Article

AI-driven assessment of animal adaptation to climate change: The web tool based on physiological, morphological, behavioral, and genetic indicators of animal species

WenJun Zhang
International Academy of Ecology and Environmental Sciences, Hong Kong, China; School of Life Sciences, Sun Yat-sen University, Guangzhou 510275, China
E-mail: wjzhang@iaees.org, zhwj@mail.sysu.edu.cn

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Abstract
In present study a system of hierarchical indicators to assess animal species' adaptation to climate change was constructed, and the AI-driven assessment tool was developed. It is a single-page web tool that: (1) Collects species and context information from the user. (2) Lets the user choose an AI provider (DeepSeek or Google Gemini) and enter an API key. (3) Builds a detailed prompt requesting a JSON-formatted climate adaptation assessment. (4) Sends the prompt to the selected provider's REST API. (5) Parses and validates the JSON-like response. (6) Renders the results into a rich UI, grouped into: Physiological indicators, Morphological indicators, Behavioral indicators, Genetic indicators, Summary assessment and conservation recommendations. With this AI tool, we can easily judge the real-time vulnerability of the given animal species to climate change and obtain conservation recommendations.

Keywords animal adaptation; climate change; AI; assessment; web tool.

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1 Introduction

Climate change stands as one of the most pressing challenges of our time, profoundly impacting not only human societies but also the natural world (Zhang and Liu, 2012; Sundar et al., 2022; Hamid and Sinha, 2023; Saradhadevi and Kalavathi, 2024; Shobairi et al., 2024). Rapidly shifting climatic conditions are imposing severe threats to animal survival across the globe (Rafiei, 2025). However, the vulnerability of species varies significantly—some face imminent extinction risks under certain regional and ecological conditions, while others demonstrate greater resilience. This disparity underscores an urgent need: to develop a dynamic, evidence-based evaluation framework capable of assessing real-time adaptation of different animal species to climate change.

Yet constructing such a system is far from straightforward. Traditional analytical approaches often fall short when confronted with the vast, complex, and rapidly evolving ocean of climatic and ecological data. The interrelated variables—from temperature anomalies and habitat fragmentation to species migration patterns and genetic adaptability—form a multidimensional puzzle that conventional tools struggle to piece together in a timely manner.

In this context, the rapid advancement of Artificial Intelligence offers a transformative pathway. Modern AI systems possess unprecedented capabilities in integrating, analyzing, and reasoning across large-scale, heterogeneous datasets (Zhang, 2025, 2026; Zhang and Qi, 2026). By leveraging machine learning, predictive modeling, and real-time data processing, AI can uncover hidden patterns, forecast trends, and generate actionable insights—tools already proving successful across numerous scientific and industrial domains. Harnessing this potential for ecological assessment and conservation could enable more precise, adaptive, and proactive strategies to safeguard biodiversity in a changing climate.

AI acts as a powerful intelligent agent that searches, comprehends, and synthesizes already-published and curated ecological and climate results. It uses natural language processing and knowledge retrieval capabilities to access global ecological and climate data and then structure that information (Zhang, 2026; Zhang and Qi, 2026). It performs Named Entity Recognition (NER) (identify and extract key biological entities), relationship extraction (understand the connections between these entities), and statistical data extraction (parse complex numerical and statistical information). The fetched information is organized into a structured format. AI can go beyond simple retrieval by connecting information from multiple sources, e.g., cross-referencing, functional enrichment, and summarization.

In present study, I will construct a system of hierarchical indicators to assess animal species' adaptation to climate change, and develop the AI-driven assessment tool. With this AI tool, we expect to easily judge the real-time vulnerability of the given animal species to climate change and obtain conservation recommendations.

2 Physiological, Morphological, Behavioral, and Genetic Indicators of Animal Species' Adaptation to Climate Change

2.1 Indicator System

Here I construct a system of hierarchical indicators to assess animal species' adaptation to climate change:

(1) Physiological Indicators

These reflect changes in internal functions and tolerances to environmental stressors like heat, drought, and hypoxia.

(a) Thermal Tolerance & Performance:

Critical Thermal Limits (CTmax/CTmin): The upper and lower temperatures at which locomotor function fails. Shifts in these limits indicate acclimatization or adaptation.

Heat Shock Protein (HSP) Expression: Levels of these molecular chaperones, which protect proteins from denaturation under heat stress.

Temperature-Dependent Performance: Changes in metabolic rate, heart rate, digestion efficiency, and growth rate across a temperature gradient (the performance breadth).

(b) Water & Osmotic Balance:

Evaporative Water Loss (EWL) Rate: Ability to reduce water loss in drier conditions.

Kidney Function & Urine Concentration: Enhanced capacity to concentrate urine to conserve water.

Plasma Osmolality Regulation: Maintaining stable internal fluid balance despite dehydration stress.

(c) Energetics and Metabolism:

Standard Metabolic Rate (SMR): Changes in baseline energy expenditure, potentially lowering it to cope with resource stress.

Aerobic Scope: The difference between maximum and standard metabolic rate. A reduced scope may indicate thermal stress, while a maintained scope suggests resilience.

(d) Reproductive & Stress Physiology:

Stress Hormone Levels (e.g., corticosterone, cortisol): Chronically elevated levels indicate environmental mismatch and can suppress reproduction and immunity.

Reproductive Hormone Timing: Shifts in the timing of reproductive cycles in response to altered seasonal cues.

(2) Morphological Indicators

These are changes in physical form, which can result from phenotypic plasticity or evolutionary change.

(a) Body Size:

Bergmann's Rule: A trend toward smaller body sizes in warmer climates within a species (e.g., birds, mammals) to facilitate heat dissipation.

Allen's Rule: Relatively longer appendages (ears, legs, tails) in warmer climates to increase surface area for heat loss.

(b) Surface Structures:

Pelage/Feather Density and Insulation: Reduced insulation (thinner fur, fewer feathers) in response to warming.

Coloration: Shifts in melanism (darker/lighter pigmentation) for better thermoregulation (e.g., darker for warmth, lighter for reflectivity) or camouflage as snow cover changes.

(c) Functional Morphology:

Bill Size in Birds: Changes in bill surface area, which acts as a thermal radiator (e.g., larger bills in warming climates for some species).

Plant Phenotypes (indirect indicator for herbivores): Changes in leaf thickness, stomatal density, and root depth in food plants, which affect herbivore nutrition.

(3) Behavioral Indicators

The most flexible and immediate response, often reflecting phenotypic plasticity.

(a) Phenological Shifts (Timing Changes):

Altered Migration Timing: Earlier spring migration and later autumn migration.

Shifted Reproductive Timing: Earlier breeding, nesting, or parturition to match earlier peak food resources (e.g., insect emergence, plant flowering).

Changed Hibernation/Aestivation Cycles: Earlier emergence from torpor or delayed entry.

(b) Habitat Use & Activity:

Range Shifts: Movement to higher latitudes or elevations to track suitable climate envelopes.

Microhabitat Selection: Increased use of shade, burrows, or aquatic environments to behaviorally thermoregulate.

Temporal Niche Shifting: Switching from diurnal to nocturnal activity to avoid daytime heat.

(c) Foraging & Diet:

Altered Prey Selection: Switching to different, more available food sources.

Changes in Foraging Effort/Duration: Reduced activity during peak heat, potentially affecting energy intake.

(d) Social & Reproductive Behavior:

Altered Territoriality: Changes in territory size due to resource availability.

Adjustments in Parental Care: Modifications in nest-building, provisioning, or guarding behaviors.

(4) Genetic Indicators

These reveal the evolutionary potential and signatures of past selection, crucial for long-term adaptation.

(a) Signatures of Selection:

Allele Frequency Changes: Shifts in the frequency of alleles associated with adaptive traits (e.g., heat tolerance, drought resistance) across generations.

Genomic Scans for Selection: Using methods like FST outlier analysis or genome-wide association studies (GWAS) to identify loci under strong natural selection linked to climate variables.

(b) Evolutionary Potential:

Standing Genetic Variation: The amount of heritable variation for climate-relevant traits within a population. Higher variation provides more "raw material" for natural selection.

Effective Population Size (Ne): Larger Ne generally supports greater adaptive potential and reduces inbreeding depression.

(c) Gene Flow and Local Adaptation:

Population Connectivity: Gene flow from populations already adapted to warmer/drier conditions can introduce beneficial alleles ("genetic rescue").

Outbreeding Depression: Breaking up locally adapted gene complexes through maladaptive gene flow can also occur.

