Modeling Carbonate Dynamics to Define Biodiversity Thresholds in Mining BIA

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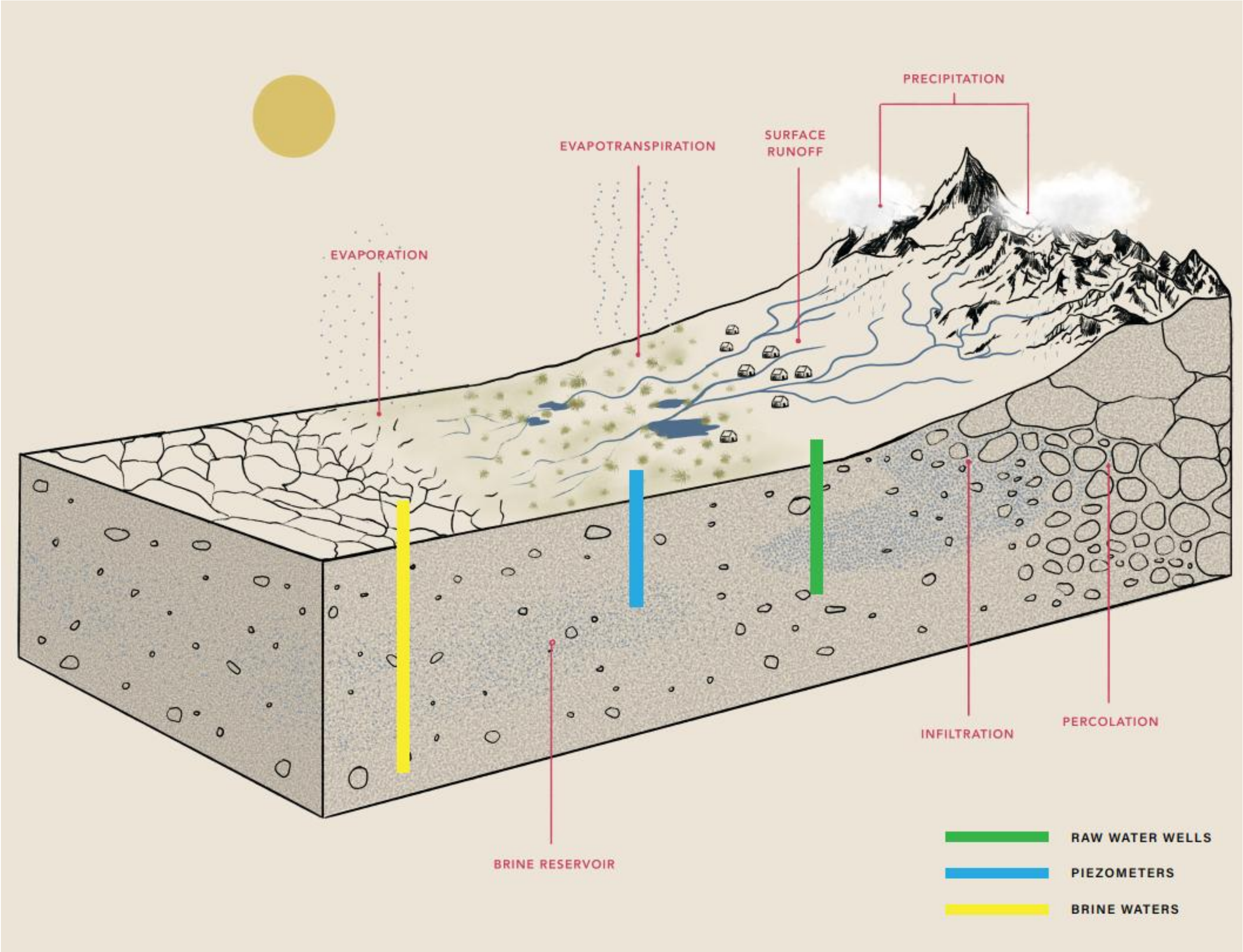
BIA in Andean water systems

- Extreme environmental gradients
- Strong seasonal variability
- Water bodies act as biodiversity hotspots
- Limited baseline information

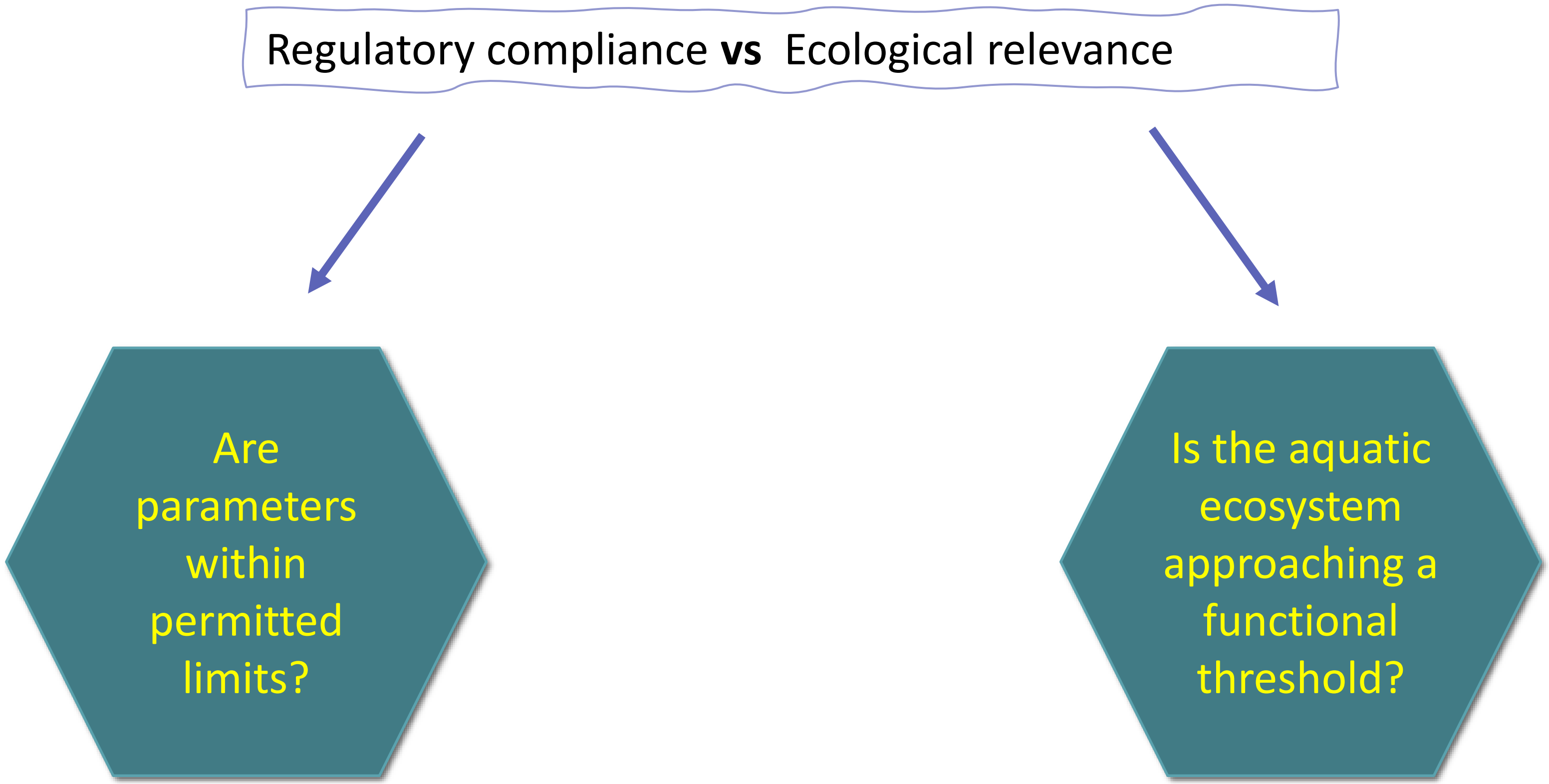
Growing pressure from lithium, gold, copper, silver and associated infrastructure projects.

