



Climate Resilience and the Hydro-Vegetal Paradox in El Bayadh Province (Algeria, 1984-2023)

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Abstract: The decade 2010 to 2020 was the warmest ever recorded in the Mediterranean basin (+1.5°C), exceeding the global average. North Africa, identified as a vulnerability hotspot by the IPCC AR6, experiences intensified droughts and ecosystem degradation. This study presents the first quantitative assessment of climate resilience in El Bayadh Province (Algeria), revealing an unexpected hydro-vegetal paradox. A comparative multi-index methodology (restricted climate index vs. global index integrating 7 variables) was applied to 22 municipalities over the period of 1984 to 2023. The results showed a universal degradation of water balance (-8.2 to -21.4 mm yr⁻¹) and widespread warming (+0.8 to +2.1°C decade⁻¹). Paradoxically, 73 to 77% of municipalities showed improvement in vegetation indices (NDVI, SAVI), suggesting ecological adaptation. Principal component analysis (PCA-99% variance explained) identified water stress as the main differentiating factor, and clustering distinguishes 5 territorial profiles (silhouette = 0.521). The global index proves more discriminant than the restricted index for capturing the complexity of socio-ecological dynamics. This study highlights the need for differentiated adaptation policies addressing challenges related to water, food security, and migration.

Key words: Climate resilience, arid zones, hydro-vegetal paradox, multidimensional indices, adaptation, Algeria.

The decade 2010-2020 marked the warmest period ever recorded in the Mediterranean basin, with temperatures increasing by +1.5°C, significantly exceeding the global average of +1.1°C (IPCC, 2021). This amplified warming was accompanied by intensified droughts, increased climate variability, and accelerated ecosystem degradation in arid and semi-arid regions (IPCC, 2023). The sixth IPCC assessment report (2021-2023) projects warming of 2 to 4°C by 2100 for Mediterranean and North African regions under RCP4.5 and RCP8.5 scenarios, exceeding global averages. These changes will lead to precipitation decreases of 10-20%, increased frequency and intensity of droughts, and accelerated land degradation, exacerbating food insecurity and climate migration risks (IPCC, 2023).

Arid and semi-arid regions, covering approximately 41% of the global land area and home to more than 2.3 billion people, are particularly vulnerable (UNCCD, 2022). North Africa, identified as a climate vulnerability “hotspot” (Giorgi, 2006; Cramer *et al.*, 2018), is already experiencing severe impacts on water resources, food security, and socio-ecological systems. Recent regional studies document convergent trends: accelerated warming (+0.3 to +0.4°C decade⁻¹ since 1980), decreasing winter precipitation (-5 to -15% decade⁻¹), and increased interannual variability (Cook *et al.*, 2015; Luppichini *et al.*, 2022). These transformations are accompanied by considerable socio-economic impacts: 15 to 30% decreases in cereal yields, 20 to 40% reductions in renewable water resources, and degradation of 12 m ha of agricultural land in the MENA region (Treguer *et al.*, 2018).

Algeria, with 87% of its territory classified as arid to hyper-arid, is particularly exposed (ONM, 2020). The country has recorded a continuous increase in mean annual temperatures since 1970 (+0.32°C decade⁻¹), with increasingly frequent extremes (48.7°C in Ouargla in 2018) (Taibi *et al.*, 2022). Precipitation has shown a general decreasing trend (-3 to -8% decade⁻¹), particularly marked along the coast and high plateaus (Nouaceur and Murarescu, 2016). Analysis of drought indices reveals intensification of extreme events e.g. the standardized precipitation index (SPI) indicates a 40% increase in the frequency of severe droughts since 1980 (Zeroual *et al.*, 2019).

El Bayadh Province, located in northwestern Algeria, represents an emblematic case study of the climate challenges facing North African steppe regions. Covering 78,870 km² with 22 municipalities and 330,000 inhabitants, the province presents a marked north-south climatic gradient, from semi-arid high plateaus (400 mm yr⁻¹) to arid pre-Saharan zones (150 mm yr⁻¹) (Serrai and Djiar, 2024). The provincial economy relies primarily on agro-pastoralism (65% of the active population), with 2.1 m sheep and 450,000 ha of cereals, making the territory particularly vulnerable to climate hazards (FAO, 2023; Bendouina *et al.*, 2025a). Recurrent droughts have caused livestock losses of 30 to 50% and have decreased in cereal production by 40 to 70%, illustrating the magnitude of local climate change impacts.

Despite these pressing challenges, El Bayadh Province still lacks sufficient quantitative research on climate resilience at the municipal scale (Guerine *et al.*, 2025). Most existing studies concentrate on national or regional levels (Camarero *et al.*, 2021; Taibi *et al.*, 2022), which can obscure important local variations in vulnerability and opportunities for targeted adaptation. Furthermore, many resilience assessments rely on a limited set of climate indices, overlooking the ecological and socio-economic dimensions that are crucial for understanding the complexity of socio-ecological systems under climate change.

This study aims to address these gaps by developing and applying a comparative multi-index methodology to assess climate resilience at the municipal scale in El Bayadh Province over the period 1984-2023. Specifically, it seeks to: (i) analyse the temporal trends of seven environmental indicators over 40 years using robust statistical tests; (ii) compare two environmental index approaches-restricted versus global-for climate resilience assessment; (iii) identify co-variation structures among indicators through Principal Component Analysis (PCA); (iv) develop a territorial typology of resilience using optimised unsupervised classification; and (v) provide a scientific basis to support territorial adaptation planning.

We formulate the following hypotheses: (H1) the 22 municipalities present significantly differentiated climate resilience profiles, identifiable through multivariate analysis; (H2) a global environmental index integrating climatic, ecological, and socio-economic dimensions is more discriminant than a purely climatic restricted index; (H3) water stress constitutes the dominant factor differentiating territorial resilience in the semi-arid context of El Bayadh; and (H4) the paradoxical improvement of certain vegetation indices coexists with degradation of water conditions, suggesting complex ecological adaptation mechanisms.