(d) Epigenetic Modifications:

DNA Methylation Patterns: Reversible, environmentally induced changes in gene expression (e.g., of stress-response genes) that can be passed to offspring, providing a rapid, non-genetic mechanism for transgenerational plasticity.

2.2 Synthesis and Importance

(1) Integrated Response: These domains are interconnected. Behavior can buffer physiological stress, buying time for genetic adaptation. Morphology often reflects the integration of genetic, physiological, and environmental influences.

(2) Distinguishing Plasticity from Evolution: A major challenge is determining if observed changes are due to individual plasticity (lifetime flexibility) or microevolution (genetic change across generations). Long-term studies and genetic tools are key.

(3) Vulnerability Assessment: Species with low adaptive capacity typically show: narrow physiological tolerances, low behavioral plasticity, limited genetic diversity, small and isolated populations, and long generation times.

(4) Conservation Implications: Monitoring these indicators helps identify vulnerable species, prioritize conservation actions (e.g., assisted migration, corridor protection), and predict future biodiversity outcomes under climate change scenarios.

By studying these four aspects, we can build a holistic picture of an animal species' resilience and trajectory in a rapidly changing global climate.

3 Algorithmic Description

3.1 Initialization & Event Wiring

Goal: Set up event listeners and initial UI state once the page loads.

Steps:

1. **API Selection Setup**

o Query all .api-option elements.

- For each option:
  - Attach a click listener.
  - On click:
    - Remove .selected from all .api-option elements.
    - Add .selected to the clicked element.
    - Set its child radio input (input[type="radio"]) to checked = true.

2. **Analyze Button Setup**
   - Select the button: #analyzeBtn.
   - Attach a click async event handler.
   - This handler orchestrates:
     - Input validation
     - UI state changes for loading
     - Calling external AI APIs
     - Rendering results or error messages

3.2 User Input Collection & Validation

Triggered by: click event on #analyzeBtn.

Steps:

1. Read values from the DOM:

```js
const speciesName       = document.getElementById('speciesName').value.trim();
const habitat           = document.getElementById('habitat').value.trim();
const region            = document.getElementById('region').value.trim();
const timeframe         = document.getElementById('timeframe').value.trim();
const additionalContext= document.getElementById('additionalContext').value.trim();
const apiKey            = document.getElementById('apiKey').value.trim();
const apiProvider       = document.querySelector('input[name="apiProvider"]:checked').value;
```

2. Validate required fields:
   - Required: speciesName, apiKey.
   - If missing:
     - Call alert('Please provide at least the species name and API key');
     - return early from the handler.
3. If validation passes, proceed to API request.

3.3 UI State Management During Analysis

Goal: Reflect processing state and prevent duplicate submissions.

Steps:

1. **Show loading indicator:**
   - #loading element: add class .active.
   - #results element: remove class .active.
2. **Disable Analyze button:**
   - this.disabled = true; inside the click event handler.
3. **After request finishes (in finally block):**
   - Remove loading state: #loading.classList.remove('active').
   - Re-enable button: this.disabled = false;.

3.4 Prompt Construction

Function: fetchAdaptationData(params)

Input:

params = { speciesName, habitat, region, timeframe, additionalContext, apiKey, apiProvider }

Steps:

1. Destructure parameters:

js

```
const { speciesName, habitat, region, timeframe, additionalContext, apiKey, apiProvider } = params;
```

2. Build a **long, structured prompt string** using template literals, embedding only the fields that are non-empty:

o Starts with role description: expert wildlife biologist & climate researcher.

o Lists:

▪ Species

▪ Habitat (conditional)

▪ Region (conditional)

▪ Timeframe (conditional)

▪ Additional context (conditional)

o Specifies **5 main sections** to analyze:

1. Physiological indicators
2. Morphological indicators
3. Behavioral indicators
4. Genetic indicators
5. Summary assessment

Requests as much quantitative data as possible and fallback behavior (“Data limited”).

Critically: Instructs the model to respond in a strict JSON schema:

json

```
{
  "physiological": {
    "thermal": { "indicators": [], "data": {} },
    "water": { "indicators": [], "data": {} },
    "energetics": { "indicators": [], "data": {} },
    "reproductive": { "indicators": [], "data": {} }
  },
  "morphological": {
    "bodySize": { "indicators": [], "data": {} },
    "surface": { "indicators": [], "data": {} },
    "functional": { "indicators": [], "data": {} }
  },
  "behavioral": {
    "phenological": { "indicators": [], "data": {} },
    "habitat": { "indicators": [], "data": {} },
    "foraging": { "indicators": [], "data": {} },
    "social": { "indicators": [], "data": {} }
  },
```

```
  "genetic": {
    "selection": { "indicators": [], "data": {} },
    "potential": { "indicators": [], "data": {} },
    "geneFlow": { "indicators": [], "data": {} },
    "epigenetic": { "indicators": [], "data": {} }
  },
  "summary": {
    "vulnerabilityScore": "Low|Moderate|High",
    "overallAssessment": "string",
    "plasticityVsEvolution": "string",
    "conservationRecommendations": []
  }
}
```

Decide which provider to call:

```js
if (apiProvider === 'deepseek') {
    return await fetchFromDeepSeek(prompt, apiKey);
} else {
    return await fetchFromGemini(prompt, apiKey);
}
```

3.5 External API Calls

3.5.1 DeepSeek API: fetchFromDeepSeek(prompt, apiKey)

Endpoint:

POST https://api.deepseek.com/v1/chat/completions

Request body:

```json
{
  "model": "deepseek-chat",
  "messages": [
    {
      "role": "system",
      "content": "You are an expert wildlife biologist and climate change researcher. Provide detailed, scientifically accurate assessments with quantitative data."
    },
    {
      "role": "user",
      "content": "<prompt>"
    }
  ],
  "temperature": 0.7,
  "max_tokens": 4000
}
```

Headers:

- Content-Type: application/json

- Authorization: Bearer <apiKey>

Algorithm:

1. Perform fetch with above configuration.
2. If response.ok is false:
   - o Throw new Error("DeepSeek API error: " + response.status + " " + response.statusText).
3. Parse the JSON: const data = await response.json();
4. Extract the message text:

const content = data.choices[0].message.content;

5. Run regex to find a JSON object (first { ... } block):

js

const jsonMatch = content.match(/\{[\s\S]*\}/);

6. If jsonMatch exists:
   - o return JSON.parse(jsonMatch[0]);
7. Else:
   - o Throw new Error('Could not parse JSON from API response');

3.5.2 Gemini API: fetchFromGemini(prompt, apiKey)

Endpoint:

POST https://generativelanguage.googleapis.com/v1beta/models/gemini-pro:generateContent?key=<apiKey>

Request body:

json

```
{
  "contents": [
    {
      "parts": [
        { "text": "<prompt>" }
      ]
    }
  ],
  "generationConfig": {
    "temperature": 0.7,
    "maxOutputTokens": 4000
  }
}
```

Headers:

- Content-Type: application/json

Algorithm:

1. Perform fetch with above configuration.
2. If response.ok is false:
   - o Throw new Error("Gemini API error: " + response.status + " " + response.statusText).
3. Parse JSON: const data = await response.json();
4. Extract first candidate’s text:

js

const content = data.candidates[0].content.parts[0].text;

5. Extract JSON block with regex:

js
```
const jsonMatch = content.match(/\{[\s\S]*\}/);
```
6. If jsonMatch exists:

o return JSON.parse(jsonMatch[0]);

7. Else:

o Throw new Error('Could not parse JSON from API response');

3.6 Error Handling Around API Calls

Inside the click handler for #analyzeBtn:

js
```
try {
    const analysisData = await fetchAdaptationData({ ... });
    displayResults(analysisData);
} catch (error) {
    document.getElementById('results').innerHTML = `
        <div class="error">
            <strong>Error:</strong> ${error.message}
        </div>
    `;
    document.getElementById('results').classList.add('active');
} finally {
    document.getElementById('loading').classList.remove('active');
    this.disabled = false;
}
```
Behavior:

- Any thrown error (network failure, non-OK response, JSON parse issues) is caught and surfaced as a friendly error message in the #results area.