Climate Change



1. The Monitoring Problem: Rich in data, poor in interpretation

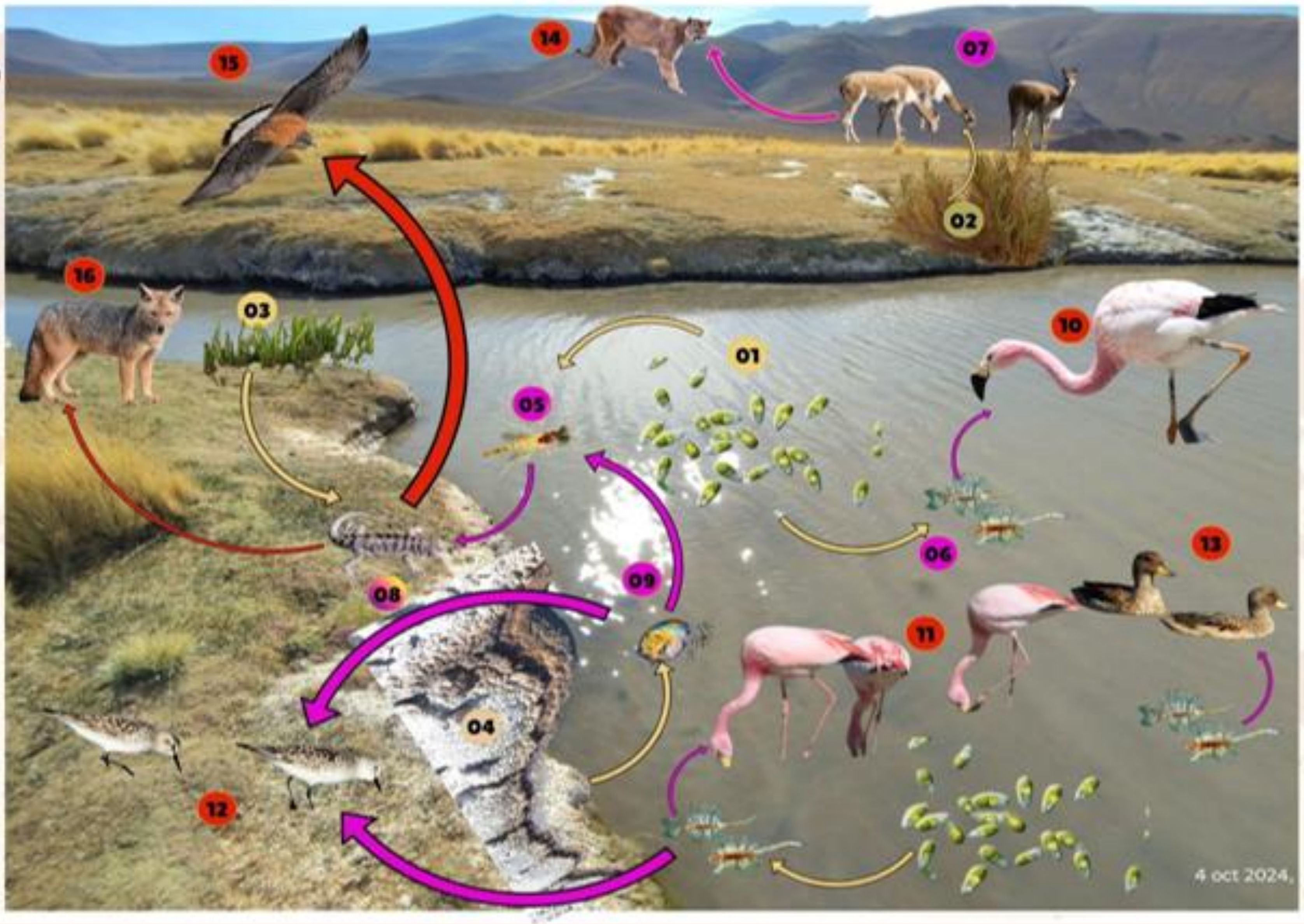
- The way we do Biodiversity Impact Assessment (BIA) **needs to be improved**
- Monitoring programs in mining regions often produce **large datasets**
- These datasets are commonly assessed against compliance limits, but rarely translated into ecological functionality, process change, or early-warning indicators
- Parameter-by-parameter interpretation can miss cumulative or process-level change



1. The Monitoring Problem

Compliance–based monitoring
One-size fits all approach
Are predetermined limits being crossed?
Parameter-by-parameter assessment
Periodic compliance tracking
Many times: imprecise and inaccurate

Ecosystem-function monitoring
Tailored to each ecosystem
Is the system actually changing?
Process-based linkages: thresholds or triggers
Adaptive management response
Precise and accurate