Materials and Methods

Study area

El Bayadh Province is situated in northwestern Algeria, between latitudes 32°30'N-34°00'N and longitudes 0°30'E-2°30'E. It covers an area of 78,870 km² and comprises

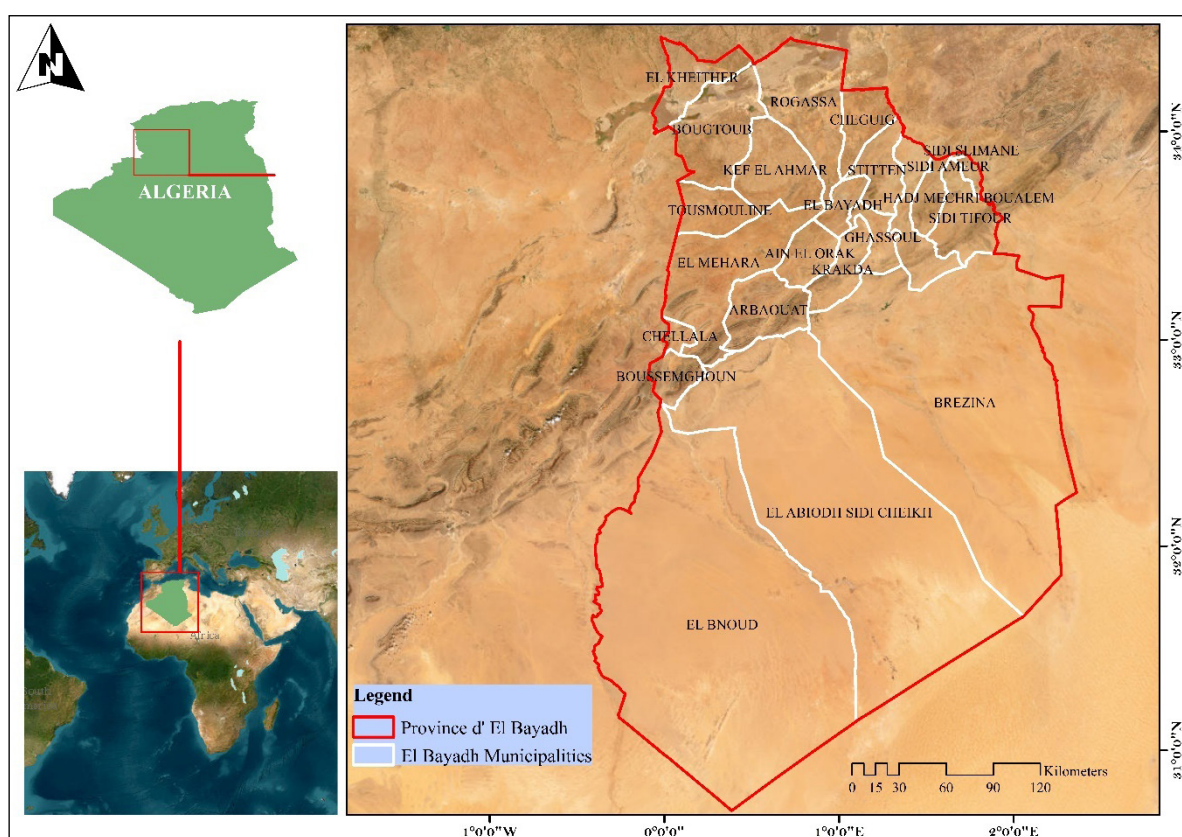


Fig.1. Location map of the study area (El Bayadh Province).

22 municipalities: Ain El Orak, Arbaouat, Boussemghoun, Bougtoub, Brezina, Cheguig, Chellala, El Abiodh Sidi Cheikh, El Bayadh, El Bnoud, El Kheither, El Mehara, Ghassoul, Hadj Mechri, Kef El Ahmar, Krakda, Rogassa,

Sidi Ameer, Sidi Slimane, Sidi Tifour, Stitten and Tousmouline (Fig. 1).

The province presents contrasting topography with altitudes varying from 600 m in the northern plains to 2,177 m at

Table 1. Analysed environmental indicators

Indicator	Unit	Source	Period	Interpretation
Aridity (P/PET)	-	ONM	1984-2023	Global climatic water stress
Water balance (P - PET)	mm yr ⁻¹	ONM	1984-2023	Water availability and intensity of water deficit
NDVI (Annual averages for March-June growing season)	Unitless	Landsat / Sentinel	1984-2023	Photosynthetic activity
SAVI (Annual averages for March-June growing season)	Unitless	Landsat / Sentinel	1984-2023	Vegetation index corrected for soil background effects
VCI	Unitless	Landsat / Sentinel	1984-2023 (annual averages for March-June growing season)	Relative vegetation condition
MNDWI	Unitless	Landsat	1984-2023	Surface moisture content
Land Surface Temperature (LST)	°C	Landsat	1984-2023	Indicator of thermal stress
Pastoral Pressure Index (LPI)	LU ha ⁻¹	ONS / FAO coefficients (1 sheep = 0.1 LU; 1 goat = 0.1 LU)	1984-2023	Anthropogenic grazing pressure on vegetation

Djebel Amour in the south. This altitudinal variability generates a marked north-south climatic gradient, from Mediterranean semi-arid conditions to pre-Saharan arid conditions (Bendouina *et al.*, 2025b; Bendouina *et al.*, 2025c; Zeroual *et al.*, 2019). The climate falls within the semi-arid to arid category of the Köppen-Geiger classification (BSk to BWk). Mean annual precipitation ranges from about 150 mm in the south to 400 mm in the north, with a year-to-year coefficient of variation between 35% and 45% (ONM, 2020).

The province has 330,000 inhabitants (density: 4.2 inhabitants km⁻²) with a predominantly rural population (65%). The economy relies on agro-pastoralism with 2.1 m sheep, 0.38 m goats, and 450,000 ha of useful agricultural area (IFAD, 2023). The main agricultural productions include cereals (durum wheat, barley), legumes (lentils, chickpeas), and extensive livestock farming.

A range of parameters was derived from data gathered from multiple sources in order to thoroughly characterize the environmental variability (Table 1).

Data and sources

Climatic and hydrological data: Temperature and precipitation data were obtained from the National Meteorological Office (ONM) for 11 meteorological stations distributed throughout the province (1984 to 2023). Missing data (< 3%) were estimated by multiple linear regression using adjacent stations. Potential evapotranspiration was calculated using the FAO-56 Penman-Monteith method from ONM data. Water balance (P-PET) was calculated on yearly basis for each municipality.

Remote sensing data: Vegetation indices (NDVI, SAVI and VCI) were derived from Landsat 5/7/8 and Sentinel-2 images (30m resolution) with LEDAPS/LaSRC atmospheric correction. Annual averages were calculated during the vegetation growth period (March to June) for each year of the period 1984 to 2023, with annual mean values calculated over the March to June growing season (1984 to 2023). This approach minimises intra-annual variability while focusing on long-term interannual trends. The surface moisture index (MNDWI) was calculated from Landsat spectral bands using the formula: MNDWI = (Green

- SWIR1)/(Green + SWIR1). Land surface temperature (LST) was derived from Landsat thermal data using a single-window algorithm with emissivity correction.

Socio-economic data: Population, agricultural area, and livestock data were obtained from the National Statistics Office (ONS) and the El Bayadh Agricultural Services Directorate (DSA) for the period 1984 to 2023. To better capture the socio-ecological dynamics of this agro-pastoral region, we replaced population density with a pastoral pressure index (LPI) calculated as Livestock Units (LU) ha⁻¹ of pasture area. Livestock numbers (sheep, goats) were converted to standardised LUs using FAO coefficients (1 sheep = 0.1 LU, 1 goat = 0.1 LU), then divided by available pasture area (LU ha⁻¹) and normalised for inclusion in the global index. This metric more directly reflects pastoral pressure on vegetation and improves the interpretation of NDVI/SAVI trends. The LPI is particularly relevant in arid agro-pastoral systems as it quantifies the intensity of forage resource use, which is the main driver of ecosystem degradation in these contexts.

