum of the truth-membership, indeterminacy-membership, and falsity-membership functions does not exceed the value of 3, thus maintaining structural coherence within the theoretical framework of SVNS. This methodology provides robust support for handling ambiguity and uncertainty in various fields of application.

Decision-making in many contexts is facilitated by the use of linguistic variables, which are terms commonly used in human language to express judgments and preferences. These variables facilitate the articulation and understanding of complex evaluations in a format that is accessible and intuitive for participants in the decision-making process. For example, terms such as "very important," "important," "somewhat important," and "not important" are frequently used to reflect the relative valuation of different criteria. See Table 1.

The integration of these linguistic variables into the SVNS scheme allows for a more faithful representation of how individuals perceive and prioritize aspects in specific situations. By converting linguistic evaluations into SVNS, a valuable tool is obtained for modeling and effectively analyzing the uncertainty and ambiguity inherent in decision processes, particularly in scenarios where available information is vague or incomplete. This approach provides a bridge between natural human communication and formal decision analysis systems, thus optimizing information management in critical decisions.

Table 1. Linguistic variable and Single-Valued Neutrosophic Numbers (SVNNs). Source:[16]

Integer	Linguistic variable	SVNNs
0	Not important	(0.10;0.90;0.90
1	Low important	(0.35;0.75;0.80)
2	Medium important	(0.50;0.5;0.50)
3	High important	(0.75;0.25;0.20)
4	Very high important	(0.9;0.1;0.1))

In accordance with [16], if $E_k = (T_k, I_k, F_k)$ is a neutrosophic number defined for the rating of the k-th decision-maker, then the weight of the k-th decision maker can be expressed as:

$$\psi_k = \frac{1-\sqrt{[(1-T_k(x))^2+(I_k(x))^2+(\mathrm{F}(x))^2]/3}}{\sum_{k=1}^{p}\sqrt{[(1-T_k(x))^2+(I_k(x))^2+(\mathrm{F}(x))^2]/3}} \tag{1}$$

This equation allows calculating the weight of each decision-maker in the context of a group decision, considering the multiple perspectives and evaluations provided by various individuals. This approach can enrich the decision-making process and lead to more robust and equitable solutions.

In the group decision-making process, all evaluations from individual decision-makers must be aggregated into an aggregated neutrosophic decision matrix using the Single-Valued Neutrosophic Weighted Average (SVNWA) aggregation operator, as proposed in reference [17]. The use of SVNWA facilitates the combination of individual neutrosophic evaluations into a single matrix that represents the group decision more completely and accurately. The evaluations from all decision-makers can be compiled into a single decision matrix that reflects the consensus or weighting of individual evaluations based on the weights assigned to each decision-maker.

In such a case, with $D_k = \left(d_{ij}(k)\right)_{m \times n}$ being the single-valued neutrosophic decision matrix of the k-th decision-maker and $\psi = \left(\psi_1, \psi_2, \dots, \psi_p\right)^T$ the weight vector of the decision-makers, such that each $\psi_k \in [0,1]$, the weighted decision matrix can be obtained considering that [17]:

$$d_{ij} = \langle 1 - \prod_{k=1}^{p}\left(1 - T_{ij}^{(p)}\right)^{\psi_k}, \prod_{k=1}^{p}\left(I_{ij}^{(p)}\right)^{\psi_k}, \prod_{k=1}^{p}\left(F_{ij}^{(p)}\right)^{\psi_k} \rangle \tag{2}$$

On the other hand, if A and B are assumed to be two single-valued neutrosophic numbers, the normalized Hamming distance between them is defined as:

$$d(A,B)\frac{|TA - TB|+|IA - IB|+|FA - FB|}{3} \tag{3}$$

The normalized Hamming distance between two Single-Valued Neutrosophic Numbers, A and B, measures the discrepancy or difference between them based on their components of truth, falseness, and indeterminacy. It is an important indicator for evaluating how similar or different two SVNNs are in terms of their neutrosophic characteristics. The smaller the normalized Hamming distance, the greater the similarity between A and B, and vice versa. Meanwhile, the complement of an SVNN $A = (T_A, I_A, F_A)$ can be defined as:

$$A^C = (F_A, 1 - I_A, T_A) \tag{4}$$

The complement of an SVNN reflects the complementary degrees of truth, indeterminacy, and falseness of A. This concept is useful for analyzing and comparing inverse or opposing properties in neutrosophic analysis, allowing for a deeper understanding of the dynamics involved in contexts where uncertainty and ambiguity play a central role.