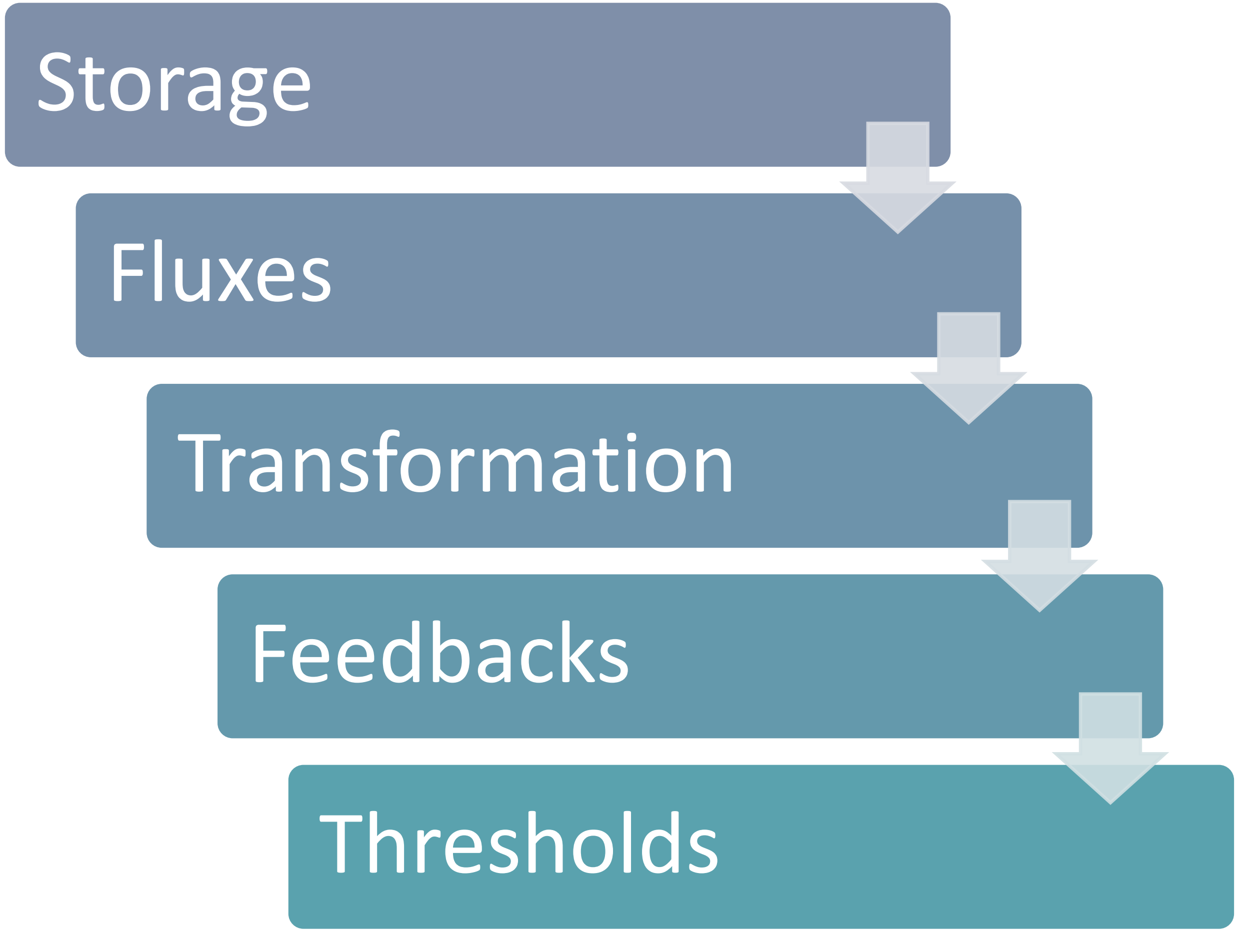


Courtesy of Andrea Barauna, ERM

- Operational **compartments**
- Matter **exchange** through mass fluxes
- Changes can be observed at a given exchange **rate**
- External forcing/perturbation drivers
- Residence time
- Tends towards **equilibrium**

3. Conceptual bridge: Reservoir Dynamics

Reservoir dynamics helps interpret **aquatic systems as open**, exchange-driven systems **where changes in fluxes** can trigger functional thresholds.



3.1 Reservoir Mechanisms

Negative Feedback

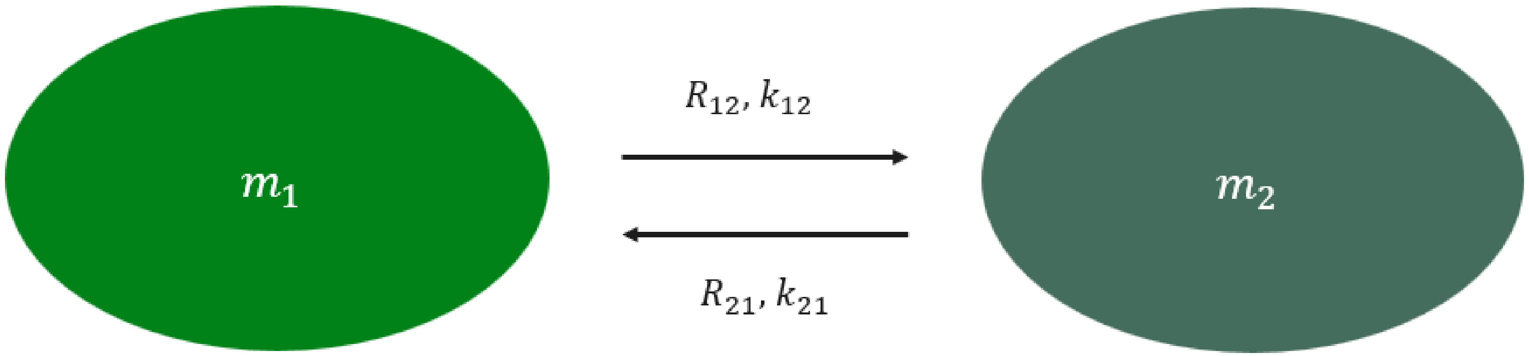
- Perturbations decay over time
- Return to steady state

Positive Feedback

- Perturbation is amplified rather than corrected
- Shifts toward alternative steady states