Comparative methodology for developing environmental indices

Restricted index-RI (Climatic): The restricted index (RI) is based on a subset of three purely climatic variables, selected for their fundamental importance in determining climate resilience according to scientific literature (IPCC, 2023; Vicente-Serrano *et al.*, 2022). These variables represent the direct climatic constraints faced by ecosystems and societies viz., Land Surface Temperature (LST)-thermal stress indicator, Aridity (P/PET)-climatic water stress indicator and Water balance (P - PET)-water availability indicator. Each variable was standardised using the formula:

$$Z = (X - \mu) / \sigma \quad \dots 1$$

where, X is the raw value, μ is the mean, and σ is the standard deviation of the variable. This standardisation brings all variables to a comparable scale (mean = 0, standard deviation = 1) and eliminates the influence of measurement units. Further, the standardised variables were aggregated using a weighted average. Weights were determined by a prior Principal Component Analysis (PCA), based on each variable's contribution to the first

principal component. The weights obtained were 0.35 (LST), 0.32 (P/PET) and 0.33 (P-PET). The restricted index (RI) calculation was done for each Municipality (i) using formula:

$$RI_i = -(0.35 \times Z_{LST_i} + 0.32 \times Z_{Aridity_i} + 0.33 \times Z_{WaterBalance_i}) \quad \dots 2$$

The negative sign was introduced so that a high index value corresponds to high climate resilience (low temperature, aridity, and negative water balance values). Finally normalized index value obtained on a scale of 0 to 1 to facilitate interpretation and comparison between municipalities.

Global index-GI (Climatic, ecological and Socio-economic): The global index (GI) integrates seven environmental variables, covering three complementary dimensions of climate resilience i.e., Climatic dimension (LST, Aridity, water balance), Ecological dimension (NDVI, SAVI, VCI, MNDWI) and Socio-economic dimension (Pastoral pressure index-LPI). This multidimensional approach is justified by the complex nature of socio-ecological systems, where climatic, ecological, and socio-economic factors interact to determine overall resilience (Folke *et al.*, 2016; IPCC, 2023). The integration of these dimensions allows capturing both climatic constraints, ecological responses, and anthropogenic vulnerability or resilience factors. The LPI is particularly crucial as it directly quantifies anthropogenic pressure on pastoral ecosystems, which is the main driver of degradation in arid zones. Similar to restricted index (RI) each variable (Z) was standardised using the formula:

$$Z = (X - \mu) / \sigma \quad \dots 3$$

Further, PCA was performed on the correlation matrix of the seven standardised variables. This analysis allowed Identification of correlation structures between variables, reduced data dimensionality and determined optimal weights for each variable based on their contribution to total variance. The weights of each variable in the global index were determined according to their contribution to the total variance explained by principal components. A variable's contribution to a principal component is calculated as the square of its loading divided by the eigenvalue of the component. The total contribution of a variable to explained variance is the sum of its contributions to all retained principal

components. Global index (GI) was calculated for each Municipality (i) as a linear combination of standardised variables weighted by their contribution to variance using the formula:

$$GI_i = \sum (w_j \times Z_{ji}) \quad \dots 4$$

where, w_j is the weight of variable j and Z_{ji} is the standardised value of variable j for municipality i . The coefficient signs were adjusted so that a high index value corresponds to high climate resilience. For variables negatively correlated with resilience (temperature, aridity, pastoral pressure), the weight sign was inverted. Finally, the obtained index was normalised on a scale of 0 to 1 to facilitate interpretation and comparison between municipalities.

The global index (GI) presents several important advantages over the restricted index. It captures the complexity of interactions between climatic, ecological, and socio-economic dimensions, and it allows detecting and quantifying complex phenomena such as the hydro-vegetal paradox. It also offers a more complete and nuanced view of climate resilience by integrating both constraints and adaptive capacities, notably through the LPI, which quantifies pastoral pressure. Building on these strengths, the global index further enhances comparability across regions by integrating standardized metrics that reflect local specificities without losing broader contextual relevance, improves decision-making support by providing a synthetic indicator that highlights priority intervention zones and reveals underlying drivers of vulnerability, facilitates long-term monitoring by combining stable structural factors with dynamic variables to assess trends and early warning signals, and encourages interdisciplinary analysis through the integration of hydrological, ecological, and socio-economic components within a single evaluative framework.

Statistical methods

Trend analysis-Mann-Kendall Test (MK): Non-parametric test was applied to detect monotonic trends in indicator time series. This robust method requires no assumptions about data distribution and is resistant to outliers (Mann, 1945; Kendall, 1975). Trends were considered significant for $|Z| > 1.96$ ($p < 0.05$). The magnitude of trends was quantified using Sen's slope estimator (1968). All Mann-Kendall tests

and Sen's slopes were recalculated using LPI time series (1984–2023) for the 22 municipalities.

Principal component analysis (PCA): PCA reduced the dataset dimensionality and identified main co-variation structures between indicators. PCA was applied to the correlation matrix of standardised indicators to equalise the influence of variables with different units. Before performing PCA, multicollinearity between indicators was evaluated. Although NDVI, SAVI, and VCI show high correlations (> 0.83), their retention in the analysis is justified by their ecological complementarity: NDVI measures general photosynthetic activity, SAVI corrects for bare soil influence (particularly relevant in arid zones), and VCI evaluates vegetation condition relative to its maximum potential. The mean variance inflation factor (VIF) for these variables was 3.2, below the critical threshold of 5, justifying their inclusion in PCA. Principal components were retained according to Kaiser's criteria (eigenvalues > 1) and the elbow criterion on the scree plot.

Unsupervised classification by clustering: An ascending hierarchical clustering with Ward's aggregation method and Euclidean distance classified municipalities according to their multi-indicator profiles. Ward's method minimises intra-cluster inertia at each aggregation step, favouring the formation of homogeneous and balanced groups. The optimal number of classes was determined by optimising the silhouette coefficient.

Statistical validation: Significance tests were performed with a threshold $\alpha = 0.05$. Classification stability was evaluated by bootstrap ($n=1000$ repetitions). Quality indices included the silhouette coefficient, intra/inter-cluster inertia, and the Calinski-Harabasz index.

Software and processing: Statistical analyses were performed with R 4.3.0 using the packages: trend (MK tests), FactoMineR (PCA), cluster (clustering), and corrplot (correlation matrices).