3.7 Results Rendering

3.7.1 Main Entry: displayResults(data)

Input: Parsed JSON object from model, expected structure:

js
```
{
  physiological: { ... },
  morphological: { ... },
  behavioral: { ... },
  genetic: { ... },
  summary: { ... }
}
```
Steps:

1. Initialize let html = '';.
2. Append sections by calling createIndicatorSection for each dimension:

o Physiological:

js
```
html += createIndicatorSection('physiological', '… Physiological Indicators', data.physiological, [
  { key: 'thermal',        title: 'Thermal Tolerance & Performance' },
```

```
   { key: 'water',             title: 'Water & Osmotic Balance' },
   { key: 'energetics',      title: 'Energetics & Metabolism' },
   { key: 'reproductive', title: 'Reproductive & Stress Physiology' }
]);
```

o Morphological:

js

```
html += createIndicatorSection('morphological', '… Morphological Indicators', data.morphological, [
   { key: 'bodySize',    title: 'Body Size Changes' },
   { key: 'surface',      title: 'Surface Structures' },
   { key: 'functional',title: 'Functional Morphology' }
]);
```

o Behavioral:

js

```
html += createIndicatorSection('behavioral', '… Behavioral Indicators', data.behavioral, [
   { key: 'phenological', title: 'Phenological Shifts' },
   { key: 'habitat',           title: 'Habitat Use & Activity' },
   { key: 'foraging',         title: 'Foraging & Diet' },
   { key: 'social',             title: 'Social & Reproductive Behavior' }
]);
```

o Genetic:

js

```
html += createIndicatorSection('genetic', '… Genetic Indicators', data.genetic, [
   { key: 'selection',    title: 'Signatures of Selection' },
   { key: 'potential',    title: 'Evolutionary Potential' },
   { key: 'geneFlow',      title: 'Gene Flow & Local Adaptation' },
   { key: 'epigenetic', title: 'Epigenetic Modifications' }
]);
```

3. Append summary:

js

```
html += createSummarySection(data.summary);
```

4. Inject into DOM:

js

```
const resultsDiv = document.getElementById('results');
resultsDiv.innerHTML = html;
resultsDiv.classList.add('active');
```

3.7.2 Indicator Sections: createIndicatorSection(className, title, sectionData, subsections)

Parameters:

- className: corresponds to a CSS modifier (physiological, morphological, behavioral, genetic).
- title: Section header text (e.g., “Physiological Indicators”).
- sectionData: Subtree of the JSON data (e.g. data.physiological).
- subsections: Array of { key, title }, mapping JSON keys to UI labels.

Algorithm:

1. Start wrapper div:

js

```
let html = `
  <div class="indicator-section">
    <div class="indicator-header ${className}">
      ${title}
    </div>
    <div class="indicator-content">
`;
```

2. Loop through subsections:

js

```
subsections.forEach(subsection => {
    const subData = sectionData[subsection.key];
    if (subData && (subData.indicators.length > 0 || Object.keys(subData.data).length > 0)) {
        html += `
          <div class="indicator-item">
            <h4>${subsection.title}</h4>
            ${subData.indicators.map(ind => `<p>• ${ind}</p>`).join('')}
            ${Object.entries(subData.data).map(([key, value]) =>
              `<span class="metric"><strong>${key}:</strong> ${value}</span>`
            ).join('')}
          </div>
        `;
    }
});
```

3. Close section:

js

```
html += `
    </div>
  </div>
`;
```

4. Return html.

Assumptions:

- Each subData has:
  - indicators: an array of strings.
  - data: an object of key–value quantitative metrics.
- If both are empty, that subsection is omitted.

3.7.3 Summary Section: createSummarySection(summary)

Input: summary object:

js

```
{
  vulnerabilityScore: "Low" | "Moderate" | "High",
  overallAssessment: "string",
  plasticityVsEvolution: "string",
  conservationRecommendations: [ "string", ... ]
}
```

Algorithm:

1. Determine color class for the score circle:

js

```
const scoreClass = summary.vulnerabilityScore === 'Low'
    ? 'score-low'
    : summary.vulnerabilityScore === 'Moderate'
        ? 'score-moderate'
        : 'score-high';
```

2. Build the HTML string with:

o Circle displaying the score.
o Assessment text.
o Section on plasticity vs. evolution.
o Recommendations as a <ul> list.

js

```
return `
  <div class="summary-section">
    <h2>… Summary Assessment</h2>

    <div class="vulnerability-score">
      <div class="score-circle ${scoreClass}">
        ${summary.vulnerabilityScore}
      </div>
      <div style="flex: 1;">
        <h3 style="margin-bottom: 10px;">Vulnerability Score</h3>
        <p style="color: #555;">${summary.overallAssessment}</p>
      </div>
    </div>

    <div class="summary-content">
      <h3 style="margin-bottom: 15px;">Plasticity vs. Evolution</h3>
      <p style="margin-bottom: 20px;">${summary.plasticityVsEvolution}</p>
    </div>

    <div class="recommendations">
      <h3>… Conservation Recommendations</h3>
      <ul>
        ${summary.conservationRecommendations.map(rec => `<li>${rec}</li>`).join('')}
      </ul>
    </div>
  </div>
`;
```

4 User Guide

The application is a single-page web tool that:

1. Collects species and context information from the user.
2. Lets the user choose an AI provider (DeepSeek or Google Gemini) and enter an API key.
3. Builds a detailed prompt requesting a JSON-formatted climate adaptation assessment.
4. Sends the prompt to the selected provider's REST API.
5. Parses and validates the JSON-like response.
6. Renders the results into a rich UI, grouped into:
    - Physiological indicators
    - Morphological indicators
    - Behavioral indicators
    - Genetic indicators
    - Summary & conservation recommendations

All logic is implemented in client-side JavaScript; there is no backend.

Below is a practical user guide.

4.1 Prerequisites

- A modern web browser (Chrome, Firefox, Edge, Safari).
- Internet connection.
- A valid API key for:
    - DeepSeek API, or
    - Google Gemini (Generative Language) API.

We must obtain these keys from the respective providers and enable the appropriate models.

4.2 Launching the Tool

1. Save the provided HTML as a file, e.g., index.html.
2. Open it directly in a browser (double-click or drag into a browser window).
3. The page will display the "Climate Change Adaptation Assessment Tool" interface.

No additional servers or dependencies are required; everything runs in the browser.

4.3 Filling Out the Species Information

1. **Species Name (required)**
    - Enter the scientific or common name.
    - Examples:
        - Polar Bear (Ursus maritimus)
        - African Elephant (Loxodonta africana)
2. **Primary Habitat (optional)**
    - Describe main habitat types.
    - Examples:
        - Arctic sea ice and coastal tundra
        - Tropical coral reef lagoons
3. **Geographic Region (optional)**
    - Specify locations or biogeographic regions.
    - Examples:
        - Arctic Circle; Beaufort Sea
        - Great Barrier Reef, Australia
4. **Study Timeframe (optional)**
    - Indicate the time window for interest.
    - Examples:

- Last 20 years
- 1980–2024

5. **Additional Context (optional)**
   - Provide climate stressors, known changes, or research focus.
   - Examples:
     - Rapid decline in sea ice extent; increased human–bear interactions.
     - Focus on coral bleaching events and recovery periods.

The more context you provide, the better the model can tailor its assessment.

4.4 Selecting the AI Provider

1. Under **“Select AI Provider”**, choose:
   - **DeepSeek API**, or
   - **Google Gemini API**.
2. Click the provider “card” itself; this:
   - Visually highlights the selection.
   - Updates the underlying radio input.
3. Make sure the API key corresponds to the provider you choose.

4.5 Entering API Key

1. In **“API Key”**, paste the key from the chosen provider.
2. Keep this field private; the key is sent directly from the browser to the provider’s API.
3. The tool does not store the key except in page memory for the current session.

4.6 Running the Analysis

1. Confirm:
   - Species Name is filled.
   - API Key is filled.
   - Appropriate provider is selected.
2. Click **“Analyze Climate Adaptation”**.

You will see:

- A spinner and message: “Analyzing adaptation indicators...”
- Analyze button becomes disabled to prevent duplicate requests.

Analysis typically completes in 10–60 seconds depending on API latency and model speed.