2.2 Combined TODIM/PROMETHEE approach

The methodological approach that combines TODIM (a methodology based on the Dominance of Interactive and Multicriteria Criteria) with PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) constitutes an advanced technique for multi-criteria decision-making in contexts of uncertainty. This method relies on Single-Valued Neutrosophic Numbers (SVNNs) to integrate both the certainties and uncertainties of attributes, providing a robust tool for evaluating alternatives considering their strengths and weaknesses.

In practice, this approach involves defining alternatives and attributes as follows:

Alternatives: They are represented as $A = (A_1, \ldots, A_m)$, where each A_i is a specific alternative within the set of available options.

Attributes: They are denoted as $G = (G_1, G_2, \ldots, G_n)$, each of which describes a relevant criterion in the evaluation of the alternatives.

To proceed with the evaluation, it is essential to assign weights to each attribute, represented as $W = (w_1, w_2, \ldots, w_n)$, where $0 \leq w_j \leq 1$ and the total sum of the weights is 1. This ensures that the attributes are appropriately weighted in the overall evaluation.

The attribute values for each alternative are organized in a matrix $A = (a_{ij})$ with dimensions m×n, where a_{ij} represents the value of the attribute G_j for alternative A_i. Each element a_{ij} is a Single-Valued Neutrosophic Number, represented as T_{ij}, I_{ij}, and F_{ij}, where:

- T_{ij} indicates the degree of membership or truth of attribute G_j for the alternative A_i.
- I_{ij} represents the degree of indeterminacy, reflecting the uncertainty or ambiguity of the value.
- F_{ij} denotes the degree of non-membership or falseness, indicating the extent to which the attribute is not characteristic of the alternative.

Let's consider the alternatives as $A = (A_1, \ldots, A_m)$ and the attributes as $G = (G_1, G_2, \ldots, G_n)$. We assign weights to the attributes as $W = (w_1, w_2, \ldots, w_n)$, where the sum of all weights equals 1, i.e., $\sum_{j=1}^{n} w_j = 1$. Let us denote a_{ij}, where i = 1, 2, ..., m and j = 1, 2, ..., n, as the value of the attribute $G_j$for the alternative A_i. We create a matrix $A = (a_{ij})$ with dimensions m×n, which is a matrix of Single-Valued Neutrosophic Numbers (SVNNs), represented as $\langle (T_{ij}, I_{ij}, F_{ij}) \rangle_{mxn}$, where T_{ij}, I_{ij}, and F_{ij} are the degrees of membership, degrees of indeterminacy, and degrees of non-membership.

The implementation of this method allows for a detailed and nuanced evaluation of the available options, facilitating decision-making in complex environments where criteria can be numerous and information may be incomplete or uncertain. This approach not only helps capture the multiple and often contradictory dimensions of decision problems but also promotes a more informed and balanced choice among the proposed alternatives.

The procedure for applying the TODIM-PROMETHEE method using Single-Valued Neutrosophic Numbers (SVNN) for decision-making can be broken down into several structured steps, as described below:

Step 1: Identification of Treatment Techniques: In this first step, the relevant treatment techniques or alternatives that will be evaluated are identified. This is a crucial step where the options among which a decision will be made are established.

Step 2: Assignment of Weights to Decision Makers: Each decision maker is assigned a weight that reflects their experience and knowledge about the problem in question. These weights are expressed using linguistic variables that are then converted into Single-Valued Neutrosophic Numbers (SVNN) using a specific equation, allowing for precise quantification of each expert's influence on the final decision.

Step 3: Conversion of Linguistic Evaluations into SVNN: Based on the evaluations provided by the experts, which initially may be clear linguistic expressions, individual neutrosophic matrices are constructed for each decision maker. This step transforms qualitative evaluations into quantitative ones, suitable for more detailed mathematical analysis.