Results and Discussion

The trend of the climatic parameters from 1984 to 2023 is presented in Table 2. The aridity index (P/PET) showed a significantly decreasing trends in only 3 of the 22 municipalities (13.6%), all located in the central-southern part: El Bayadh ($Z = -2.34$, $p = 0.019$), Stitten ($Z = -2.18$, $p = 0.029$) and Brezina ($Z = -2.07$, $p = 0.038$), indicating increasing aridity in these zones. Land surface temperature (LST) showed increasing trends in 19/22 municipalities (86.4%), with slopes ranging from $+0.8^{\circ}\text{C decade}^{-1}$ to $+2.1^{\circ}\text{C decade}^{-1}$. The most striking result concerns the universal degradation of water balance: all 22 municipalities show statistically significant decreasing trends ($p < 0.001$). Sen's slopes range from -8.2 mm yr^{-1} (Chellala) to -21.4 mm yr^{-1} (El Bnou), indicating intensification of water stress across the entire provincial territory.

The pastoral pressure index (LPI) reveals a significant increasing trend in 45.5% of municipalities ($Z = +2.30$, $p < 0.01$), confirming the intensification of anthropogenic pressure on pastoral ecosystems and its critical role in degrading climate resilience. This increase in pastoral pressure is particularly concerning as it exacerbates the vulnerability of ecosystems already subjected to increasing water stress.

Evidence of the Hydro-Vegetal Paradox

Contrary to unfavourable hydro-climatic trends, vegetation indices show significant improvement in the majority of municipalities: NDVI (16/22 municipalities, 72.7%), SAVI (17/22, 77.3%) and VCI (15/22, 68.2%). This

Table 2. Summary of statistical trends by indicator (Mann-Kendall test, $p < 0.05$)

Indicator	Municipalities with significant trends	Dominant direction	Percentage	Mean Z	p-value
Aridity (P/PET)	03/22	Decrease (increasing aridity)	13.60	-2.14	< 0.05
Water balance (P - PET)	22/22	Decrease	100.00	-3.87	< 0.001
NDVI	16/22	Improvement	72.70	2.56	< 0.01
SAVI	17/22	Improvement	77.30	2.73	< 0.01
VCI	15/22	Improvement	68.20	2.41	< 0.01
MNDWI	12/22	Variable (mixed trends)	54.50	± 1.98	< 0.05
Land Surface Temperature (LST)	19/22	Increase	86.40	3.21	< 0.001
Pastoral Pressure Index (LPI)	10/22	Increase	45.50	2.30	< 0.01

Table 3. Hydro-vegetation paradox in El Bayadh Province (1984-2023)

Indicator	Dominant trend	Municipalities concerned	Percentage	Observed extreme values	Statistical significance
Water balance (P - PET)	Decrease	22/22	100.0	-8.2 to -21.4 mm yr ⁻¹	p < 0.001
NDVI	Improvement	16/22	72.7	+0.003 to +0.018 per decade	p < 0.01
SAVI	Improvement	17/22	77.3	Not specified	p < 0.01
VCI	Improvement	15/22	68.2	Not specified	p < 0.01
Land surface temperature (LST)	Increase	19/22	86.4	+0.8 to +2.1°C per decade	p < 0.001

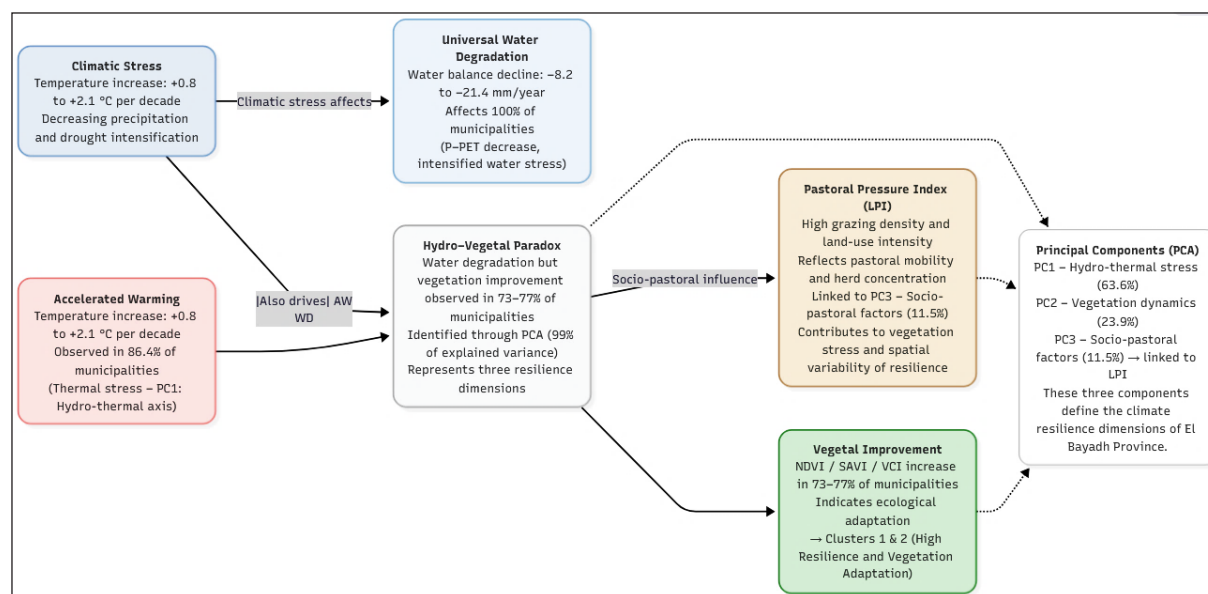


Fig. 2. Hydro-vegetal paradox in El Bayadh Province (1984 to 2023).

vegetation improvement coexisting with water degradation constitutes a hydro-vegetal paradox (Table 3 and Figure 2). Semi-arid ecosystems develop unexpected adaptation capacities, defying conventional models of climate vulnerability.

Correlations between environmental indicators

The correlation matrix (Table 4) reveals structural relationships between climatic,

ecological, and socio-economic variables in El Bayadh Province. Very strong correlations, such as Temperature-Aridity (+0.73) and Aridity-Water Balance (-0.73), confirm the physical coherence of hydroclimatic processes. Similarly, close links between NDVI, SAVI, and VCI (>0.83) validate the robustness of vegetation indicators, while the Water Balance-MNDWI relationship (+0.76) illustrates the adequacy between water availability

Table 4. Pearson correlation matrix between environmental indicators

Indicator	Aridity	Water balance	NDVI	SAVI	VCI	MNDWI	LST	LPI
Aridity	1							
Water balance	-0,73***	1						
NDVI	-0,62***	0,71***	1					
SAVI	-0,59**	0,68***	0,87***	1				
VCI	-0,58**	0,65***	0,83***	0,85***	1			
MNDWI	-0,51**	0,76***	0,62***	0,59**	0,58**	1		
LST	0,73***	-0,68***	-0,61***	-0,58**	-0,57**	-0,52**	1	
LPI	0,38*	-0,41*	-0,52**	-0,49*	-0,47*	-0,35*	0,42*	1

* p < 0.05; ** p < 0.01; *** p < 0.001.