4.7 Reading the Results

Once the response is received and parsed:

1. **Physiological Indicators**
   - Sections:
     - Thermal Tolerance & Performance
     - Water & Osmotic Balance
     - Energetics & Metabolism
     - Reproductive & Stress Physiology
   - You will see:
     - Bullet points for qualitative indicators (e.g., “Observed upward shift in CTmax by ~1.2°C over 30 years.”).
     - Small “metric” tags for quantitative data (e.g., CTmax: 32–35 °C, Cortisol increase: 25%).
2. **Morphological Indicators**

o Sections:
▪ Body Size Changes (e.g., changes consistent with Bergmann’s rule)
▪ Surface Structures (pelage, feathers, coloration)
▪ Functional Morphology (bill size, limb length; Allen’s rule)
o Metrics may include:
▪ % body mass change
▪ Limb length differences
▪ Coloration indices
3. **Behavioral Indicators**
o Sections:
▪ Phenological Shifts (e.g., altered migration or breeding timing)
▪ Habitat Use & Activity (range shifts, microhabitat selection)
▪ Foraging & Diet
▪ Social & Reproductive Behavior
o Data examples:
▪ Migration start date shifts
▪ Range centroid movement in km
▪ Changes in nocturnal vs diurnal activity percentages
4. **Genetic Indicators**
o Sections:
▪ Signatures of Selection
▪ Evolutionary Potential
▪ Gene Flow & Local Adaptation
▪ Epigenetic Modifications
o Typical metrics:
▪ Heterozygosity, Fst
▪ Effective population size (Ne)
▪ Allele frequency changes
5. **Summary Assessment**
o **Vulnerability Score**: “Low”, “Moderate”, or “High” inside a color-coded circle:
▪ Green: Low
▪ Yellow/Orange: Moderate
▪ Red: High
o **Overall Assessment**: Narrative synthesis explaining the vulnerability rating.
o **Plasticity vs. Evolution**:
▪ Discussion of whether observed changes are:
▪ Short-term plastic responses, or
▪ Longer-term evolutionary/adaptive genetic changes.
o **Conservation Recommendations**:
▪ 3–5 concrete actionable suggestions, such as:
▪ Habitat protection strategies
▪ Assisted migration
▪ Population monitoring protocols
▪ Policy or management interventions

4.8 Handling Errors

If something goes wrong, the **Results** area will show a red error box:

- Common messages:
  - DeepSeek API error: 401 Unauthorized
  - Gemini API error: 400 Bad Request
  - Could not parse JSON from API response
- What to check:
  - **API key** is valid and has permissions for the specific model.
  - **Provider selection** matches the key used.
  - **Rate limits**: you may have exceeded our quota.
  - **Network** connection is stable.

You can correct the issue and click **Analyze** again.

4.9 Best Practices for Users

- Use **precise species names** and include **region + timeframe** for better context.
- In **Additional Context**, mention:
  - Main climate stressors (warming, drought, precipitation changes, ocean acidification).
  - Known data sources or monitoring programs if relevant.
- Recognize that:
  - If empirical data is sparse, the tool will state “Data limited” and rely on theory or related species.
  - The output is an AI-generated synthesis and should be cross-checked against primary literature for critical decisions.

4.10 Security & Privacy Notes

- API key is only used client-side, but:
  - Anyone with access to the browser session could see or reuse it if they inspect the page memory.
  - Avoid using shared or public computers.
- Do not paste confidential, internal, or unpublished data that must not leave your organization, unless you fully trust and are allowed to use the selected provider under your organization’s policies.