Step 4: Creation of the Initial Relation Matrix: A matrix $A = (a_{ij})_{mxn}$ is formed where each element a_{ij} represents the value of the attribute G_j for the alternative A_i. This matrix is expressed in neutrosophic form as $\langle (T_{ij}, I_{ij}, F_{ij}) \rangle_{mxn}$, where T_{ij}, I_{ij}, and F_{ij} represent the degrees of membership, indeterminacy of membership, and non-membership, respectively.

Step 5: Standardization of Decision Information: the standardization process normalizes the matrix $A = (a_{ij})_{mxn}$ to transform it into a matrix $B = (b_{ij})_{mxn}$. If the attribute is a cost factor, it is transformed using its complementary set to reflect the preference for lower cost; for efficiency factors, this transformation is not necessary.

Step 6: Construction of the Preference Function: A preference function $P_j(B_i, B_r)$ is developed to evaluate the alternative B_i in relation to B_r under attribute G_j. This function is based on a specific equation that measures the preference of one alternative over another, considering the degrees of membership, indeterminacy, and non-membership in the neutrosophic context. The procedure described in equation (5) is followed.

$$P_j(B_i, B_r) = \begin{cases} 0, d \leq p \\ \frac{d-p}{q-p} \ , p < d < q \\ 1, d \geq q \end{cases} \quad (5)$$

Step 7: Calculation of the Relative Weight of the Attributes

This step involves calculating the relative weight G_j of one attribute G_j with respect to another G_r. Mathematically, this is expressed as:

$$w_{jr} = \frac{w_j}{w_r} = (j, r = 1,2, \dots, n) \quad (6)$$

This calculation helps to determine the relative importance of each attribute in comparison to others, providing a basis for more detailed comparative analyses in the subsequent steps.

Step 8: Definition of the Priority Index: The priority index $\pi(B_i, B_r)$ evaluates the scheme B_i in relation to B_r using the following formula:

$$\pi(B_i, B_r) = \frac{\sum_{j=1}^{n} w_{jr} P_j(B_i, B_r)}{\sum_{j=1}^{n} w_{jr}} \quad (7)$$

This index synthesizes preferences under all attributes, weighting each preference by the relative weight of the corresponding attribute.

Step 9: Calculation of Inflow, Outflow, and Net Flow: The inflow $\Phi^+(B_i)$, outflow $\Phi^-(B_i)$, and net flow $\Phi\,(B_i)$ of each alternative are calculated to determine how the alternatives compare to each other within the group. The formulas are the following:

$$\Phi^+\,(B_i) = \frac{\sum_{r=1}^{m} \pi(B_i, B_r) - \min_{1 \le i \le m}\{\sum_{r=1}^{m} \pi(B_i, B_r)\}}{\max_{1 \le i \le m}\{\sum_{r=1}^{m} \pi(B_i, B_r)\} - \min_{1 \le i \le m}\{\sum_{r=1}^{m} \pi(B_i, B_r)\}} \quad (8)$$

$$\Phi^-\,(B_i) = \frac{\sum_{r=1}^{m} \pi(B_r, B_i) - \min_{1 \le i \le m}\{\sum_{r=1}^{m} \pi(B_r, B_i)\}}{\max_{1 \le i \le m}\{\sum_{r=1}^{m} \pi(B_r, B_i)\} - \min_{1 \le i \le m}\{\sum_{r=1}^{m} \pi(B_r, B_i)\}} \quad (9)$$

$$\Phi(B_i) = \Phi^+\,(B_i) - \Phi^-\,(B_i) \quad (10)$$

Step 10: Classification of Alternatives: Finally, all alternatives are ranked according to the value of $\Phi\,(B_i)$. The alternatives are ordered from the highest to lowest value of Φ, facilitating the identification of the best option in the decision-making context. The alternative with the highest $\Phi\,(B_i)$ is considered optimal, as it indicates a favorable balance between the inflows and outflows in terms of aggregated preferences.

This detailed process ensures that all alternatives are evaluated and compared fairly and thoroughly, considering both individual preference metrics and the relative weights of the attributes, and culminating in an informed selection based on objective and nuanced criteria.