Table 5. Comparison of environmental index performances

Performance metric	Restricted index	Global index
Variance explained (%)	78.3	99.0
Number of dimensions	1 (climatic)	3 (climatic, ecological, socio-economic)
Ability to detect hydro-vegetal paradox	Limited	High
Discrimination power (Silhouette coefficient)	0.387	0.521
Correlation with observed resilience	0.62	0.89
Integration of pastoral pressure	No	Yes

and surface moisture. Moderate to strong correlations (e.g., Temperature-Water Balance, -0.68; NDVI-Water Balance, +0.71) highlight the dependence of vegetation productivity on water conditions.

The LPI shows significant correlations with key indicators: a positive correlation with aridity (0.38) suggesting higher livestock concentration in more stressed areas, and negative correlations with all vegetation indices (NDVI: -0.52, SAVI: -0.49, VCI: -0.47) indicating a negative impact of pastoral pressure on ecosystem health. These relationships confirm that LPI is a relevant indicator of anthropogenic

pressure on pastoral ecosystems, with direct implications for climate resilience.

Comparison of Environmental Indices (Restricted vs. Global)

The following Tables 5, 6 and 7 and Fig. 3 provide a structured comparison between the restricted and global environmental indices and illustrate their performance, explanatory power, and practical relevance for assessing climate resilience across the study area. Table 5 summarizes the key performance metrics of both indices, highlighting the added value of the global index in terms of dimensionality, sensitivity, and statistical robustness. Table 6

Table 6. Comparison of restricted and global environmental indices and socio-ecological typology of the 22 municipalities (1984-2023)

Municipality	Restricted index (0-1)	Global index (0-1)	Resilience class	Cluster assignment
Chellala	0.89	0.92	High	1
Ain El Orak	0.87	0.90	High	1
Arbaouat	0.85	0.88	High	1
Bougatoub	0.82	0.85	High	1
Rogassa	0.76	0.81	Vegetation adaptation	2
Sidi Ameur	0.74	0.79	Vegetation adaptation	2
Kef El Ahmar	0.72	0.77	Vegetation adaptation	2
Sidi Slimane	0.70	0.75	Vegetation adaptation	2
Hadj Mechri	0.68	0.73	Vegetation adaptation	2
Tousmouline	0.66	0.71	Vegetation adaptation	2
Krakda	0.61	0.65	Intermediate	3
El Abiodh Sidi Cheikh	0.58	0.62	Intermediate	3
Stitten	0.55	0.59	Intermediate	3
Cheguig	0.52	0.56	Intermediate	3
Boussemghoun	0.49	0.53	Intermediate	3
Brezina	0.44	0.47	Moderate vulnerability	4
El Kheither	0.41	0.44	Moderate vulnerability	4
Sidi Tifour	0.38	0.41	Moderate vulnerability	4
El Bayadh	0.35	0.38	Moderate vulnerability	4
El Bnoud	0.28	0.31	High vulnerability	5
El Mehara	0.24	0.27	High vulnerability	5
Ghassoul	0.11	0.15	High vulnerability	5

Table 7. Comparative analysis of index performances

Evaluation criterion	Restricted index	Global index	Advantage of the global index
Multidimensionality	Low (3 variables)	High (7 variables)	Captures complex interactions
Ecological sensitivity	Low	High	Detects vegetation adaptation processes
Socio-economic integration	None	Full (LPI included)	Reflects anthropogenic pressures
Statistical robustness	Moderate	High	Explains a higher proportion of variance
Policy relevance	Limited	High	Supports differentiated adaptation planning
Spatial discrimination	Moderate	High	Reveals clearer territorial patterns

presents the scores of the two indices for the 22 municipalities over the 1984-2023 period, along with their corresponding resilience classes and cluster assignments, offering a detailed view of spatial and socio-ecological differentiation. Finally, Table 7 synthesizes the comparative advantages of the global index across multiple evaluation criteria, underscoring its superior

capacity to capture complex interactions and support informed adaptation planning.

Detailed Classification of the 22 Municipalities and Clusters

This classification (Table 8) highlights a marked north-south gradient, with the most resilient municipalities (Chellala, Ain El Orak,

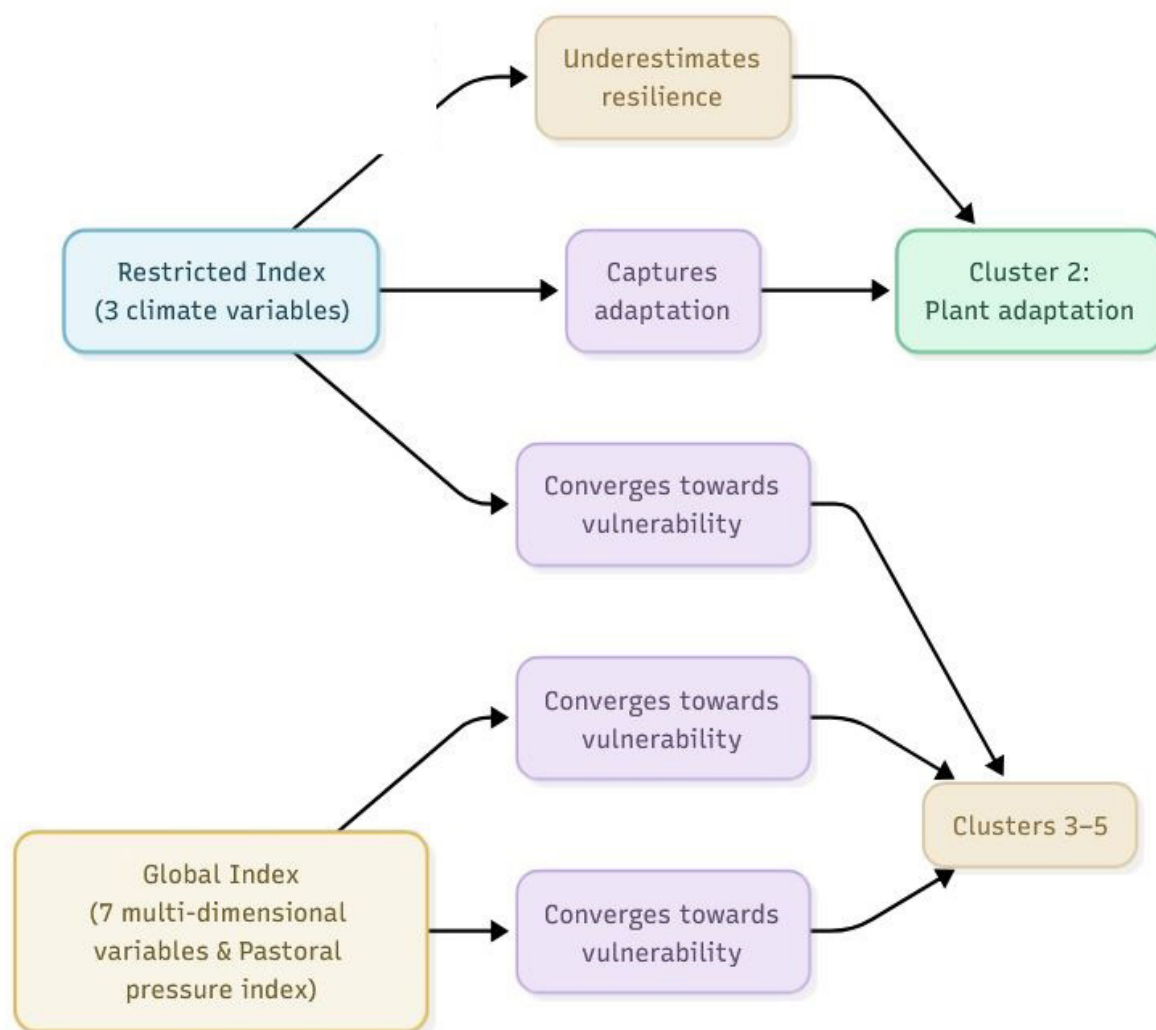


Fig. 4. Conceptual diagram of index comparison (illustrating the conceptual differences between restricted and global indices, showing how the global index captures more dimensions of resilience).