5 Codes

The following are the HTML+JavaScript codes of the AI assessment tool
(http://www.iaees.org/publications/journals/ces/articles/2026-16(1)/animalAdaptAI.htm; Fig. 1):

```
<!DOCTYPE html>
<html lang="en">
<head>
    <meta charset="UTF-8">
    <meta name="viewport" content="width=device-width, initial-scale=1.0">
    <title>Animal Climate Adaptation Assessment Tool</title>
    <style>
        * {
            margin: 0;
            padding: 0;
            box-sizing: border-box;
```

```
}

body {
    font-family: 'Segoe UI', Tahoma, Geneva, Verdana, sans-serif;
    background: linear-gradient(135deg, #667eea 0%, #764ba2 100%);
    min-height: 100vh;
    padding: 20px;
}

.container {
    max-width: 1400px;
    margin: 0 auto;
    background: white;
    border-radius: 20px;
    box-shadow: 0 20px 60px rgba(0,0,0,0.3);
    overflow: hidden;
}

.header {
    background: linear-gradient(135deg, #1e3c72 0%, #2a5298 100%);
    color: white;
    padding: 30px;
    text-align: center;
}

.header h1 {
    font-size: 2.5em;
    margin-bottom: 10px;
}

.header p {
    font-size: 1.1em;
    opacity: 0.9;
}

.main-content {
    padding: 30px;
}

.input-section {
    background: #f8f9fa;
    padding: 25px;
    border-radius: 15px;
    margin-bottom: 30px;
    border: 2px solid #e9ecef;
```

```
}

.input-group {
    margin-bottom: 20px;
}

.input-group label {
    display: block;
    font-weight: 600;
    margin-bottom: 8px;
    color: #2c3e50;
    font-size: 1.1em;
}

.input-group input,
.input-group select,
.input-group textarea {
    width: 100%;
    padding: 12px;
    border: 2px solid #ddd;
    border-radius: 8px;
    font-size: 1em;
    transition: all 0.3s;
}

.input-group input:focus,
.input-group select:focus,
.input-group textarea:focus {
    outline: none;
    border-color: #667eea;
    box-shadow: 0 0 0 3px rgba(102, 126, 234, 0.1);
}

.input-row {
    display: grid;
    grid-template-columns: 1fr 1fr;
    gap: 20px;
}

.api-selector {
    display: flex;
    gap: 20px;
    margin-bottom: 20px;
}
```

```
.api-option {
    flex: 1;
    padding: 15px;
    border: 2px solid #ddd;
    border-radius: 10px;
    cursor: pointer;
    text-align: center;
    transition: all 0.3s;
}

.api-option:hover {
    border-color: #667eea;
    background: #f8f9ff;
}

.api-option.selected {
    border-color: #667eea;
    background: #667eea;
    color: white;
}

.api-option input[type="radio"] {
    margin-right: 8px;
}

.btn {
    background: linear-gradient(135deg, #667eea 0%, #764ba2 100%);
    color: white;
    padding: 15px 40px;
    border: none;
    border-radius: 10px;
    font-size: 1.1em;
    font-weight: 600;
    cursor: pointer;
    transition: all 0.3s;
    width: 100%;
}

.btn:hover {
    transform: translateY(-2px);
    box-shadow: 0 10px 25px rgba(102, 126, 234, 0.3);
}

.btn:disabled {
    background: #ccc;
```

```
    cursor: not-allowed;
    transform: none;
}

.loading {
    text-align: center;
    padding: 40px;
    display: none;
}

.loading.active {
    display: block;
}

.spinner {
    border: 4px solid #f3f3f3;
    border-top: 4px solid #667eea;
    border-radius: 50%;
    width: 50px;
    height: 50px;
    animation: spin 1s linear infinite;
    margin: 0 auto 20px;
}

@keyframes spin {
    0% { transform: rotate(0deg); }
    100% { transform: rotate(360deg); }
}

.results {
    display: none;
}

.results.active {
    display: block;
}

.results-grid {
    display: grid;
    grid-template-columns: repeat(2, 1fr);
    gap: 30px;
    margin-bottom: 30px;
}

.indicator-section {
```

```
    border: 2px solid #e9ecef;
    border-radius: 15px;
    overflow: hidden;
    height: fit-content;
}

.indicator-header {
    background: linear-gradient(135deg, #f093fb 0%, #f5576c 100%);
    color: white;
    padding: 20px;
    font-size: 1.3em;
    font-weight: 600;
    display: flex;
    align-items: center;
    gap: 10px;
}

.indicator-header.physiological {
    background: linear-gradient(135deg, #4facfe 0%, #00f2fe 100%);
}

.indicator-header.morphological {
    background: linear-gradient(135deg, #43e97b 0%, #38f9d7 100%);
}

.indicator-header.behavioral {
    background: linear-gradient(135deg, #fa709a 0%, #fee140 100%);
}

.indicator-header.genetic {
    background: linear-gradient(135deg, #30cfd0 0%, #330867 100%);
}

.indicator-content {
    padding: 25px;
    background: white;
}

.indicator-item {
    margin-bottom: 20px;
    padding: 15px;
    background: #f8f9fa;
    border-radius: 10px;
    border-left: 4px solid #667eea;
}
```

```
.indicator-item h4 {
    color: #2c3e50;
    margin-bottom: 10px;
    font-size: 1.1em;
}

.indicator-item p {
    color: #555;
    line-height: 1.6;
}

.metric {
    display: inline-block;
    background: #e3f2fd;
    padding: 5px 12px;
    border-radius: 5px;
    margin: 5px 5px 5px 0;
    font-size: 0.9em;
    font-weight: 500;
}

.summary-section {
    background: linear-gradient(135deg, #ffecd2 0%, #fcb69f 100%);
    padding: 30px;
    border-radius: 15px;
    grid-column: 1 / -1;
}

.summary-section h2 {
    color: #2c3e50;
    margin-bottom: 20px;
    font-size: 1.8em;
}

.summary-content {
    background: white;
    padding: 25px;
    border-radius: 10px;
    line-height: 1.8;
}

.vulnerability-score {
    display: flex;
    align-items: center;
```

```
    gap: 20px;
    margin: 20px 0;
    padding: 20px;
    background: #f8f9fa;
    border-radius: 10px;
}

.score-circle {
    width: 100px;
    height: 100px;
    border-radius: 50%;
    display: flex;
    align-items: center;
    justify-content: center;
    font-size: 2em;
    font-weight: bold;
    color: white;
}

.score-low {
    background: linear-gradient(135deg, #11998e 0%, #38ef7d 100%);
}

.score-moderate {
    background: linear-gradient(135deg, #f2994a 0%, #f2c94c 100%);
}

.score-high {
    background: linear-gradient(135deg, #eb3349 0%, #f45c43 100%);
}

.recommendations {
    background: #e8f5e9;
    padding: 20px;
    border-radius: 10px;
    margin-top: 20px;
}

.recommendations h3 {
    color: #2e7d32;
    margin-bottom: 15px;
}

.recommendations ul {
    list-style-position: inside;
```

```
            color: #1b5e20;
        }

        .recommendations li {
            margin-bottom: 10px;
            line-height: 1.6;
        }

        .error {
            background: #ffebee;
            color: #c62828;
            padding: 15px;
            border-radius: 10px;
            margin: 20px 0;
            border-left: 4px solid #c62828;
        }

        @media (max-width: 768px) {
            .input-row {
                grid-template-columns: 1fr;
            }

            .api-selector {
                flex-direction: column;
            }

            .header h1 {
                font-size: 1.8em;
            }

            .vulnerability-score {
                flex-direction: column;
            }

            .results-grid {
                grid-template-columns: 1fr;
            }
        }
    </style>
</head>
<body>
    <div class="container">
        <div class="header">
            <h1>□ Climate Change Adaptation Assessment Tool</h1>
            <p>Comprehensive analysis of animal species' adaptation indicators</p>
```

```
        </div>
    <a href="http://www.iaees.org/publications/journals/ces/articles/2026-16(1)/3-Zhang-Abstract.asp">Zhang WJ. 2026. AI-driven assessment of animal adaptation to climate change: The web tool based on physiological, morphological, behavioral, and genetic indicators of animal species. Computational Ecology and Software, 16(1): 58-98</a>

        <div class="main-content">
            <div class="input-section">
                <h2 style="margin-bottom: 20px; color: #2c3e50;">Species Information</h2>

                <div class="input-row">
                    <div class="input-group">
                        <label for="speciesName">Species Name *</label>
                        <input type="text" id="speciesName" placeholder="e.g., Polar Bear (Ursus maritimus)" required>
                    </div>

                    <div class="input-group">
                        <label for="habitat">Primary Habitat</label>
                        <input type="text" id="habitat" placeholder="e.g., Arctic tundra, sea ice">
                    </div>
                </div>

                <div class="input-row">
                    <div class="input-group">
                        <label for="region">Geographic Region</label>
                        <input type="text" id="region" placeholder="e.g., Arctic Circle, Northern Canada">
                    </div>

                    <div class="input-group">
                        <label for="timeframe">Study Timeframe</label>
                        <input type="text" id="timeframe" placeholder="e.g., Last 20 years, 2000-2024">
                    </div>
                </div>

                <div class="input-group">
                    <label for="additionalContext">Additional Context (Optional)</label>
                    <textarea id="additionalContext" rows="3" placeholder="Any specific climate stressors, observed changes, or research focus areas..."></textarea>
                </div>

                <div class="input-group">
                    <label>Select AI API *</label>
                    <div class="api-selector">
                        <label class="api-option selected">
                            <input type="radio" name="apiProvider" value="deepseek" checked>
                            <strong>DeepSeek API</strong>
```

```
                        </label>
                        <label class="api-option">
                            <input type="radio" name="apiProvider" value="gemini">
                            <strong>Google Gemini API</strong>
                        </label>
                    </div>
                </div>

                <div class="input-group">
                    <label for="apiKey">API Key *</label>
                    <input type="password" id="apiKey" placeholder="Enter your API key">
                </div>

            □ How to get AI API keys:<br>
            • DeepSeek: <a href="https://platform.deepseek.com/">platform.deepseek.com</a><br>
            • Gemini: <a href="https://makersuite.google.com/app/apikey">makersuite.google.com/app/apikey</a><br>
          </div><br>

                <button class="btn" id="analyzeBtn">□ Analyze Climate Adaptation</button>
            </div>

            <div class="loading" id="loading">
                <div class="spinner"></div>
                <p style="color: #667eea; font-size: 1.2em; font-weight: 600;">Analyzing adaptation indicators...</p>
                <p style="color: #666; margin-top: 10px;">This may take 30-60 seconds</p>
            </div>

            <div class="results" id="results">
                <!-- Results will be populated here -->
            </div>
        </div>
    </div>

    <script>
        // API Selection
        document.querySelectorAll('.api-option').forEach(option => {
            option.addEventListener('click', function() {
                document.querySelectorAll('.api-option').forEach(opt => opt.classList.remove('selected'));
                this.classList.add('selected');
                this.querySelector('input[type="radio"]').checked = true;
            });
        });

        // Main Analysis Function
        document.getElementById('analyzeBtn').addEventListener('click', async function() {
```

```
        const speciesName = document.getElementById('speciesName').value.trim();
        const habitat = document.getElementById('habitat').value.trim();
        const region = document.getElementById('region').value.trim();
        const timeframe = document.getElementById('timeframe').value.trim();
        const additionalContext = document.getElementById('additionalContext').value.trim();
        const apiKey = document.getElementById('apiKey').value.trim();
        const apiProvider = document.querySelector('input[name="apiProvider"]:checked').value;

        if (!speciesName || !apiKey) {
