LEVERAGING CLIMATE CHANGE VULNERABILITY ASSESSMENT WITH MCDA

Author 1. *Tatiana Merino-Benítez*[1]
Author 2. *Claudio Garuti*[2]
Author 3. *Luis A. Bojórquez-Tapia*[3]

Highlights

- MCDA enhances technical support for international sustainability frameworks.
- Our approach identifies thresholds, proximity, and prioritizes interventions for adaptation.
- Methodological support advances policies for global sustainability efforts.

ABSTRACT

Sustainability faces interconnected global challenges, including climate change, biodiversity loss, and resource depletion, posing significant threats to current and future generations. Addressing climate change vulnerability is an urgent priority for policymakers aiming to achieve SDG 13, which emphasizes resilience-building and adaptive capacity through scientific knowledge. While Climate Change Vulnerability Assessments (CCVA) are commonly used in this context, they often fail to pinpoint critical thresholds—those that separate adaptive (desirable) states from vulnerable (undesirable) states. This paper presents a Multi-Criteria Decision Analysis (MCDA) approach designed to reinforce the scientific and technical foundations of CCVA. We illustrate this approach with a case study on small-scale fishing communities, demonstrating its broader applicability. By enhancing methodological support, this approach aims to identify effective policies and interventions that contribute to global sustainability efforts.

Keywords: sustainable development, thresholds, policymaking.

[1] Tatiana Merino-Benítez, PhD, Laboratorio Nacional de Ciencias de la Sostenibilidad, Instituto de Ecología, Universidad Nacional Autónoma de México, Mexico City, Mexico, & Institut für Technikfolgenabschätzung und Systemanalyse, Karlsruher Institut für Technologie, Karlsruhe, Germany, e-mail: tatianam@ iecologia.unam.mx (ORCID: 0000-0002-7587-1498).

[2] Claudio Garuti, Fulcrum Ingeniería Ltd., Santiago, Chile, e-mail: claudiogaruti@fulcrum.cl

[3] Luis A. Bojórquez-Tapia, PhD, Professor, Laboratorio Nacional de Ciencias de la Sostenibilidad, Instituto de Ecología, Universidad Nacional Autónoma de México, Mexico City, Mexico, e-mail: bojorquez@ecologia.unam.mx (ORCID: 0000-0001-6764-8803).

1. Introduction

Our world is grappling with interconnected challenges, including climate change, biodiversity loss, and resource depletion. Together, these issues pose significant threats to the sustainability of both current societies and future generations. Particularly, policymakers worldwide are tasked with the critical and urgent responsibility of assessing climate change vulnerability—an endeavor at the heart of achieving the Sustainable Development Goals (SDGs). SDG 13 underscores explicitly the need for immediate and transformative action to counter the escalating threats posed by climate change. Such action should primarily aim to strengthen resilience and adaptive capacity to climate-related disasters (Target 13.1) and to integrate climate change measures into policies and planning (Target 13.2). Achieving these targets demands integrating "the best available scientific and traditional knowledge" into regional planning and decision-making. Failure to act will lead to more severe climate disasters and destabilized communities (Schipper, 2020).

Climate Change Vulnerability Assessments (CCVA) provide the technical and scientific basis to develop practical, context-specific plans and policies that effectively address climate change's immediate and long-term impacts. CCVA is, however, a notoriously difficult analytical process that implies the aggregation of multiple indicators of exposure, sensitivity, and resilience (IPCC, 2014). Not only is vulnerability a multifactorial concept but also its assessment requires a nuanced and context-specific understanding of multiple indicators regarding three key considerations: (1) What are the thresholds that delineate the adaptive and vulnerable states? (2) How can the closeness to a threshold be assessed? (3) Which interventions are essential to prevent exceeding such thresholds?