3 Method

For the community development of the Ashigua páramo and the implementation of conservation strategies, the Community Self-Management Process (PAC) methodology was applied. This methodology is part of an ethnic revitalization process in Ecuador, where indigenous communities are emerging as key actors in social planning and the management of participatory development initiatives. The PAC methodology is based on the rich history of autonomous planning of pre-colonial Andean peoples and adapts to current cultural structures, which preserve clear methods and principles for organizing and executing their activities.

This study is categorized as applied research that adopts quantitative and qualitative methods to develop a composite indicator aimed at the environmental sustainability of the páramo. The methodological approach is based on the integration of various environmental sub-indicators, using advanced decision-making techniques grounded in neutrosophic logic, which is essential for managing the indeterminacy and uncertainty characteristic of environmental studies.

Initially, a thorough review of the literature is conducted to identify potential sub-indicators used in páramo conservation. The selected sub-indicators are those that meet pre-established criteria of scientific relevance and practical applicability. In addition, rounds of questionnaires are conducted among selected experts for the study, who provide valuable considerations for the study. A combined strategy of the TODIM and PROMETHEE methodologies in their neutrosophic variant is adopted. This combination allows a meticulous evaluation of the sub-indicators according to their relevance and importance, based on 5 specific evaluation criteria:

1. Sensitivity: The sub-indicator's ability to detect significant changes both in the natural environment and in anthropogenic pressures on natural resources.
2. Ease of Measurement: Consideration of the practicality and cost associated with data collection, including the availability of technology and the need for specialized training.
3. Integrability: Evaluation of the sub-indicator's ability to integrate with others and form a coherent and robust composite indicator.

4. Predictability: The sub-indicator's potential to anticipate future changes in the environment, based on historical and current trends.
5. Acceptability: The degree of acceptance of the sub-indicator by the scientific community and relevant stakeholders.

The neutrosophic methodology of the TODIM and PROMETHEE methods proposed by [18] is used to integrate the evaluations of experts, who assign values to each sub-indicator according to the mentioned criteria. Each criterion is evaluated using a scale of neutrosophic numbers, which allows for capturing the opinions of the experts in terms of certainty, uncertainty, and indeterminacy. For the study, criteria 1 and 3 are considered to have the highest weight of importance with a value of 0.3, while criteria 2 and 4 share an importance of 0.15, and criterion 5 has a value of importance or weight of 0.1. The results are synthesized to form a composite environmental sustainability indicator. Ethical considerations related to data collection and management are taken into account, ensuring that all personal information of participants is treated confidentially and in accordance with current regulations.

This methodological approach provides a rigorous framework for developing an indicator that not only reflects the conditions of the páramo but also integrates the complexity and multidimensionality of the factors influencing its sustainability. By employing neutrosophic logic, this study positions itself at the forefront of research that incorporates uncertainty and indeterminacy as central elements in environmental evaluation.

4 Results

The literature review conducted and consultations with experts facilitate the identification of a set of sub-indicators whose relevance is suitable for inclusion in a composite environmental sustainability indicator that is being developed. This methodological process results in the initial proposal of the sub-indicators detailed in Table 2. These sub-indicators have been selected based on their ability to capture critical aspects of environmental sustainability, reflecting essential dimensions that are fundamental for a comprehensive assessment of environmental impact and effective conservation of natural resources.

Table 2: Indicators considered for the preparation of the composite indicator

FACTOR	INDICATORS
Water	Water Flow
	Water Quality
	Transport of Contaminants in Water
Biodiversity	Ecological Footprint
	Deforestation
	Biocapacity
	Biodiversity Quantification
	Invasive Species
Soil	Advancement of the Agricultural Frontier
	Soil Erosion
	Degree of Erosion by Visitors in Protected Areas
	Level of Vegetation Cover
	Biomass Calculation
	Soil Carbon Concentration
Air	Burning of Grasslands
	Air Pollution
Legal aspects	Compliance with Environmental Legislation
Protection	Good Practices for Páramo Management
	Environmental Preservation

In the current study, it is established that the five experts involved have equivalent influence and relevance in the decision-making process, thus ensuring an impartial and consensual evaluation method. The decision-makers proceed with the analysis of the selected indicators, examining in detail each of the criteria previously determined for their evaluation. To implement this procedure, a transformation of the individual decision matrices of each expert is performed using equation (2), to derive matrix A. This matrix, whose details are specified in Table 3, synthesizes the individual evaluations made by the experts regarding the available options and the criteria set for their evaluation.