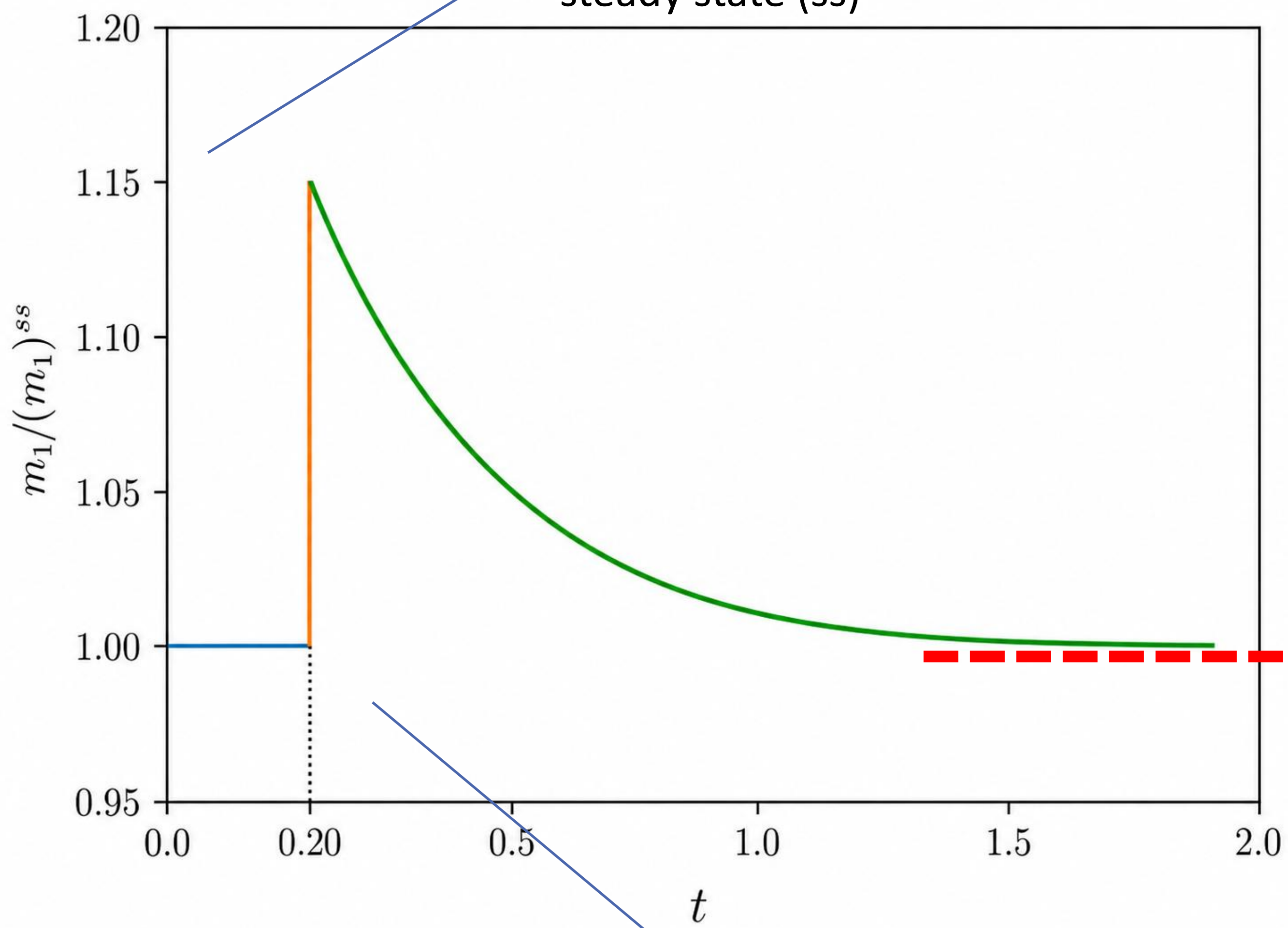
3.2 Reservoir exchange

Matter moves between connected reservoirs.



mi = **mass** of carbon stored in reservoir
Rji= flux of carbon **entering** reservoir i from reservoir j
Rij = flux of carbon **leaving** reservoir i toward reservoir j
$dmi\ /dt$ = **rate** of change of the carbon stock in reservoir i.
Kij= transfer coefficient between reservoirs

15% increase relative to steady state (ss)



T = Timescale over which reservoir relaxes back toward steady state after the perturbation.