This paper presents an analytical approach using Multi-Criteria Decision Analysis (MCDA) to enhance the scientific and technical foundations of CCVA. This framework is tailored to support sustainable regional planning and decision-making. We present the application of our approach through an illustrative example based on a real case involving small-scale fishing communities. Despite limited disclosure, this example effectively demonstrates the broader applicability of our approach. Our objective is to enhance methodological support for identifying policies and interventions that promote global sustainability.

2. Literature Review

El-Zein and Tonmoy (2015) underscore two important challenges in CCVA: the lack of clear guidelines for setting thresholds when converting indicators into vulnerability rankings and the limited understanding of the precise relationships between these indicators and vulnerability. As the authors point out, these challenges introduce uncertainty, making it difficult to ensure that vulnerability rankings accurately reflect real-world conditions. To address this issue, they emphasize the importance of focusing CCVA on multi-stakeholder engagement and accounting for the non-linear relationships between indicators and vulnerability levels (Kane *et al*., 2015; Furrer *et al*., 2022). Accordingly, our approach addresses the development of indicators, enabling a common understanding of the priority of interventions while considering stakeholder viewpoints and preferences.

This method not only contributes analytically by addressing key challenges identified to achieve sustainable outcomes but also offers prescriptive guidance for policymakers on where and how to act to reduce overall vulnerability. We thus provide technical support to transform theoretical concepts and frameworks into an analytical, systematic, and transparent approach.

3. Analytical approach

Our analytical approach consists of the following 9-step algorithm.

a. Develop an AHP or ANP model.

b. Develop rating scales.

c. Aggregate the results. Obtain a single value for each j-th alternative.

d. Obtain local thresholds. Using rating scales, compute the following equation (Garuti and Mu, 2024):

$$L_i = \frac{2w_\alpha w_\beta}{w_\alpha + w_\beta} \tag{1}$$

where L_i is the local threshold of the i-th criterion, α and β are the overall categories; $\alpha \prec \beta$, $w_\alpha > w_\beta$, and $w_\alpha, w_\beta = [0,1]$, $\alpha \neq \beta$, $\alpha + 1 = \beta$ (consecutive levels).

e. Generate threshold profiles. Organize L_i as vectors, $P_{\alpha-\beta}$, where $i = 1,2,\dots,I$.

f. Implement compatibility analysis to compare AHP output with threshold profiles. Given the threshold profiles $P_{\alpha-\beta}$, the global weights w_i, and the rating values x_{ij}, the compatibility indices for each j-th alternative are obtained with:

$$G^{x_{ij},P_{\alpha-\beta}} = \sum_i^I w_{ij} \frac{\min(x_{ij}, P_{\alpha-\beta})}{\max(x_{ij}, P_{\alpha-\beta})} \tag{2}$$

Accordingly, $G^{x_{ij},P_{\alpha-\beta}}$, as the closeness between x_{ij} and $P_{\alpha-\beta}$ is interpreted as shown in Table 1.

Table 1. Scale of compatibility. Adapted from Garuti (2017)

Category	$G^{a,b}$ value range	Description
Very high	[0.90, 1.00]	Compatible vectors
High	[0.85, 0.89]	Almost compatible vectors
Moderate	[0.75, 0.84]	Moderate compatible vectors
Low	[0.65, 0.74]	Low compatible vectors
Very low	[0.60, 0.64]	Almost incompatible vectors (random values)
Null	[0.00, 0.59]	Total incompatible vectors (random values)

g. Obtain global thresholds. Compute the weighted linear combination of the global weights, w_i, and the local thresholds, L_i (Garuti and Mu, 2024):

$$T_{\alpha-\beta} = \sum_i^I w_i L_i \qquad i = 1,2,\dots,I;\ 0 \leq T \leq 1 \tag{3}$$

where $T_{\alpha-\beta}$ is the global threshold for the α-th and β-th categories.