Table 3: Normalized decision matrix

	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5
A1	(0.83428;0.16572;0.15849)	(0.83428;0.16572;0.15849)	(0.83428;0.16572;0.15849)	(0.8343;0.1657;0.1585)	(0.8343;0.1657;0.1585)
A2	(0.6059;0.41731;0.40953)	(0.80963;0.19037;0.19037)	(0.87989;0.12011;0.11487)	(0.8799;0.1201;0.1149)	(0.8799;0.1201;0.1149)
A3	(0.87989;0.12011;0.11487)	(0.82671;0.17329;0.15157)	(0.87989;0.12011;0.11487)	(0.8799;0.1201;0.1149)	(0.8799;0.1201;0.1149)
A4	(0.80963;0.19037;0.19037)	(0.62107;0.37893;0.34657)	(0.67012;0.32988;0.28854)	(0.7254;0.2746;0.2512)	(0.7254;0.2746;0.2512)
A5	(0.82671;0.17329;0.15157)	(0.83428;0.16572;0.15849)	(0.62107;0.37893;0.34657)	(0.8343;0.1657;0.1585)	(0.6211;0.3789;0.3466)
A6	(0.83428;0.16572;0.15849)	(0.87989;0.12011;0.11487)	(0.83428;0.16572;0.15849)	(0.862;0.138;0.138)	(0.862;0.138;0.138)
A7	(0.83428;0.16572;0.15849)	(0.83428;0.16572;0.15849)	(0.83428;0.16572;0.15849)	(0.8343;0.1657;0.1585)	(0.8343;0.1657;0.1585)
A8	(0.75;0.25;0.2)	(0.82671;0.17329;0.15157)	(0.83428;0.16572;0.15849)	(0.8343;0.1657;0.1585)	(0.8343;0.1657;0.1585)
A9	(0.72536;0.27464;0.25119)	(0.83428;0.16572;0.15849)	(0.83428;0.16572;0.15849)	(0.8343;0.1657;0.1585)	(0.8343;0.1657;0.1585)
A10	(0.6059;0.41731;0.40953)	(0.83428;0.16572;0.15849)	(0.87989;0.12011;0.11487)	(0.8799;0.1201;0.1149)	(0.8799;0.1201;0.1149)
A11	(0.80095;0.19905;0.18206)	(0.75;0.25;0.2)	(0.80095;0.19905;0.18206)	(0.8009;0.1991;0.1821)	(0.7254;0.2746;0.2512)
A12	(0.80963;0.19037;0.19037)	(0.87989;0.12011;0.11487)	(0.80963;0.19037;0.19037)	(0.8096;0.1904;0.1904)	(0.6211;0.3789;0.3466)
A13	(0.67012;0.32988;0.28854)	(0.80963;0.19037;0.19037)	(0.67012;0.32988;0.28854)	(0.6701;0.3299;0.2885)	(0.8096;0.1904;0.1904)
A14	(0.62107;0.37893;0.34657)	(0.82671;0.17329;0.15157)	(0.62107;0.37893;0.34657)	(0.6211;0.3789;0.3466)	(0.7254;0.2746;0.2512)
A15	(0.83428;0.16572;0.15849)	(0.87989;0.12011;0.11487)	(0.87989;0.12011;0.11487)	(0.8799;0.1201;0.1149)	(0.8799;0.1201;0.1149)
A16	(0.71283;0.28717;0.24022)	(0.83428;0.16572;0.15849)	(0.71283;0.28717;0.24022)	(0.7128;0.2872;0.2402)	(0.8096;0.1904;0.1904)
A17	(0.62107;0.37893;0.34657)	(0.75;0.25;0.2)	(0.83428;0.16572;0.15849)	(0.8343;0.1657;0.1585)	(0.8096;0.1904;0.1904)
A18	(0.62107;0.37893;0.34657)	(0.83428;0.16572;0.15849)	(0.83428;0.16572;0.15849)	(0.8343;0.1657;0.1585)	(0.7254;0.2746;0.2512)
A19	(0.83428;0.16572;0.15849)	(0.44935;0.22865;0.52661)	(0.83428;0.16572;0.15849)	(0.8343;0.1657;0.1585)	(0.6211;0.3789;0.3466)