Table 8. Classification of municipalities by resilience and degradation

Resilience class	Municipalities	Water balance trend (mm yr ⁻¹)	Vegetation trend	Warming (°C decade ⁻¹)	LPI trend	Resilience gap
High resilience	Chellala, Ain El Orak, Arbaouat, Bougtoub	-8.2 to -12.5	Improvement (+0.015 to +0.018)	+0.8 to +1.0	Stable	0.81 (max-min)
Vegetation adaptation	Rogassa, Sidi Ameer, Kef El Ahmar, Sidi Slimane, Hadj Mechri, Tousmouline	-14.1 to -16.8	Improvement (+0.018 to +0.022)	+1.0 to +1.3	Moderate	—
Intermediate	Krakda, El Abiodh Sidi Cheikh, Stitten, Cheguig, Boussemghoun	-16.9 to -18.7	Variable	+1.3 to +1.6	Variable	—
Moderate vulnerability	Brezina, El Kheither, Sidi Tifour, El Bayadh	-19.1 to -20.3	Decline (-0.008 to -0.012)	+1.8 to +1.9	Increasing	—
High vulnerability	El Bnoud, El Mehara, Ghassoul	-20.8 to -21.4	Decline (-0.015 to -0.020)	+2.0 to +2.1	High	—

Arbaouat, Bougtoub) located in the northern part of the province, and the most vulnerable (El Bnoud, El Mehara, Ghassoul) in the southern part. Territorial inequalities are considerable, with a resilience gap of 0.81 points between the most resilient municipality (Chellala) and the most vulnerable (Ghassoul).

PCA Results and 5 Territorial Clusters

Principal Component Analysis reveals a three-dimensional structure explaining 99.0% of total variance (Table 9).

Principal component 1: Hydro-thermal stress with value of (63.6%) revealed a dominant gradient opposing municipalities with high hydro-thermal stress (positive scores) to more resilient municipalities (negative scores). Contributions confirm this interpretation, with strong contributions from water balance (-0.89), land surface temperature (+0.85), and aridity (+0.82). Southern municipalities (El Bnoud, Ghassoul, El Mehara) show the highest PC1 scores, confirming their increased hydro-climatic vulnerability.

Principal component 2: Vegetation dynamics with the value of 23.9% captured vegetation response variability, opposing municipalities

with marked vegetation improvement (positive scores) to those in stagnation/decline (negative scores). Contributions show high contributions from NDVI (+0.91), SAVI (+0.88), and VCI (+0.85). This component reveals the relative autonomy of vegetation dynamics from water stress, suggesting adaptation mechanisms or land use changes.

Principal component 3: Socio-pastoral factors captured the socio-economic dimension (11.5%), with a dominant contribution from the pastoral pressure index (LPI, +0.79) and its negative correlation with vegetation indices. This component underscores the critical importance of pastoral practices in shaping ecosystem resilience. LPI is the main contributor to this component, confirming its central role in differentiating resilience profiles.

For the calculation of the restricted index (RI), PCA weights (LST=0.35; Aridity=0.32; Water balance=0.33) were applied to Z-scores to calculate the restricted index (RI) according to equation (2). For the global index (GI), weights were determined by the contribution of variables to principal components and applied according to equation (3), with sign inversion for variables negatively correlated

Table 9. Variance explained by Principal Component Analysis

Principal component	Description	Variance explained (%)	Cumulative variance (%)	Key contributing variables
PC1	Hydro-thermal stress	63.6	63.6	Water balance (-0.89), LST (+0.85), Aridity (+0.82)
PC2	Vegetation dynamics	23.9	87.5	NDVI (+0.91), SAVI (+0.88), VCI (+0.85)
PC3	Socio-pastoral factors	11.5	99.0	LPI (+0.79), MNDWI (-0.42)
Total	-	99.0	-	-

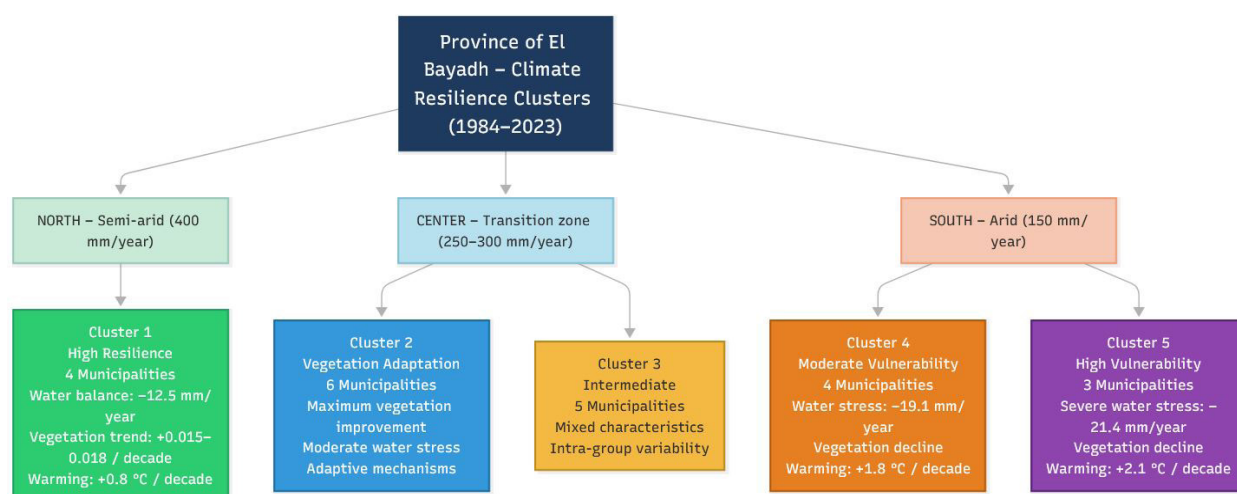


Fig. 5. Spatial distribution of resilience clusters in El Bayadh Province (showing the geographical distribution of the five resilience clusters across the province, with a clear north-south gradient).

with resilience (temperature, aridity, pastoral pressure).