            alert('Please provide at least the species name and API key');
            return;
        }

        // Show loading, hide results
        document.getElementById('loading').classList.add('active');
        document.getElementById('results').classList.remove('active');
        this.disabled = true;

        try {
            // Fetch data from selected API
            const analysisData = await fetchAdaptationData({
                speciesName,
                habitat,
                region,
                timeframe,
                additionalContext,
                apiKey,
                apiProvider
            });

            // Display results
            displayResults(analysisData);
        } catch (error) {
            document.getElementById('results').innerHTML = `
                <div class="error">
                    <strong>Error:</strong> ${error.message}
                </div>
            `;
            document.getElementById('results').classList.add('active');
        } finally {
            document.getElementById('loading').classList.remove('active');
            this.disabled = false;
        }
    });
```

```
        // Fetch Adaptation Data from AI APIs
        async function fetchAdaptationData(params) {
            const { speciesName, habitat, region, timeframe, additionalContext, apiKey, apiProvider } = params;

            const prompt = `You are an expert wildlife biologist and climate change researcher. Provide a comprehensive assessment of the following species' adaptation to climate change based on four key indicator categories.

Species: ${speciesName}
${habitat ? `Habitat: ${habitat}` : ''}
${region ? `Region: ${region}` : ''}
${timeframe ? `Timeframe: ${timeframe}` : ''}
${additionalContext ? `Additional Context: ${additionalContext}` : ''}

Please provide a detailed analysis covering:

1. PHYSIOLOGICAL INDICATORS
   - Thermal tolerance and performance (CTmax/CTmin shifts, HSP expression, metabolic changes)
   - Water and osmotic balance (evaporative water loss, kidney function)
   - Energetics and metabolism (SMR, aerobic scope)
   - Reproductive and stress physiology (hormone levels, timing shifts)
   Provide specific quantitative data where available (e.g., temperature ranges, metabolic rates, hormone levels).

2. MORPHOLOGICAL INDICATORS
   - Body size changes (Bergmann's rule effects)
   - Surface structures (pelage/feather density, coloration)
   - Functional morphology (bill size, appendage length - Allen's rule)
   Provide measurements and percentage changes where available.

3. BEHAVIORAL INDICATORS
   - Phenological shifts (migration timing, breeding timing, hibernation changes)
   - Habitat use and activity patterns (range shifts, microhabitat selection, temporal niche shifts)
   - Foraging and diet changes
   - Social and reproductive behavior modifications
   Provide specific dates, distances, or behavioral frequency changes where available.

4. GENETIC INDICATORS
   - Signatures of selection (allele frequency changes, adaptive loci)
   - Evolutionary potential (genetic variation, effective population size)
   - Gene flow and local adaptation
   - Epigenetic modifications
   Provide genetic diversity metrics, Ne values, or adaptation rates where available.

5. SUMMARY ASSESSMENT
   - Overall vulnerability score (Low/Moderate/High) with justification
   - Integration of physiological, morphological, behavioral, and genetic responses
```

```
   - Distinction between plasticity vs. evolutionary adaptation
   - Conservation implications and recommendations (3-5 specific actions)

Format your response as a JSON object with this structure:
{
  "physiological": {
    "thermal": { "indicators": [], "data": {} },
    "water": { "indicators": [], "data": {} },
    "energetics": { "indicators": [], "data": {} },
    "reproductive": { "indicators": [], "data": {} }
  },
  "morphological": {
    "bodySize": { "indicators": [], "data": {} },
    "surface": { "indicators": [], "data": {} },
    "functional": { "indicators": [], "data": {} }
  },
  "behavioral": {
    "phenological": { "indicators": [], "data": {} },
    "habitat": { "indicators": [], "data": {} },
    "foraging": { "indicators": [], "data": {} },
    "social": { "indicators": [], "data": {} }
  },
  "genetic": {
    "selection": { "indicators": [], "data": {} },
    "potential": { "indicators": [], "data": {} },
    "geneFlow": { "indicators": [], "data": {} },
    "epigenetic": { "indicators": [], "data": {} }
  },
  "summary": {
    "vulnerabilityScore": "Low|Moderate|High",
    "overallAssessment": "string",
    "plasticityVsEvolution": "string",
    "conservationRecommendations": []
  }
}

Include as much quantitative data as possible. If specific data is not available for this species, indicate "Data limited" but provide general expectations based on similar species or theoretical predictions.`;

            if (apiProvider === 'deepseek') {
                return await fetchFromDeepSeek(prompt, apiKey);
            } else {
                return await fetchFromGemini(prompt, apiKey);
            }
        }
```

```
// DeepSeek API Call
async function fetchFromDeepSeek(prompt, apiKey) {
    const response = await fetch('https://api.deepseek.com/v1/chat/completions', {
        method: 'POST',
        headers: {
            'Content-Type': 'application/json',
            'Authorization': `Bearer ${apiKey}`
        },
        body: JSON.stringify({
            model: 'deepseek-chat',
            messages: [
                {
                    role: 'system',
                    content: 'You are an expert wildlife biologist and climate change researcher. Provide detailed, scientifically accurate assessments with quantitative data.'
                },
                {
                    role: 'user',
                    content: prompt
                }
            ],
            temperature: 0.7,
            max_tokens: 4000
        })
    });

    if (!response.ok) {
        throw new Error(`DeepSeek API error: ${response.status} ${response.statusText}`);
    }

    const data = await response.json();
    const content = data.choices[0].message.content;

    // Extract JSON from response
    const jsonMatch = content.match(/\{[\s\S]*\}/);
    if (jsonMatch) {
        return JSON.parse(jsonMatch[0]);
    } else {
        throw new Error('Could not parse JSON from API response');
    }
}

// Gemini API Call
async function fetchFromGemini(prompt, apiKey) {
```

```
            const response = await
fetch(`https://generativelanguage.googleapis.com/v1beta/models/gemini-pro:generateContent?key=${apiKey}`, {
                method: 'POST',
                headers: {
                    'Content-Type': 'application/json'
                },
                body: JSON.stringify({
                    contents: [{
                        parts: [{
                            text: prompt
                        }]
                    }],
                    generationConfig: {
                        temperature: 0.7,
                        maxOutputTokens: 4000,
                    }
                })
            });

            if (!response.ok) {
                throw new Error(`Gemini API error: ${response.status} ${response.statusText}`);
            }

            const data = await response.json();
            const content = data.candidates[0].content.parts[0].text;

            // Extract JSON from response
            const jsonMatch = content.match(/\{[\s\S]*\}/);
            if (jsonMatch) {
                return JSON.parse(jsonMatch[0]);
            } else {
                throw new Error('Could not parse JSON from API response');
            }
        }

        // Display Results
        function displayResults(data) {
            const resultsDiv = document.getElementById('results');

            let html = '<div class="results-grid">';

            // Physiological Indicators
            html += createIndicatorSection('physiological', '□□ Physiological Indicators', data.physiological, [
                { key: 'thermal', title: 'Thermal Tolerance & Performance' },
                { key: 'water', title: 'Water & Osmotic Balance' },
```

```
            { key: 'energetics', title: 'Energetics & Metabolism' },
            { key: 'reproductive', title: 'Reproductive & Stress Physiology' }
        ]);

        // Morphological Indicators
        html += createIndicatorSection('morphological', '□ Morphological Indicators', data.morphological, [
            { key: 'bodySize', title: 'Body Size Changes' },
            { key: 'surface', title: 'Surface Structures' },
            { key: 'functional', title: 'Functional Morphology' }
        ]);

        // Behavioral Indicators
        html += createIndicatorSection('behavioral', '□ Behavioral Indicators', data.behavioral, [
            { key: 'phenological', title: 'Phenological Shifts' },
            { key: 'habitat', title: 'Habitat Use & Activity' },
            { key: 'foraging', title: 'Foraging & Diet' },
            { key: 'social', title: 'Social & Reproductive Behavior' }
        ]);

        // Genetic Indicators
        html += createIndicatorSection('genetic', '□ Genetic Indicators', data.genetic, [
            { key: 'selection', title: 'Signatures of Selection' },
            { key: 'potential', title: 'Evolutionary Potential' },
            { key: 'geneFlow', title: 'Gene Flow & Local Adaptation' },
            { key: 'epigenetic', title: 'Epigenetic Modifications' }
        ]);

        // Summary Assessment
        html += createSummarySection(data.summary);

        html += '</div>';

        resultsDiv.innerHTML = html;
        resultsDiv.classList.add('active');
    }

    // Create Indicator Section
    function createIndicatorSection(className, title, sectionData, subsections) {
        let html = `
            <div class="indicator-section">
                <div class="indicator-header ${className}">
                    ${title}
                </div>
                <div class="indicator-content">
        `;
```

```
    subsections.forEach(subsection => {
        const subData = sectionData[subsection.key];
        if (subData && (subData.indicators.length > 0 || Object.keys(subData.data).length > 0)) {
            html += `
                <div class="indicator-item">
                    <h4>${subsection.title}</h4>
                    ${subData.indicators.map(ind => `<p>• ${ind}</p>`).join('')}
                    ${Object.entries(subData.data).map(([key, value]) =>
                        `<span class="metric"><strong>${key}:</strong> ${value}</span>`
                    ).join('')}
                </div>
            `;
        }
    });

    html += `
            </div>
        </div>
    `;

    return html;
}

// Create Summary Section
function createSummarySection(summary) {
    const scoreClass = summary.vulnerabilityScore === 'Low' ? 'score-low' :
                      summary.vulnerabilityScore === 'Moderate' ? 'score-moderate' : 'score-high';

    return `
        <div class="summary-section">
            <h2>□ Summary Assessment</h2>

            <div class="vulnerability-score">
                <div class="score-circle ${scoreClass}">
                    ${summary.vulnerabilityScore}
                </div>
                <div style="flex: 1;">
                    <h3 style="margin-bottom: 10px;">Vulnerability Score</h3>
                    <p style="color: #555;">${summary.overallAssessment}</p>
                </div>
            </div>

            <div class="summary-content">
                <h3 style="margin-bottom: 15px;">Plasticity vs. Evolution</h3>
```

```
                <p style="margin-bottom: 20px;">${summary.plasticityVsEvolution}</p>
            </div>

            <div class="recommendations">
                <h3>□ Conservation Recommendations</h3>
                <ul>
                    ${summary.conservationRecommendations.map(rec => `<li>${rec}</li>`).join('')}
                </ul>
            </div>
        </div>
    `;
}
</script>
</body>
</html>
```