h. Rank alternatives in terms of overall influence. The global thresholds delimit the overall scale cuts. When computing two global thresholds, three categories are obtained: low, $L = \{V_j < T_{L-M}\}$; *moderate*, $M = \{T_{L-M} \leq V_j < T_{M-H}\}$; and *high*, $H = \{V_j \geq T_{M-H}\}$.

i. Identify feasible interventions. Obtain the difference between each i-th sub-criterion weight and its closeness to the respective threshold profile, for each j-th alternative in descendent order:

$$R_{ij} = w_i - G_{ij} \tag{4}$$

4. Results

A multidisciplinary group of specialists on small-scale fisheries developed an AHP model **(step a)** to assess the vulnerability of a fishing community to climate change (Merino-Benítez *et al*., 2019). The model consisted of three hierarchical levels: Level 1 defined the goal of identifying the vulnerability of small-scale fisheries along the coastal zone; Level 2 included three main criteria representing the primary drivers of vulnerability; and Level 3 incorporated sub-criteria corresponding to specific drivers of change (Figure 1, Table 2).

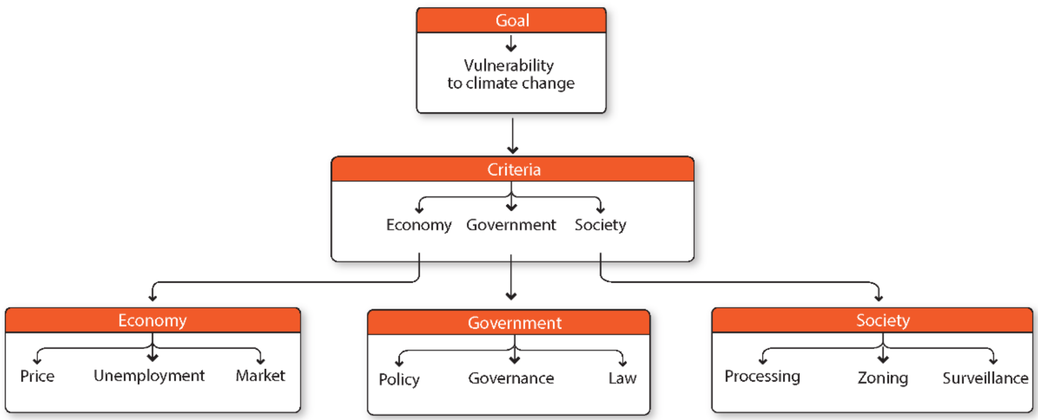

Figure 1. Vulnerability model.

Table 2. Description of vulnerability model (normalized weights in parenthesis).

Criterion	Sub-criterion	Definition
Economy (0.32)	Price (0.09)	Decrease in the monetary value of fishery products.
	Market (0.06)	Decrease in the demand for fishery products.
	Unemployment (0.15)	Lack of available employment opportunities in small-scale fishing.
Government (0.46)	Governance (0.16)	Inadequate coordination and collaboration between fisheries sectors.
	Law (0.19)	Absence or inadequacy of national and state-level norms, regulations, and legal frameworks.
	Policy (0.10)	Lack of governmental support for subsidizing, developing, and planning fishing activities.
Society (0.22)	Processing (0.12)	Inability to access or participate in various stages of the fishing value chain.
	Surveillance (0.05)	Insufficient measures to combat illegal, unreported, and unregulated fishing activities.
	Zoning (0.08)	Restricted access to maritime and inland zones for fishing activities.

Using the AHP, nine rating scales were developed **(step b)**. Pairwise comparison matrices were used to compare a five-level linguistic vulnerability scale {very low (VL) $\succ$

low(L) ≻ moderate (M) ≻ high(H) ≻ very high (VH)} to generate the cut-off values for each category (Figure 2). The rating scales reflected different perceptions of vulnerability. *Policy*, *Governance*, and *Law* corresponded to a more pronounced change in the cuts for each category, followed by the sub-criteria related to *Society* and *Economy*. This pattern revealed that *Government* sub-criteria had greater relevance starting from category *high*.