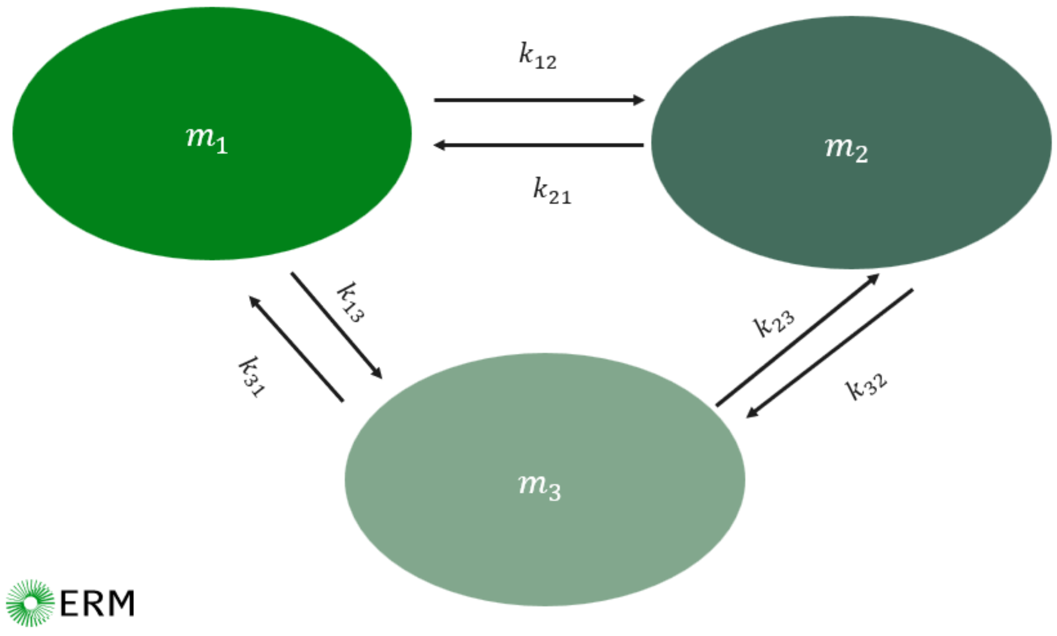
T = response time

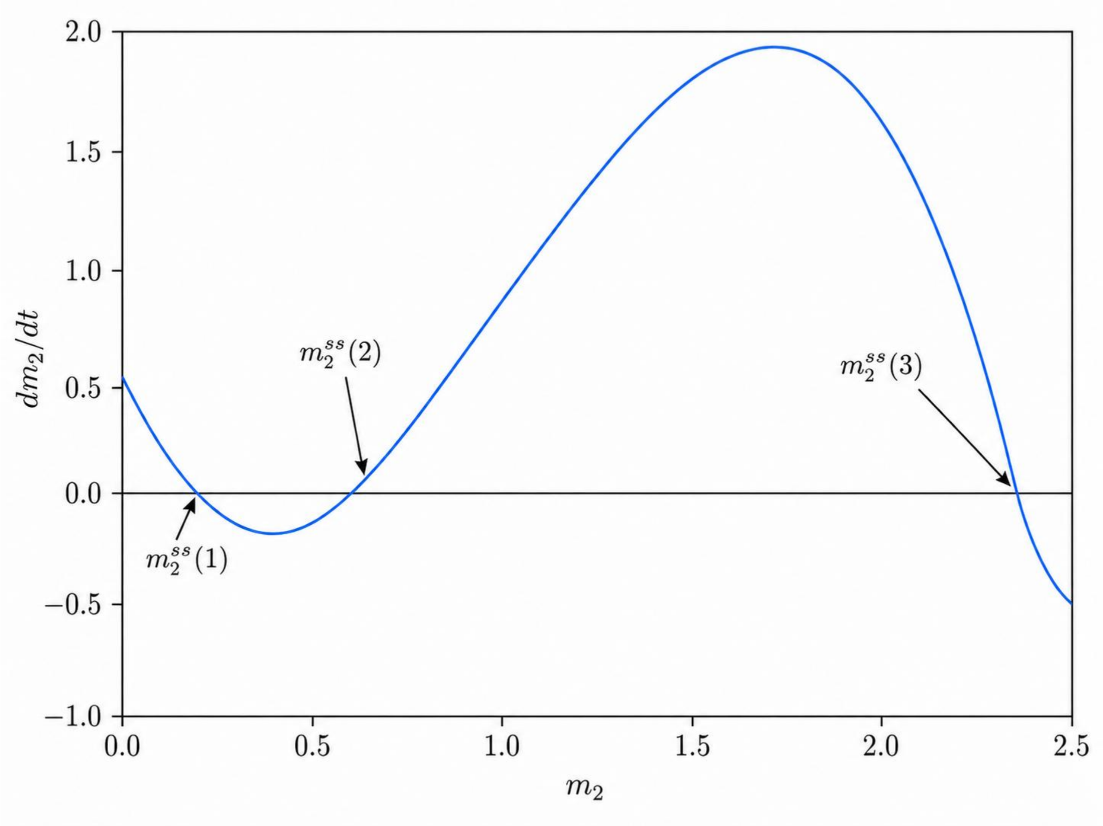
The perturbation occurs at $t = 0.20$

$$\frac{dmi}{dt} = \sum_j R_{ij} - \sum_j R_{ji} = 0$$

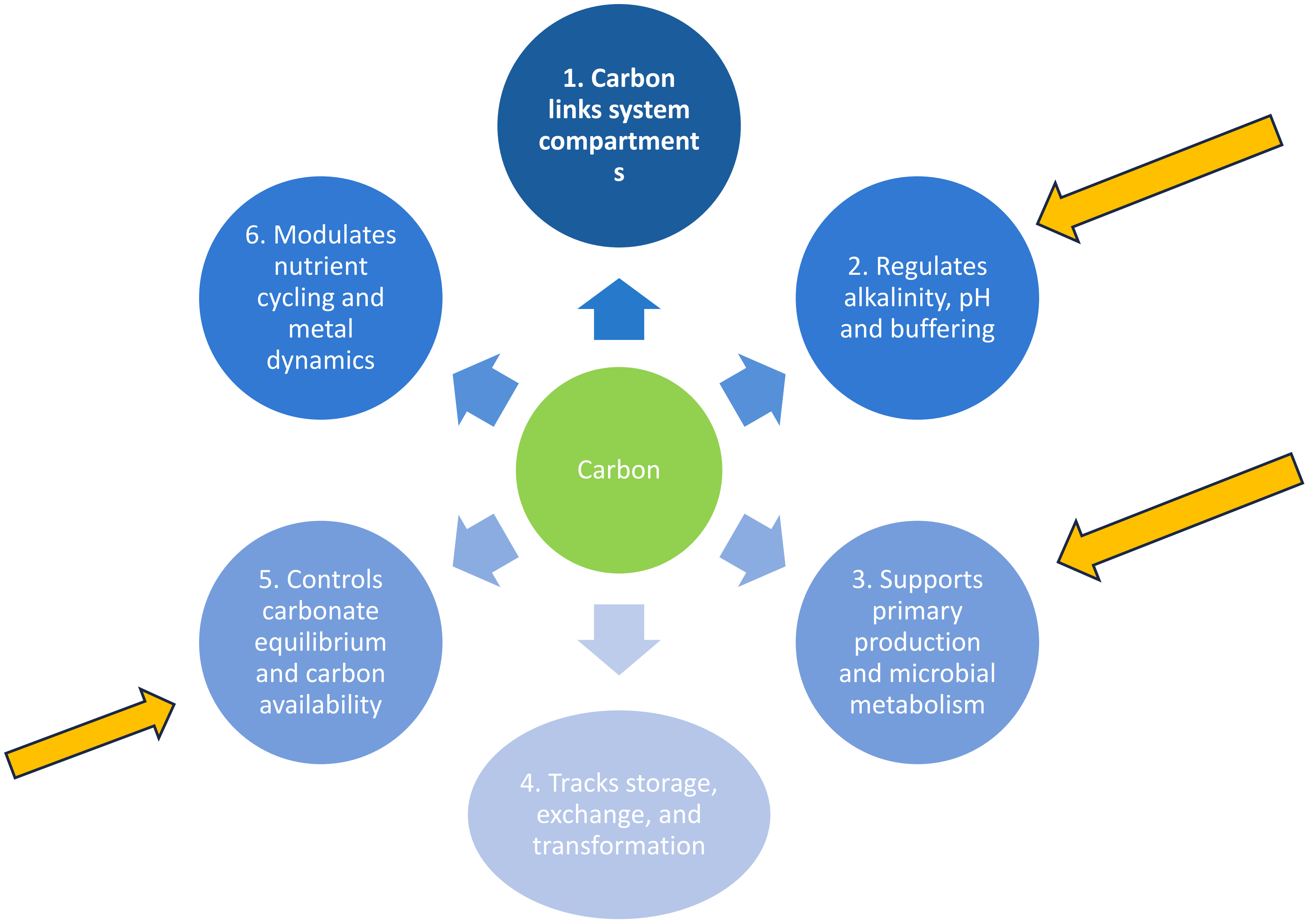
3.3. Reservoir exchange : three reservoirs

Real aquatic systems behave as connected reservoir networks, where changes in one compartment can propagate across the whole system.





4. Carbon as the Reservoir Framework



4.1. Why carbon?

Atmospheric CO_2 removal pathways	Equation	Diagnostic relevance
Dissolution into the water column	$CO_2(g) \rightarrow CO_2(aq)$	This connects gas exchange, pH, alkalinity, carbonate chemistry, and inorganic carbon availability.
Biological fixation through photosynthesis	$CO_2(g) + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$	This mechanism links carbon cycling with chlorophyll-a, pigments, phytoplankton productivity, microbial mats, High-Andean wetlands, EPS formation, and biological carbon fixation.
Mineral fixation through carbonate precipitation	$CO_2(g) + CaO(s) \rightarrow CaCO_3(s)$	In saline and alkaline systems, this pathway is expressed through carbonate equilibrium, **calcite/aragonite** saturation indices, mineral precipitation potential, and sediment carbon storage.

5. Carbon-cycle in Andean water bodies

I: Hydrogeochemical input of bicarbonate- and calcium-rich waters, likely linked to groundwater inflow, weathering,

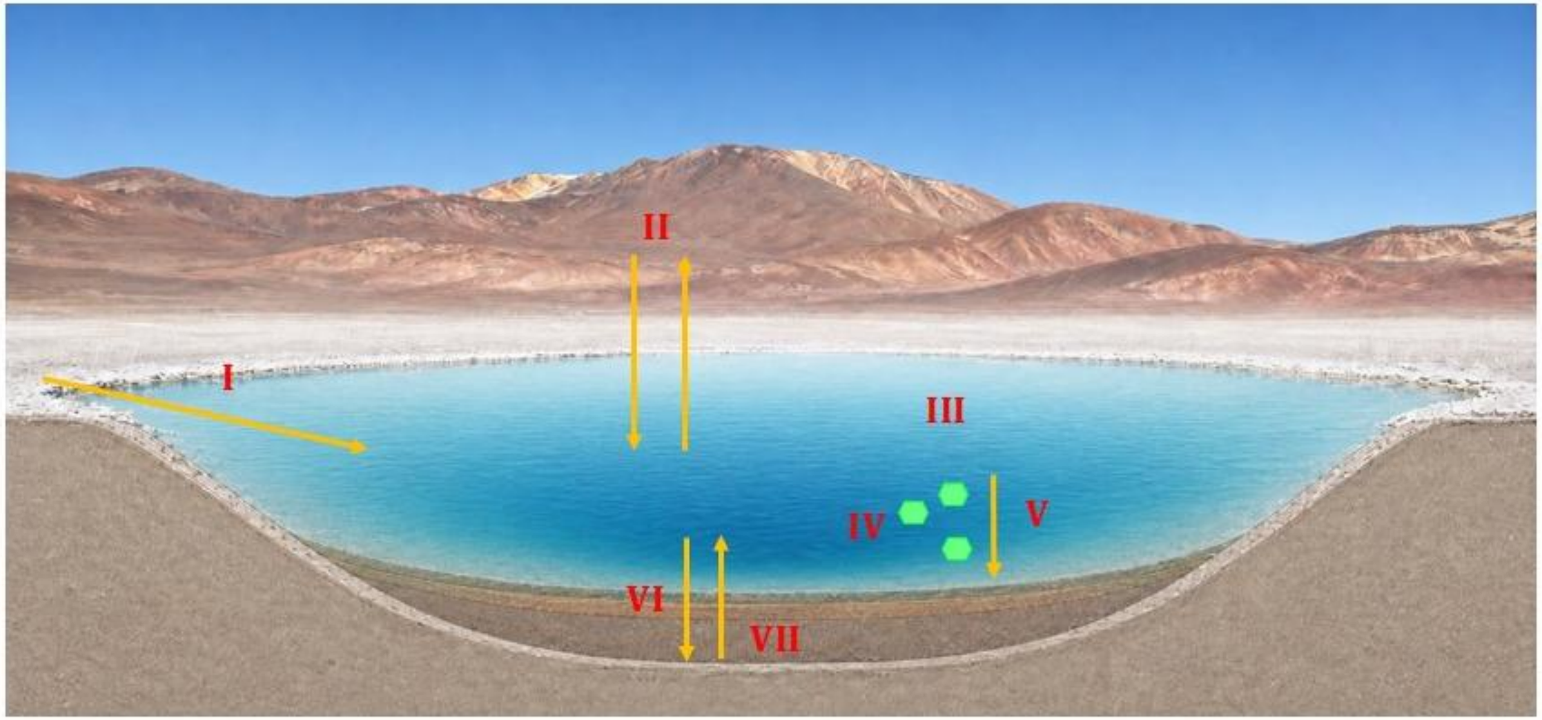
II: CO_2 exchange with the atmosphere;