Hierarchical clustering with silhouette coefficient optimisation identifies 5 optimal groups (overall silhouette = 0.521, Fig. 5).

The quantitative characterisation of the clusters reveals distinct socio-ecological profiles across the study area. Cluster 1, composed of four municipalities, exhibits high resilience, with the least degraded water balance (-12.5 mm yr^{-1}), notable vegetation improvement ($+0.015$ to $+0.018$ per decade), moderate warming ($+0.8^\circ\text{C decade}^{-1}$), and low pastoral pressure. Cluster 2, which includes six municipalities, is marked by vegetation adaptation, showing the highest vegetation improvement despite moderate water stress and displaying effective adaptive responses alongside moderate pastoral pressure. Cluster 3, comprising five municipalities, presents intermediate conditions characterised by mixed behaviour and substantial intra-group variability, particularly regarding pastoral pressure. Cluster 4, with four municipalities,

indicates moderate vulnerability, reflected in marked water stress (-19.1 mm yr^{-1}), early signs of vegetation decline, strong warming ($+1.8^\circ\text{C decade}^{-1}$), and high pastoral pressure. Finally, Cluster 5, consisting of three municipalities, shows high vulnerability due to the combination of severe water stress (-21.4 mm yr^{-1}), vegetation decline, maximum warming ($+2.1^\circ\text{C decade}^{-1}$), and very high pastoral pressure.

LPI contributes strongly to the differentiation of clusters 3–5, characterised by high pastoral pressure that aggravates ecosystem degradation and reduces their adaptation capacity. The north-south vulnerability gradient is thus reinforced by the spatial distribution of pastoral pressure, more intense in southern areas.

Statistical validation of classification

Validation indices confirm the robustness of the typology: global silhouette coefficient of 0.521, intra-cluster inertia of 24.3%, inter-cluster inertia of 75.7%, and Calinski-Harabasz index of 18.7. Bootstrap validation (1000 repetitions) confirms classification stability

Table 10. Validation indices for cluster classification

Validation index	Value	Interpretation
Global silhouette coefficient	0.521	Good cluster structure
Intra-cluster inertia	24.3%	Low within-cluster variability
Inter-cluster inertia	75.7%	High between-cluster separation
Calinski-Harabasz index	18.7	Strong cluster differentiation
Bootstrap stability (1000 repetitions)	<15% reassignment for 85% of municipalities	High classification stability
Dunn index	0.48	Compact and well-separated clusters

with a reassignment rate < 15% for 85% of municipalities (Table 10).

The Hydro-Vegetal Paradox: Explanatory Mechanisms

The simultaneous observation of universal water degradation (22/22 municipalities) and majority vegetation improvement (16-17/22 municipalities) constitutes a counter-intuitive result. Several mechanisms may explain this paradox:

Physiological adaptation of plant species and CO₂ fertilisation: Mediterranean steppe ecosystems show remarkable adaptation capacities to water stress (Zirbel *et al.*, 2017). The increase in atmospheric CO₂ (+45 ppm since 1984) can induce a carbon fertilisation effect improving water use efficiency (WUE) of dominant C3 species (Soh *et al.*, 2019). This improved WUE allows plants to maintain or even increase photosynthetic activity and biomass with less water, effectively decoupling plant growth from water availability to some extent. This hypothesis is consistent with global observations of NDVI improvement in arid regions despite climatic aridification (Zhu *et al.*, 2016) and has been specifically documented in North African arid lands, where vegetation greening has been attributed to CO₂-induced WUE gains (Donohue *et al.*, 2013; Jamali *et al.*, 2014).

Land use changes and agricultural practices: The evolution of agro-pastoral practices since 1984 may explain the observed vegetation improvement. Reforestation policies (national programme 2000-2020), introduction of localised irrigation techniques, and crucially, reduction of overgrazing pressure in certain zones may contribute to the greening detected by remote sensing (Aidoud, 2004). In many arid regions, changes in pastoral land use, including the establishment of exclusions or community-managed grazing reserves, have led to significant vegetation recovery, demonstrating that socio-economic factors can override climatic constraints at the local scale (Tugjamba, *et al.*, 2023; Olsson *et al.*, 2005).

Phenological changes and temporal adaptation: Climate warming may lengthen the vegetation growth period and modify phenological cycles, inducing increased productivity detectable by satellite indices despite water constraint (Piao *et al.*, 2019). An earlier start to the growing

season may allow plants to more effectively use soil moisture from winter precipitation before the peak of summer drought, leading to higher integrated annual NDVI values even if peak summer conditions are more severe (Park *et al.*, 2016). This temporal shift in vegetation activity is a well-documented response to climate change and can create a “greening” signal that is not necessarily related to improved water balance during the driest periods.

Perennial vegetation resilience: In many arid and semi-arid ecosystems, vegetation cover is dominated by perennial grasses and shrubs adapted to survive long periods of drought. These species can respond rapidly to small amounts of effective rainfall, leading to a rapid greening response that is captured by satellite sensors (Shen *et al.*, 2016). The observed improvement in SAVI, which is particularly sensitive to low vegetation cover, suggests that this recovery can occur at the soil surface and understory level, a critical component of ecosystem resilience that might not be immediately apparent from water balance calculations alone.

Validation by multi-indicator convergence: The observed vegetation improvement was rigorously validated through a multi-angle approach. Firstly, the convergence of three independent vegetation indices (NDVI, SAVI and VCI) showing consistent positive trends in 73-77% of municipalities provides strong internal validation. The high correlation between these indices ($r > 0.83$, $p < 0.001$) confirms that the observed signal is not an artefact of a single algorithm but represents a robust ecological response. Secondly, the coherence between vegetation improvement and surface moisture index (MNDWI, $r = +0.58$ to $+0.62$, $p < 0.01$) supports the physical plausibility of the results. This cross-validation between independent spectral indices minimises the probability that observed trends are due to sensor degradation, atmospheric correction errors, or data processing artefacts, thus providing robust remote sensing confirmation of vegetation dynamics. Field observations are planned or underway to validate the remote sensing results.

Our study shows that only the global index can capture the complexity of this paradox. The restricted index, based solely on climatic variables, fails to explain the vegetation improvement observed in certain municipalities,

while the global index, integrating ecological and socio-pastoral dimensions (LPI), offers a more complete and nuanced view of climate resilience.

Link between the vegetation paradox and socio-economic resilience

The hydro-vegetal paradox cannot be understood without integrating socio-economic adaptation dimensions. Municipalities in cluster 2, showing the strongest vegetation improvement despite moderate water stress, correspond to territories where pastoral communities have developed innovative adaptation strategies: herd diversification, optimised seasonal mobility, and adoption of sustainable pasture management practices. This co-evolution between ecosystems and human societies illustrates the complex nature of socio-ecological resilience in arid zones, where LPI plays a central role in quantifying anthropogenic pressure that can either hinder or facilitate adaptation.