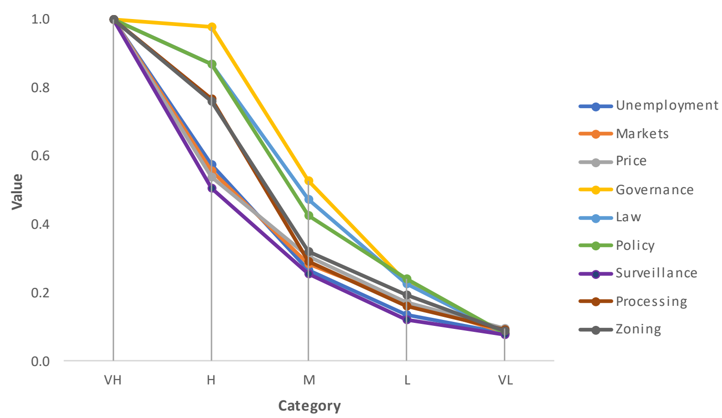

Figure 2. Rating scales.

4.1 Example with one fishing community

The aggregated **(step c)** vulnerability value, V_j, of the j-th fishing community was obtained from the weighted linear combination of the sub-criterion weights, w_i, and the corresponding ratings, x_i:

$$V_j = \sum_{i}^{I} w_i x_i = 0.78 \tag{5}$$

The local thresholds were arranged into two threshold profiles, P_{L-M} and P_{M-H}, for $\alpha = low$ and $\beta = moderate$ **(steps d, e)**:

$$P_{L-M} = (0.22, 0.22, 0.18, 0.31, 0.32, 0.31, 0.16, 0.24, 0.21)$$

and for $\alpha = moderate$ and $\beta = high$:

$$P_{M-H} = (0.39, 0.38, 0.36, 0.57, 0.69, 0.61, 0.34, 0.45, 0.42)$$

Then, the compatibility analysis **(step f)** resulted in $G^{x_{i2}, P_{L-M}} = 0.40$ and $G^{x_{i2}, P_{M-H}} = 0.59$. According to Table 2, this result indicated that the fishing community's profile aligns more closely with a high-vulnerability profile (P_{M-H}) than with a low-vulnerability profile (P_{L-M}). Thus, interventions aimed at reducing this vulnerability are recommended.

Additionally, the global thresholds (step g), $T_{L-M} = 0.25$ and $T_{M-H} = 0.49$, were used to develop a three-category vulnerability scale: $L = \{V_j < 0.25\}, M = \{0.25 \le V_j < 0.49\}, H = \{0.49 < V_j\}$.Thus, the corresponding vulnerability category **(step h)** for the fishing community was H, $V_j = 0.78$.

These diagnostics raised the question of which driver to attend first. To address this question, we identified the feasible interventions **(step i)**. Given the vector

$$[R] = [0.02 \quad 0.01 \quad 0.13 \quad 0.07 \quad 0.11 \quad 0.07 \quad 0.05 \quad 0.05 \quad 0.01]$$

the specific drivers where interventions should be prioritized were *Unemployment* ($R_{ij} = 0.13$) and *Law* ($R_{ij} = 0.07$), followed by *Governance* ($R_{ij} = 0.11$) and *Processing* ($R_{ij} = 0.05$).

By implementing interventions to reduce the ratings of *Unemployment* and *Law* from *very high* (VH, 1.00) to *very low* (VL, 0.08), the community's overall vulnerability score (V_j) would drop from 0.78 to 0.46. This reclassification would place the fishing community in the *moderate* vulnerability category. These adjustments would also be reflected in the compatibility of the fishing community's profile with the threshold profiles (Figure 3), resulting in less compatibility with the high-vulnerability profile ($G^{x_{ij},P_{M-H}} = 0.52$).

