Supplementary Methods for the Disturbed Equilibrium Index (DEI)

1. Indicator Normalization

All indicators for Human Pressure (H), Exogenous Stress (A), and Resilience (R) were normalized to a 0–1 scale to enable comparability across different units and magnitudes.

- **Min–Max scaling** was applied for most variables:

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)}$$

- For skewed data (e.g., extraction rates with long-tailed distributions), **log-transform normalization** was used.

2. Weighting Scheme

Indicators within each block (H, A, R) were aggregated using weighted sums:

$H = \sum A$, $w_i h_i = \sum R$, $u_j a_j = \sum u_k r_k$

- **Data-driven weights:** Entropy weighting and Principal Component Analysis (PCA) were applied where sufficient data coverage existed.
- **Expert-driven weights:** Analytical Hierarchy Process (AHP) and Delphi panels informed cases with limited data.
- **Hybrid weighting:** Data-driven values were cross-validated with expert consensus.

3. Calibration of κ (Kappa)

The calibration factor **κ** expresses the relative weight of exogenous stress (A) compared to human pressure (H):

$$DEI(t) = \frac{H(t) + \kappa A(t)}{R(t)}$$

- κ was calibrated using regression optimization against historical collapse events (Lake Urmia, Aral Sea).
- In most case studies, $\kappa \approx 1$ provided consistent results; sensitivity analysis explored $\kappa = 0.5–1.5$.

4. Threshold Classification

Thresholds for interpreting DEI values were derived using ROC analysis and historical collapse events:

- **Green (Safe):** DEI < 0.7
- **Yellow (Caution):** 0.7 ≤ DEI < 1.0
- **Orange (High Risk):** 1.0 ≤ DEI < 1.3
- **Red (Crisis):** DEI ≥ 1.3

These classes represent states of systemic stress where the likelihood of ecological collapse increases with rising DEI.

5. Data Sources and Gaps

- **Remote sensing:** Landsat, Sentinel-2, MODIS (land cover, vegetation, water extent).
- **Hydrology:** GRACE groundwater data, national water authority statistics.
- **Climate:** SPI/SPEI drought indices, ERA5 reanalysis, ETCCDI extremes.
- **Ecology:** IUCN Red List, biodiversity surveys.
- **Governance:** National adaptation plans, budgets, participatory indices.

Where data gaps existed (e.g., resilience indicators in Lake Urmia), **proxy values** and **validated estimates** were used, always reported transparently.

6. Limitations

- DEI does **not predict exact timing** of ecological reactions but indicates systemic states approaching or exceeding thresholds.
- Data gaps in developing regions may introduce uncertainty; results should be interpreted as risk assessments, not deterministic forecasts.
- Calibration of κ may vary across ecosystems; further refinement is encouraged.

7. Replication Notes

- A sample dataset and code (Python script `dei_calculator.py`) are provided in the Supplementary Repository.
- Users can adapt weight schemes and κ to specific ecosystems.
- Replication is encouraged to test generalizability of DET/DEI across biomes.