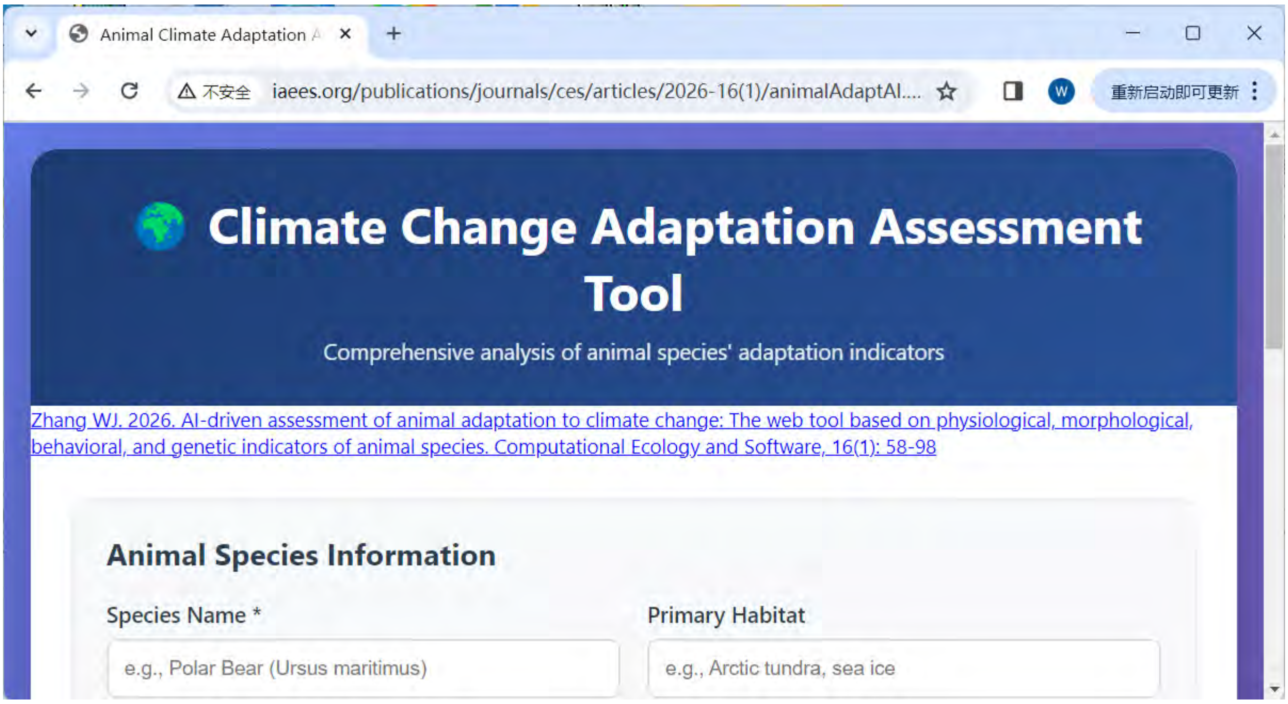


Fig. 1 The web tool page.

6 A Demo

In present demo, the Species Name is polar bear (Ursus maritimus), Primary Habitat is sea ice, Geographic Region is arctic circle, Study Timeframe is last 20 years. Use DeepSeek for AI assessment. Before using this tool, we need to obtain an AI API key. For DeepSeek, for example, log in to https://platform.deepseek.com/, register for an account, and prepay a very small fee to use the assigned API key. The results are as follows (Fig. 2):

(1) Physiological Indicators

Thermal Tolerance & Performance

• CTmax tolerance
• Heat stress response
• Thermoregulatory capacity

CTmax_estimate: 38-40°C (limited direct measurement)
thermal_neutral_zone: -10 to +10°C (narrowing with habitat loss)
heat_stress_onset: >20°C ambient temperature
hsp_expression: Data limited - expected upregulation in marginal populations
metabolic_response: Increased resting metabolic rate during fasting periods by 15-20%

Water & Osmotic Balance

• Evaporative water loss
• Kidney function adaptation
• Hydration strategies

water_requirement: Primarily from prey metabolism (seal fat: 73% water)
fasting_water_loss: 0.5-1.0 L/day during summer fasting
renal_concentration: Data limited - likely efficient but challenged by prolonged fasting
osmoregulation: Specialized for high-fat marine diet, not terrestrial resources

Energetics & Metabolism

• Standard metabolic rate
• Aerobic scope
• Energy expenditure patterns

SMR_adult_male: 12,000-16,000 kcal/day (increased during ice-free periods)
aerobic_scope: Reduced by 30-40% during prolonged swimming (>50 km)
hunting_success_rate: Declined from 10% to <2% in some Hudson Bay populations
fasting_duration: Increased from 120 to 180 days in Southern Hudson Bay
energy_deficit: Up to 1.6 MJ/day during extended ice-free periods

Reproductive & Stress Physiology

• Corticosterone levels
• Reproductive hormone cycles

• Denning physiology

cortisol_levels: Increased 25-40% in ice-deprived populations
reproductive_interval: Extended from 3 to 4-5 years in stressed populations
litter_size: Declined from 2.0 to 1.5 cubs/female in Western Hudson Bay
den_emergence: Advanced by 2-3 weeks in some regions
cub_survival: Declined from 65% to 40% in first year (Southern Beaufort Sea)

(2) Morphological Indicators

Body Size Changes
• Body mass trends
• Length measurements
• Condition indices

adult_male_mass: Declined 15-20% (from 550kg to 450kg avg in Western Hudson Bay)
body_condition_index: Declined 0.3-0.5 units across multiple populations
skull_size: No significant change detected (maintaining bite force capacity)
cub_mass_at_emergence: Declined 10-15% in Southern Beaufort Sea

Surface Structures
• Pelage density
• Guard hair characteristics
• Subcutaneous fat thickness

blubber_thickness: Reduced 30-40% in fasting bears
guard_hair_density: No measurable change (maintaining insulation)
pelage_condition: Deterioration observed with increased swimming
thermal_conductivity: Maintained but compromised by reduced fat layers

Functional Morphology
• Limb proportions
• Paw size
• Swimming adaptations

forelimb_length: No significant change (maintaining swimming capacity)
paw_surface_area: No change (maintaining ice traction)
swimming_efficiency: Maintained but energetically costly (2-3x land locomotion)
cranial_morphology: Stable (specialized for seal predation)

(3) Behavioral Indicators

Phenological Shifts
• Ice break-up departure

• Den emergence
• Breeding season timing

ice_breakup_advance: 3.1 days/decade earlier (Hudson Bay)
shore_arrival: 2-3 weeks earlier than 20 years ago
den_emergence_advance: 1.5 days/decade earlier
fasting_period_extension: Increased from 120 to 180 days in some regions

Habitat Use & Activity
• Home range shifts
• Marine vs terrestrial use
• Microhabitat selection

range_shift_northward: 1-2° latitude northward in 20 years
terrestrial_time: Increased from 90 to 150 days/year in Hudson Bay
swimming_distance: Increased from <50km to >400km records
ice_edge_following: Maintained but with reduced optimal habitat

Foraging & Diet
• Diet composition
• Hunting success
• Alternative food sources

seal_dependence: Still >90% of diet where available
terrestrial_foraging: Increased from <5% to 20-30% summer diet in some areas
bird_egg_consumption: Increased 10-fold in some populations
berry_consumption: Increased but provides <3% of energy needs
human_interaction: Increased 300% in 20 years (food-conditioned bears)

Social & Reproductive Behavior
• Aggression levels
• Mating behavior
• Maternal care

cannibalism_incidence: Increased from rare to 3-5 observations/year
infanticide_rate: Increased in nutritionally stressed populations
mating_success: Declined with reduced encounter rates on fragmented ice
maternal_investment: Reduced with poorer body condition

(4) Genetic Indicators

Signatures of Selection
• Climate-associated alleles
• Selection signatures

• Adaptive loci

identified_adaptive_loci: Limited evidence - APOB associated with fat metabolism
selection_strength: Data limited - likely weak due to long generation time (8-10 years)
candidate_genes: Thermoregulation and metabolism genes under investigation

Evolutionary Potential
• Genetic diversity
• Effective population size
• Inbreeding

nucleotide_diversity: $\pi = 0.0003\text{-}0.0005$ (moderate for large carnivore)
effective_population_size: Ne = 8,000-10,000 (global)
heterozygosity: He = 0.45-0.55 across populations
inbreeding_coefficient: F = 0.05-0.15 in isolated subpopulations

Gene Flow & Local Adaptation
• Population connectivity
• Migration rates
• Local adaptation

historical_gene_flow: High during glacial periods, currently reduced
modern_migration_rate: Nm = 1-5 individuals/generation between adjacent populations
population_structure: FST = 0.1-0.2 between major populations
isolation_by_distance: Strong ($r = 0.65$, $p < 0.001$)

Epigenetic Modifications
• DNA methylation patterns
• Transgenerational effects
• Stress response markers

methylation_studies: Data limited - pilot studies ongoing
stress_epigenetics: Expected but unquantified
transgenerational_plasticity: Theoretically possible but undocumented

(5) Summary Assessment

High Vulnerability Score

Polar bears exhibit severe maladaptation to rapid Arctic warming, with physiological stress, declining body condition, and behavioral plasticity insufficient to compensate for sea ice loss. The species' specialized ecology creates fundamental constraints: 1) Metabolic dependence on seal predation requiring sea ice platform, 2) Limited capacity for dietary shift due to digestive physiology, 3) High energy demands incompatible with terrestrial foraging, and 4) Slow life history (8-10 year generation time) preventing rapid evolutionary response. Current adaptations are primarily behavioral plasticity with limited evidence of evolutionary adaptation.