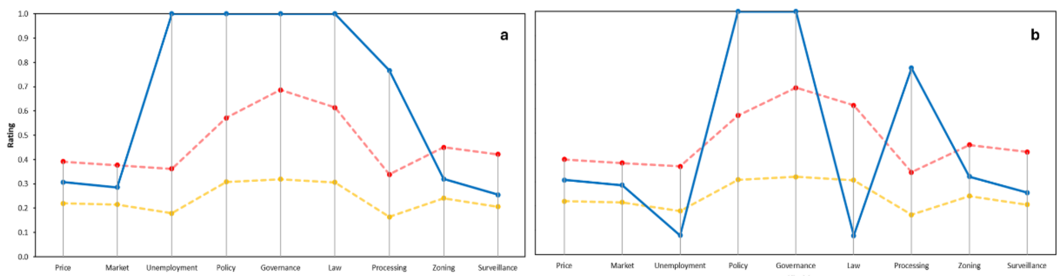

Figure 3. Thresholds profiles P_{L-M} (yellow) and P_{M-H} (red). Rating values, x_{ij}, (blue) are shown a) before and b) after interventions to decrease vulnerability.

4.2 Example with multiple fishing communities

The implementation of the algorithmic process for analyzing fifth teen fishing communities (Figure 4) revealed that eleven of them had *high* vulnerability, three (FC_2, FC_{15}, FC_7) had *moderate* vulnerability, and one (FC_9) had *low* vulnerability (**steps c** and **h**).

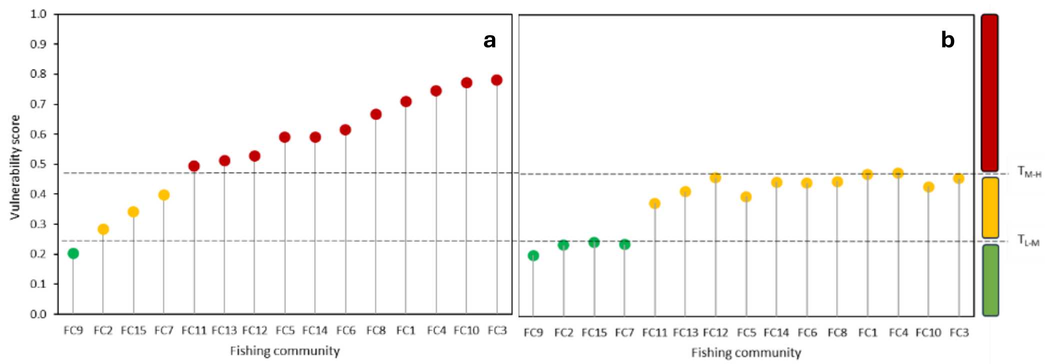

Figure 4. Vulnerability score a) before and b) after interventions.

Following **steps f** and **i**, results indicated an intervention plan (Table 3) to reduce overall vulnerability in fishing communities: FC_{10}: Unemployment and Governance, FC_4: Governance and Law, FC_{15}: Law and Governance, FC_1: Law, FC_2: Law, FC_6: Law and Governance, FC_5: Unemployment and Governance, FC_3: Unemployment and Law, FC_8: Governance and Law, FC_{14}: Law, FC_{13}: Law, FC_{11}: Unemployment, FC_7: Policy and Unemployment, and FC_{12}: Unemployment.

Table 3. Suggested interventions: Larger dots represent changes in three or more rating categories, smaller dots indicate changes in two or fewer. The order of FC_{j} follows $G^{x_{\mathrm{ij}},P_{M-H}}$ as intervention priority.