III: Biogenic production of organic matter and biogenic/physicochemical precipitation of $CaCO_3$;

IV: Settling of detrital material (carbonates and organic polymers);

V: Decomposition of organic matter
VI: sedimentation of carbonates and organic matter;

VII. Potential carbonate dissolution driven by decomposition of organic matter in sediments.



5.1. Carbon Cycling: Mechanisms

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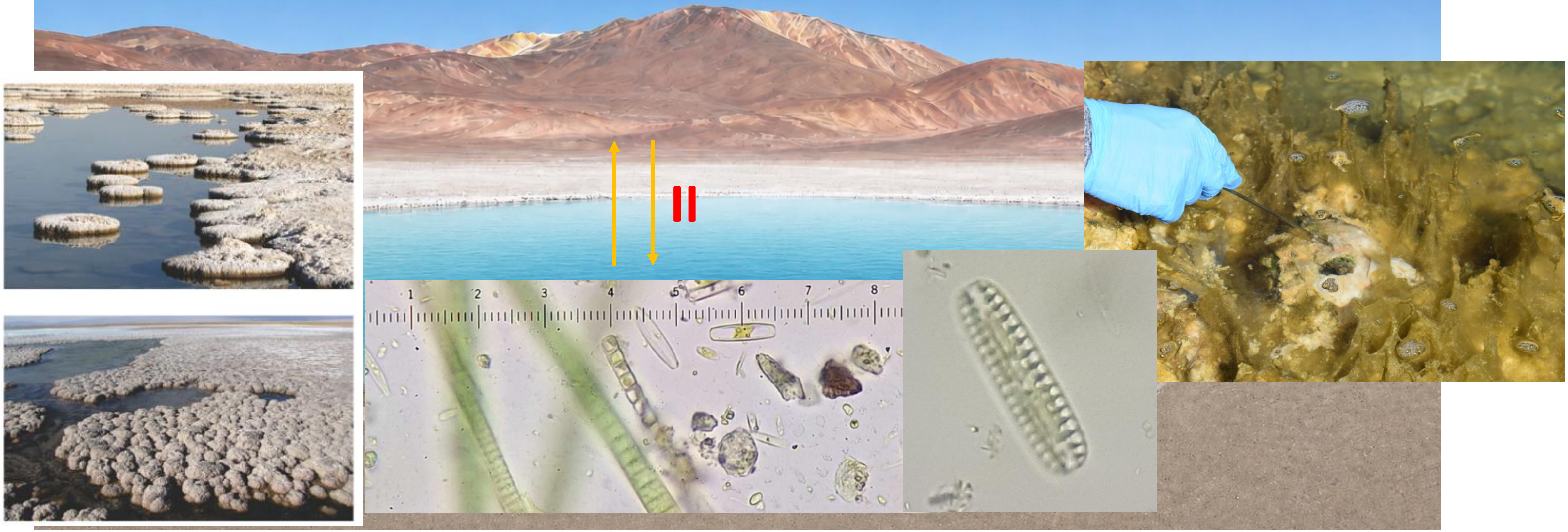
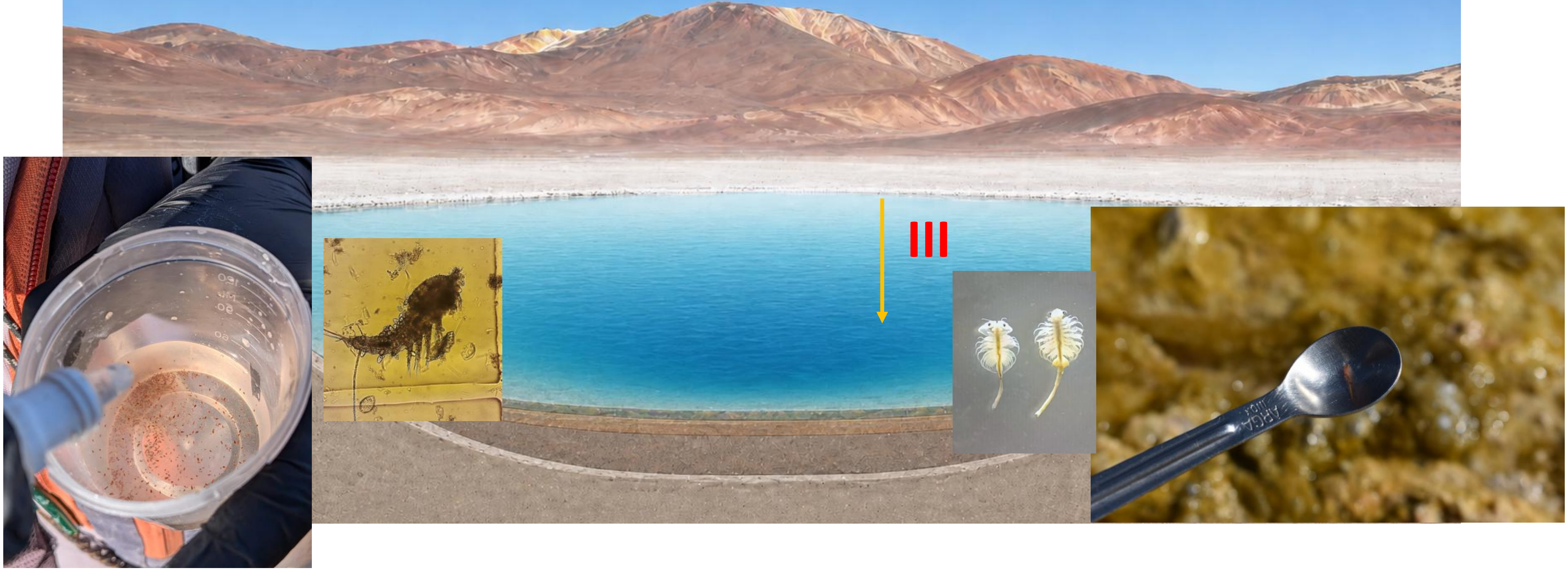
II. Photosynthesis, Respiration , diffusion, degassing, CO_2 dissolution, surface turbulence.