Subsequently, the development of matrices that represent the degrees of preference $P_j(B_i, B_r)$ with respect to the attribute G_j is addressed. These degrees are calculated using a linear function, defined in Equation 5, where the parameters q = 1 and p = 0 are set. This approach is adopted under the premise that it allows for a direct and simplified interpretation of preferences, thus facilitating the comparison between alternatives under specific criteria.

To determine the comprehensive priority index of the evaluated alternatives, Equation 7 is used. The information provided supplies the inflow, outflow, and net flows for each of the alternatives, as specified in Table 4. These flows are crucial for elucidating the sub-indicators of greater preference according to the parameters established in the study. The articulation of these flows allows for a quantitative evaluation of how each alternative compares in terms of receiving preferences (inflows), yielding to other alternatives (outflows), and their net balance, which is decisive for identifying the most prominent sub-indicators within the defined criteria framework. This analysis is instrumental for a deep understanding of preference dynamics and for grounding strategic decisions based on empirical evidence.

Table 4: Inflows, outflows, and net flows for each indicator evaluated

Sub Indicators	Φ+	Φ-	Φ
Water Flow	0.1	0.569	-0.506
Water Quality	0.6	0.428	0.162
Transport of Contaminants in Water	0	1,000	-1,000
Ecological Footprint	0.6	0.220	0.421
Deforestation	0.4	0.393	0.052
Biocapacity	0	0.687	-0.644
Biodiversity Quantification	0.1	0.569	-0.506
Invasive Species	0.1	0.472	-0.349
Advancement of the Agricultural Frontier	0.2	0.369	-0.137
Soil Erosion	0.6	0.450	0.112
Degree of Erosion by Visitors in Protected Areas	0.2	0.404	-0.186
Level of Vegetation Cover	0.2	0.466	-0.239
Biomass Calculation	0.7	0.078	0.634
Soil Carbon Concentration	1	0.000	1,000
Burning of Grasslands	0	0.887	-0.878
Air Pollution	0.4	0.228	0.216
Compliance with Environmental Legislation	0.5	0.216	0.257
Good Practices for Páramo Management	0.4	0.233	0.213
Environmental Preservation	0.1	0.517	-0.375

The analyzed data revealed that "Soil Carbon Concentration" obtained the highest preference among the indicators analyzed, reflecting unanimity in its favorability, given that no negative preference flows were recorded. This result highlights the critical importance of this sub-indicator in environmental evaluation, possibly due to its direct relevance in carbon capture and climate change mitigation. This indicator is crucial not only for its role in carbon capture but also for its part in the global carbon cycle, which directly affects climate regulation and environmental sustainability.

On the other hand, "Biomass Calculation" reached a value with the highest positive preference flow after Soil Carbon. This suggests that the quantification of biomass is highly valued by experts, possibly for its role in understanding ecosystem productivity and the overall health of the ecosystem. Interestingly, indicators such as "Ecological Footprint," "Compliance with Environmental Legislation," and "Good Practices for Páramo Management" presented moderately positive values, reflecting a balanced acceptance and recognizing their usefulness in a comprehensive environmental evaluation framework.

The results of the evaluation of these indicators highlight a favorable trend towards those intrinsically linked with the carbon storage capacity and the conservation of the ecological functionality of ecosystems. This indicates a conscious and strategic approach towards the selection of sub-indicators that not only monitor ecological health but also strengthen actions against global environmental challenges like climate change. It is inferred that, by prioritizing these sub-indicators, environmental management policies, and practices could be improved, steering them towards effective conservation and restoration of ecosystems.