Fishing community	**Sub-criterion**			
	Unemployment	**Policy**	**Governance**	**Law**
FC_{10}	●		●	
FC_{4}			●	●
FC_{15}			•	•
FC_{1}				●
FC_{2}				•
FC_{6}			•	●
FC_{5}	●		●	
FC_{3}	●			●
FC_{8}			●	●
FC_{14}				●
FC_{13}				●
FC_{11}	●			
FC_{7}	●	●		
FC_{12}	●			

5. Conclusions

We have introduced an analytical approach that enhances the scientific and technical foundations of CCVA. We argue that it fulfills a critical role in regional planning and policymaking and attends key considerations in vulnerability analysis, risk management, drivers of change, and governance. The approach uses an algorithmic process that integrates the AHP with relevant metrics to create a traceable and rigorous climate change vulnerability assessment in a multi-stakeholder context.

Analytically, our approach allows the definition of thresholds by considering not only spatial scales (alternatives) sectors (criteria), and jurisdictional boundaries (sub-criteria) but also different viewpoints (specialists' consultations). Building on Garuti and Mu (2024), the use of rating scales effectively addresses the non-linear relationships between indicators and the real world. It is thus safe to assert the quantitative metrics serve as analytical and prescriptive support for policymaking.

Further applications of this approach include identifying thresholds, assessing proximity to those thresholds, and prioritizing interventions within international frameworks, such as CEPAL's Conceptual Framework on Territorial Development, Spatial Planning, and Disaster Risk Reduction; IPBES's Global Assessment Report on Biodiversity and

Ecosystem Services; and the IPCC Climate Change 2023 Report, all of which address vulnerability, risk, and planning as multifactorial and interconnected challenges.

6. Limitations

In future work, it will be important to consider the application of optimization models to further refine and facilitate the identification of influential changes while considering economic and political constraints. Optimization models can provide a quantitative basis for addressing the logistical challenges of policy making. This next step will enhance the robustness and applicability of our approach, making it a more effective tool for policymakers seeking to implement sustainable and adaptive strategies in response to regional environmental changes.

7. Key References

El-Zein, A., Tonmoy, F.N. (2015). Assessment of vulnerability to climate change using a multicriteria outranking approach with application to heat stress in Sydney. *Ecological Indicators*, 48, 207-217. http://dx.doi.org/10.1016/j.ecolind.2014.08.012

Furrer, M., Mostofi, H., Spinler, S. (2022). A study on the impact of extreme weather events on the ceramic manufacturing in Egypt. *Resources, Environment and Sustainability*, 7, 100049. https://doi.org/10.1016/j.resenv.2022.100049

Garuti, C. (2017). The compatibility index G. Creating an index of closeness within weighted environment. *Revista Escuela de Perfeccionamiento Investig Operacional*, 25(41).

Garuti, C. (2021). How to obtain a global reference threshold in AHP/ANP. *International Journal of the Analytic Hierarchy Process*, 13(1). https://doi.org/10.13033/ijahp.v13i1.802

Garuti, C., Mu, E. (2024). A rate of change and center of gravity approach to calculating composite indicator thresholds: moving from an empirical to a theoretical perspective. *Mathematics*, 12. https://doi.org/10.3390/math12132019

Merino-Benítez, T., Grave, I., Bojórquez-Tapia, L.A. (2020). AHP- based social vulnerability index for small fisheries in Yucatan, Mexico. *International symposium of the analytic hierarchy process 2020, web conference. DEC. 3 – DEC.* 6. 2, pp. 1–5. https://doi.org/10.13033/isahp.y2020.010

Kane, H.H., Fletcher, C.H., Frazer, L.N., *et al*. (2015). Modeling sea-level rise vulnerability of coastal environments using ranked management concerns. *Climatic Change*, 131, 349–361. https://doi.org/10.1007/s10584-015-1377-3

Schipper, E.L.F. (2020). Maladaptation: when adaptation to climate change goes very wrong. *One Earth*, 3(4), 409-414. https://doi.org/10.1016/j.oneear.2020.09.014

8. Acknowledgements

This is a partial fulfillment of the requirements for the degree of Doctor in Sustainability Science, of the second author, who acknowledges the support of CONAHCYT scholarship 1003060 and the Posgrado en Ciencias de la Sostenibilidad, UNAM.