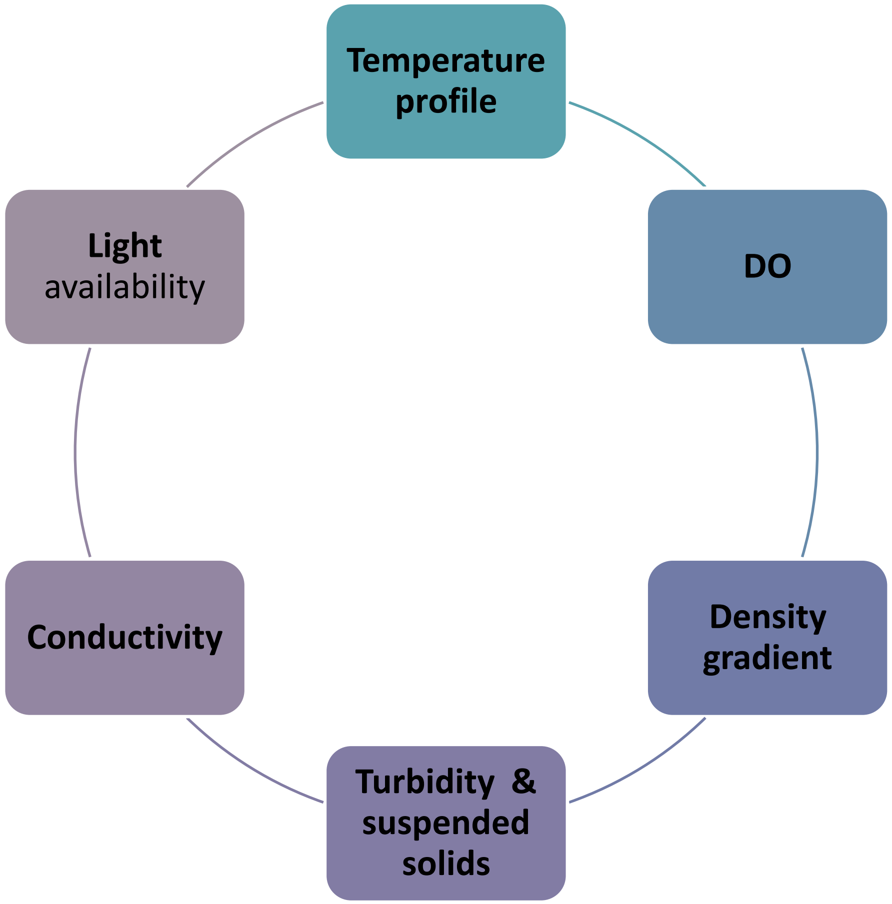
5.1. Carbon Cycling: Mechanisms

III. Photosynthesis, Respiration, carbon fixation, carbonate precipitation, biomineralization, EPS production.



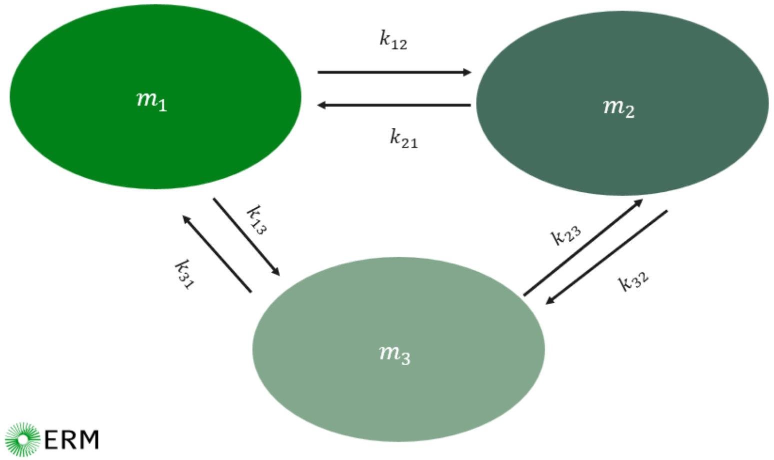
5.3. Physical controls on habitat and metabolism

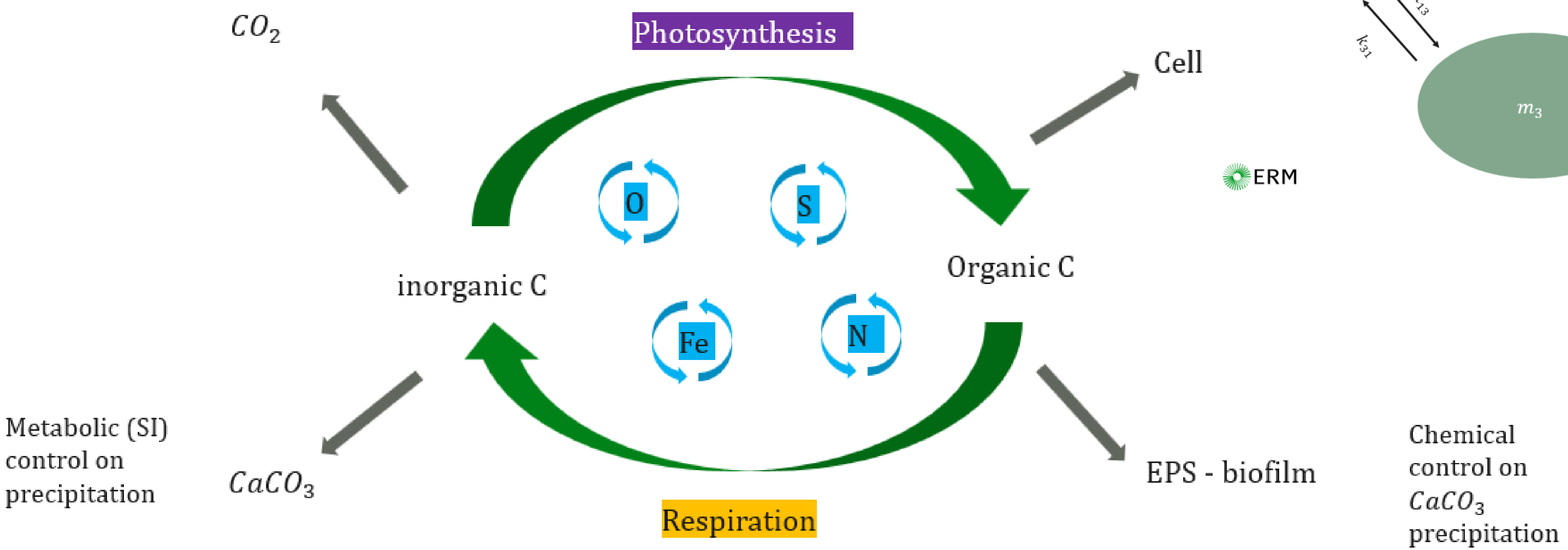
- Physical structure defines where biological activity can occur and how fast the system can respond to perturbation.