Multiple subpopulations face extirpation within decades under current warming trajectories.

Plasticity vs. Evolution

Responses are overwhelmingly plastic (behavioral, physiological acclimatization) rather than evolutionary. Behavioral plasticity includes increased terrestrial foraging, extended fasting, and altered movement patterns. Physiological changes represent stress responses (elevated cortisol, reduced body condition) rather than adaptation. No documented evolutionary adaptations to warming have been confirmed; genetic studies show maintenance of ancestral adaptations to cold/ice environments. The mismatch between rapid environmental change and slow evolutionary potential (due to long generation time and small effective population size) creates an 'adaptation debt' that cannot be repaid through natural selection alone.

Conservation Recommendations

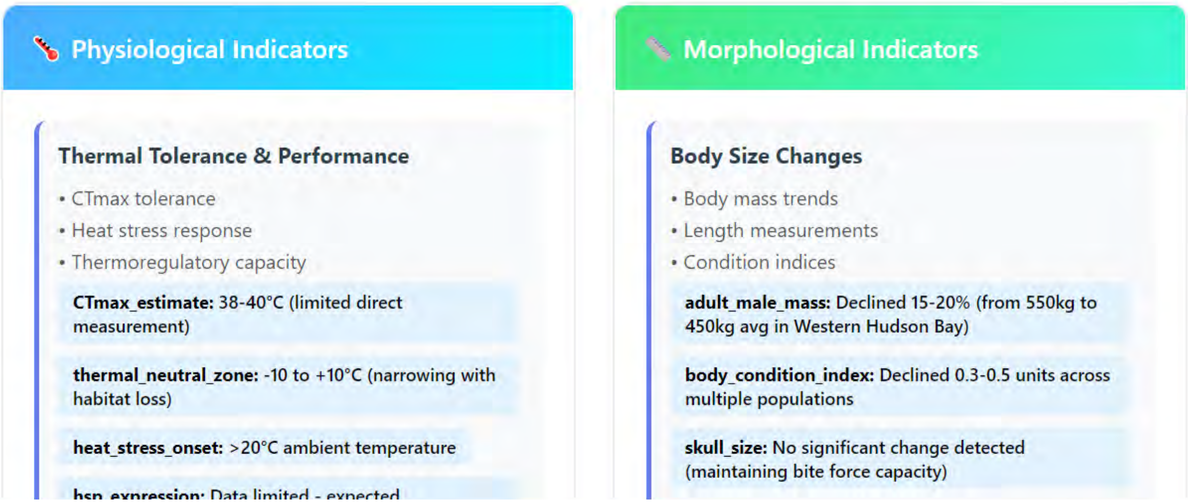
(a) Aggressive global greenhouse gas mitigation to preserve critical sea ice habitats, particularly in the Last Ice Area (northern Canada and Greenland)

(b) Protected movement corridors between subpopulations to maintain genetic connectivity and facilitate range shifts

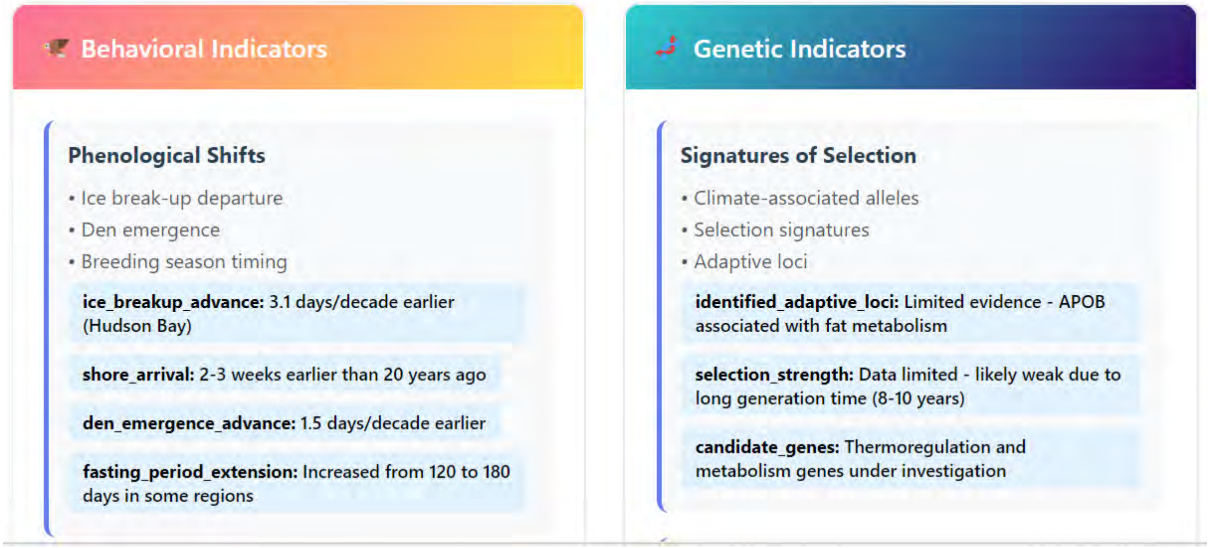
(c) Reduction of concurrent stressors including contaminants, shipping disturbance, and oil development in Arctic refugia

(d) Development of adaptive management frameworks for nutritionally stressed populations, including regulated supplemental feeding in crisis situations

(f) Expanded genetic monitoring and biobanking to preserve evolutionary potential and support potential future assisted evolution interventions



(a)



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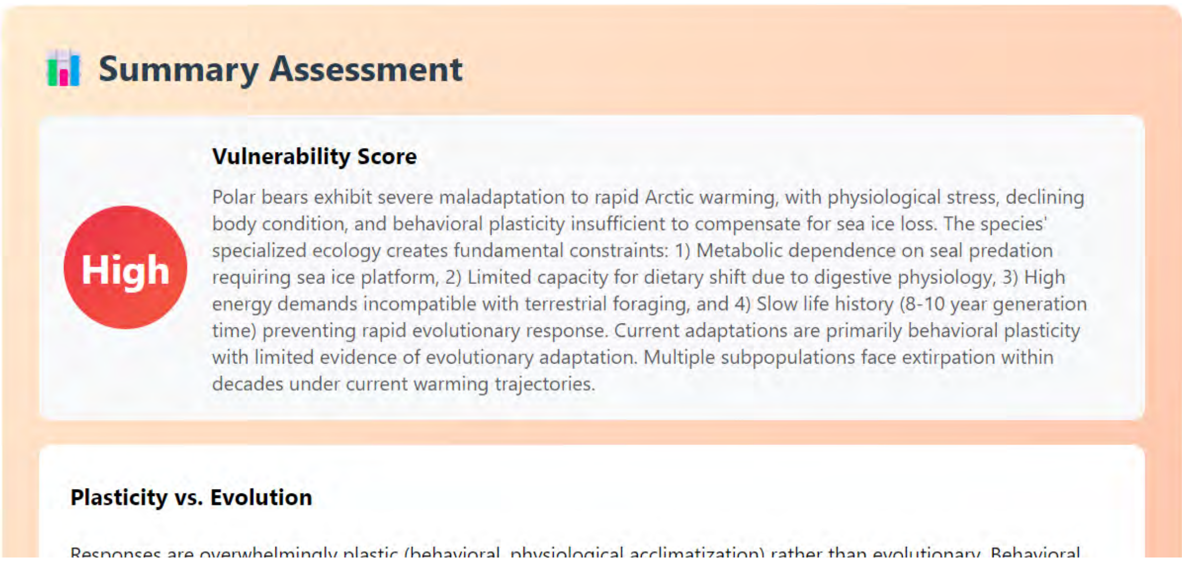

(c)

Fig. 2 Results.

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