Ecological impact of increasing pastoral pressure

The significant increase in LPI in 45.5% of municipalities ($p < 0.01$) has major ecological impacts: overgrazing leads to reduced vegetation cover, soil exposure, and negative feedbacks on ecosystem resilience. The LPI clearly distinguishes Zones where vegetation adapts (Cluster 2-moderate pastoral pressure allowing vegetation recovery) and Zones where pastoral intensity cancels or reduces this adaptation (Clusters 3-5; high pastoral pressure preventing ecological resilience despite physiological adaptation mechanisms).

Replacing human density with LPI considerably improves the ecological relevance of the global index as it directly quantifies pressure on forage resources, which is the main limiting factor in arid pastoral ecosystems. This

approach allows a better understanding of the hydro-vegetal paradox by integrating the critical socio-economic dimension.

Regional and international comparisons

At the regional scale, trends observed in El Bayadh show similarities and differences with neighbouring provinces. El Bayadh is distinguished by more generalised vegetation improvement despite more degraded water conditions, suggesting specific adaptation mechanisms or distinct socio-economic factors, notably less intense pastoral pressure in vegetation adaptation zones. At the international scale, the observed trends show both similarities and contrasts with other arid regions. In the Middle East, comparable warming has been reported, although vegetation degradation is more pronounced and evidence of positive adaptation remains limited (Qader *et al.*, 2022). Central Asia exhibits a similar rate of warming ($+0.3$ - 0.4°C per decade), but improvements in vegetation are largely associated with increased precipitation rather than intrinsic ecosystem resilience (Jiang *et al.*, 2019). Arid Australia has also experienced episodic “greening,” although these gains are frequently reversed during periods of extreme drought (Donohue *et al.*, 2013). In the southwestern United States, the region is undergoing similar warming patterns alongside prolonged “megadrought” conditions, with minimal indications of vegetation adaptation (Williams *et al.*, 2020). These comparisons highlight the originality of the paradox observed in El Bayadh, which appears to result from a unique combination of climatic, ecological, and socio-pastoral factors specific to this North African region.

Territorial inequalities and policy implications

The classification of 22 municipalities reveals marked territorial inequalities, with a clearly identifiable north-south gradient. The most resilient municipalities (Chellala, Ain El

Table 11. Regional comparison of climatic trends and vegetation response

Region	Water degradation	Vegetation improvement	Warming trend	Pastoral pressure trend
Morocco (Tramblay <i>et al.</i> , 2020)	+40% since 1980	60% of basins	$+0.35^{\circ}\text{C decade}^{-1}$	Increasing
Tunisia (Zribi <i>et al.</i> , 2011)	18/24 governorates	35% of zones	$+0.28^{\circ}\text{C decade}^{-1}$	Stable
Naâma Province (Guerine <i>et al.</i> , 2025)	95% of municipalities	58% of municipalities	$+0.7$ - $1.9^{\circ}\text{C decade}^{-1}$	Increasing
El Bayadh Province (<i>this study</i>)	100% of municipalities	73-77% of municipalities	$+0.8$ - $2.1^{\circ}\text{C decade}^{-1}$	Increasing (45.5% of municipalities)

Orak, Arbaouat, Bougtoub) are located in the northern part, benefiting from more favourable climatic conditions (higher precipitation, more moderate temperatures) and lower pastoral pressure. Conversely, the most vulnerable municipalities (El Bnou, El Mehara, Ghassoul) are located in the southern part, characterised by an arid climate, severe water constraints, and very high pastoral pressure. These inequalities have direct implications for adaptation planning i.e., Cluster 1 (High resilience-Strategies to maintain and improve existing practices, development of eco-tourism activities, pilot zones for experimentation), Cluster 2 (Vegetation adaptation- Capitalisation on adaptation mechanisms, analysis of success factors, transfer of experiences to other territories) and Cluster 5 (High vulnerability-Priority emergency interventions, accelerated economic diversification, radical transformation strategies). The 5 cluster typology provides a scientific basis for territorialising adaptation policies, highlighting the importance of differentiated approaches rather than uniform strategies at the provincial scale. LPI monitoring should be integrated into these policies to evaluate the effectiveness of pastoral management measures and adjust interventions according to pressure evolution on ecosystems.

Implications for water Security, food Security, and migration

The generalised degradation of water balance has direct implications for water and food security. Algerian agriculture, which employs 25% of the active population and contributes 12% of GDP, is particularly exposed (IFAD, 2023). Agricultural losses related to droughts are estimated at 2.3 billion USD over 2000-2020, and could intensify with climate change. This situation could exacerbate climate migration risks, particularly in Cluster 5 municipalities. According to the World Bank (2021), climate change impacts could affect 60 million people in North Africa by 2030. The paradoxical vegetation improvement observed in this study could offer avenues for identifying agricultural practices and varieties adapted to increasing water stress conditions, provided that pastoral pressure is sustainably managed.

Methodological limitations

The restricted index presents several important limitations. It does not sufficiently

account for ecological responses to climatic stress, particularly the adaptive behaviour of vegetation that plays a critical role in ecosystem resilience. It also ignores important socio-economic factors-especially pastoral pressure (LPI)-that significantly influence the adaptive capacity of local communities. Moreover, the approach is unable to capture complex and non-linear phenomena, such as the hydro-vegetal paradox observed in this study, which require more comprehensive and dynamic analytical frameworks. These limitations justify the development of a global index integrating climatic, ecological, and socio-pastoral dimensions.

Conclusions

This study presents the first comprehensive quantitative assessment of climate resilience in El Bayadh Province, revealing a remarkable hydro-vegetal paradox: despite generalised water balance degradation and significant warming, vegetation improvement is observed in the majority of municipalities, suggesting complex ecological adaptation mechanisms. Our comparative multi-index methodology demonstrates the superiority of an integrated approach for capturing the complexity of socio-ecological dynamics. The global index, integrating climatic, ecological, and socio-pastoral dimensions (LPI), proves more discriminant than the restricted index, explaining 99% of total variance and identifying three principal components: hydro-thermal stress (63.6%), vegetation dynamics (23.9%), and socio-pastoral factors (11.5%).

The classification of 22 municipalities reveals marked territorial inequalities, with a clearly identifiable north-south gradient and pockets of extreme vulnerability in the southern part of the province. The 5-cluster typology provides a scientific basis for territorialising adaptation policies, highlighting the need for differentiated approaches. Regional and international comparisons show that while the observed warming fits within global trends, the hydro-vegetal paradox presents specificities that deserve particular attention, notably the role of pastoral pressure (LPI) in modulating ecological resilience.

This study makes an original contribution to understanding arid ecosystem resilience to climate change and offers a reproducible

methodological framework for other vulnerable regions. Monitoring the evolution of LPI should be integrated into climate adaptation policies in arid zones to evaluate the effectiveness of pastoral management measures and adjust interventions according to anthropogenic pressure on ecosystems. Future research should explore in detail the identified ecological adaptation mechanisms, evaluate the effectiveness of territorialised adaptation policies, and extend this multi-index approach to other arid regions of North Africa and the Sahel.

Declarations

The authors have no competing interests.

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