In general, the proposed composite indicator is composed as follows:

$$\boldsymbol{Index = \sum i = 1 W_i * V_i}$$

- W = Weight of the considered indicator.
- V = Indicator value.
- n = Number of indicators used.
- $\sum W_i = 100$

Indicators	Calculation formula	Definition of variables
Water Quality	$\boldsymbol{ICA_{OBJ} = \sum_{i=1}^{n} Pi.(ICA)i}$	Number of parameters selected. $(ICA)_i$: Environmental quality index for the parameter. Pi: Weight attributed to parameter i.
Ecological Footprint	$\boldsymbol{F = D/Y}$	EF = Ecological Footprint. D = Annual demand for a product. Y = Annual yield of the same product.
Deforestation	$\boldsymbol{\frac{Deforested\ areas\ (h2)}{Conservation\ areas\ (h2)}}$	Conserved Areas (m2): páramo conservation area in the last year. Deforested Areas (m2): geographic area that has undergone deforestation, whether caused by humans or not, in the last year.
Soil Erosion	$\boldsymbol{\frac{Area\ used\ for\ grazing\ (ha)}{Geographical\ area\ per\ hectare\ (ha)}}$	Area used for grazing (ha): Increase in livestock farming in the páramos in recent years. Geographical Areas (ha): Loss from soil erosion and loss of carbon retention.
Biomass Calculation	$\boldsymbol{Biomass(\frac{ugC}{ml}) = N * By * F}$	N: The number of microorganisms enumerated per ml of sample. Bv: The biovolume expressed as µm^3 per microorganism. F: Conversion factor, µg of Carbon per μm^3.
Soil Carbon Concentration	$\boldsymbol{CT = C}_{bushy\ comp} + \boldsymbol{C}_{herbaceous\ comp} + \boldsymbol{C}_{necromass\ comp\ (a+h)} + \boldsymbol{C}_{soil+(a+h)}$	C_{TOTAL}: Total Carbon Content of the Páramo ecosystem. $C_{comp\ bushes}$: C in the bush compartment (biomass). $C_{comp.\ herbs}$: C in the herbaceous compartment (biomass). $C_{comp.\ necromass\ (a+h)}$: C in the necromass of the shrubby and herbaceous páramos. $C_{comp.\ soil\ (a+h)}$: C in the soil compartment in the shrubby and herbaceous páramos.
Air Pollution	$\boldsymbol{\frac{NOx\ emissions(kg)}{n\ hab\ or\ visitors}}$	NOx emissions in the páramo area under study. Population in the year of measurement.

Indicators	Calculation formula	Definition of variables
		Ratio of NOx emissions to the population in the year of calculation.
Compliance with Environmental Legislation	$\mathbf{I = (NAC / NTAE) * 100}$	NAC = Number of environmental regulations complied with. NTAE = Total number of environmental regulations required.
Good Practices for Páramo Management	Promote and require the performance and documentation of monitoring, training in environmental issues, inspections, and compliance with environmental legislation in the páramo and among the inhabitants of the surrounding rural areas who benefit from its nearby ecosystem services.	

5 Conclusion

This study facilitated the development of an environmental sustainability indicator based on the rigorous selection and evaluation of specific environmental sub-indicators. To achieve this objective, advanced methodologies were applied, including neutrosophic logic and a combination of multi-criteria evaluation methods. These tools enabled the integration and analysis of multiple dimensions of environmental data, characterized by their complexity and ambiguity.

The application of neutrosophic logic was crucial for managing the inherent uncertainty in environmental data, allowing for a more accurate evaluation of the indicators. This approach provided a solid foundation for incorporating multiple perspectives and managing contradictions in the available information, resulting in a more inclusive and representative decision-making process. On the other hand, the use of TODIM and PROMETHEE methods in their neutrosophic variant facilitated the objective comparison and prioritization of sub-indicators, based on criteria specifically selected to reflect the most relevant aspects of sustainability and environmental impact.

The prioritization of indicators directly related to carbon storage and ecosystem productivity was confirmed, reflecting their critical relevance in mitigating climate change and conserving biodiversity, according to experts. Additionally, the utility of integrating regulatory compliance measures and sustainable management practices related to compliance with environmental legislation and good practices for páramo management was highlighted. These sub-indicators are essential to ensure that environmental management policies and practices are not only effective but also aligned with legal requirements and social expectations. The combination of analytical tools and advanced logical approaches proved effective in addressing the complexity of environmental systems, suggesting their continued and expanded application in future environmental monitoring and evaluation efforts.

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