5.2. Carbon as the link between life and hydrochemistry

Life transforms carbon, and carbon chemistry shapes habitat conditions for life.





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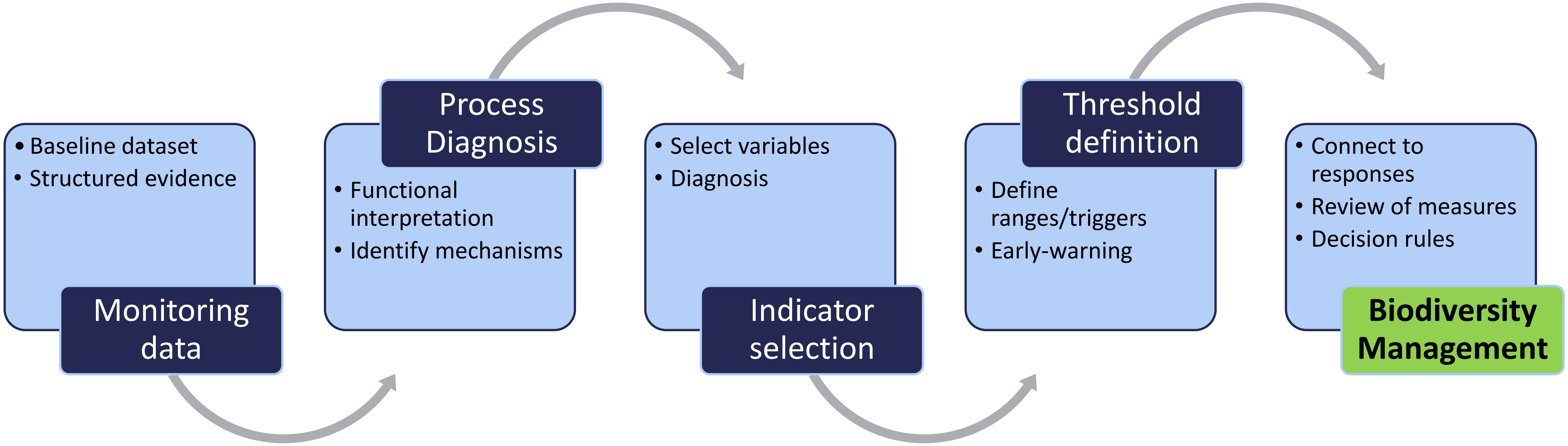
Where carbon-cycle processes shift, hydrochemical and biological responses tend to shift together.

6. BIA Thresholds: Methodological workflow



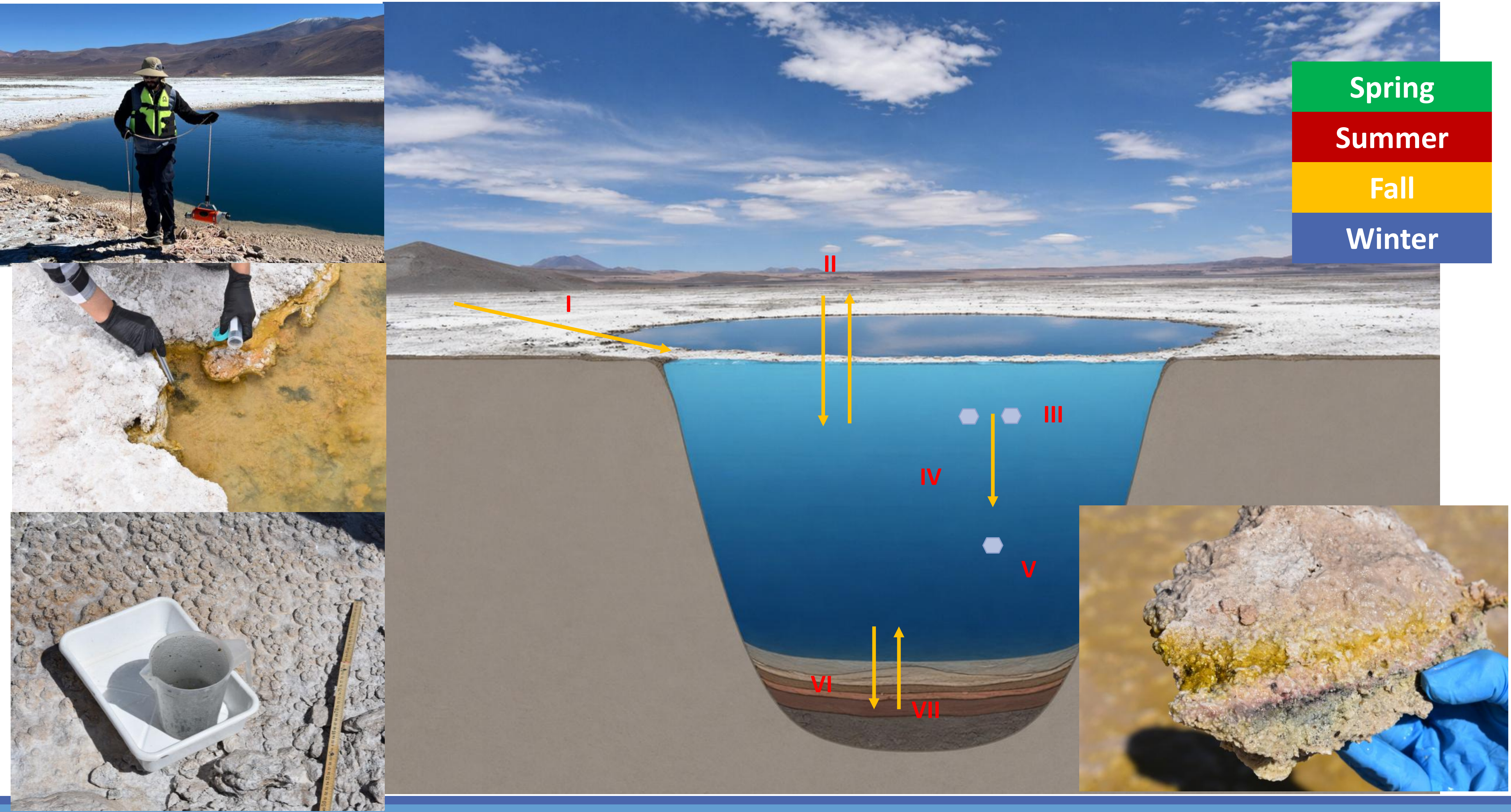
6.1. Feasibility: site-specific thresholds

- Carbon-based thresholds should not be interpreted as universal fixed values
- Their diagnostic value depends on **site-specific baselines**, **seasonal variability**
- **Biological tolerance ranges**
- Convergence among independent **lines of evidence**

A single parameter rarely defines a biodiversity threshold

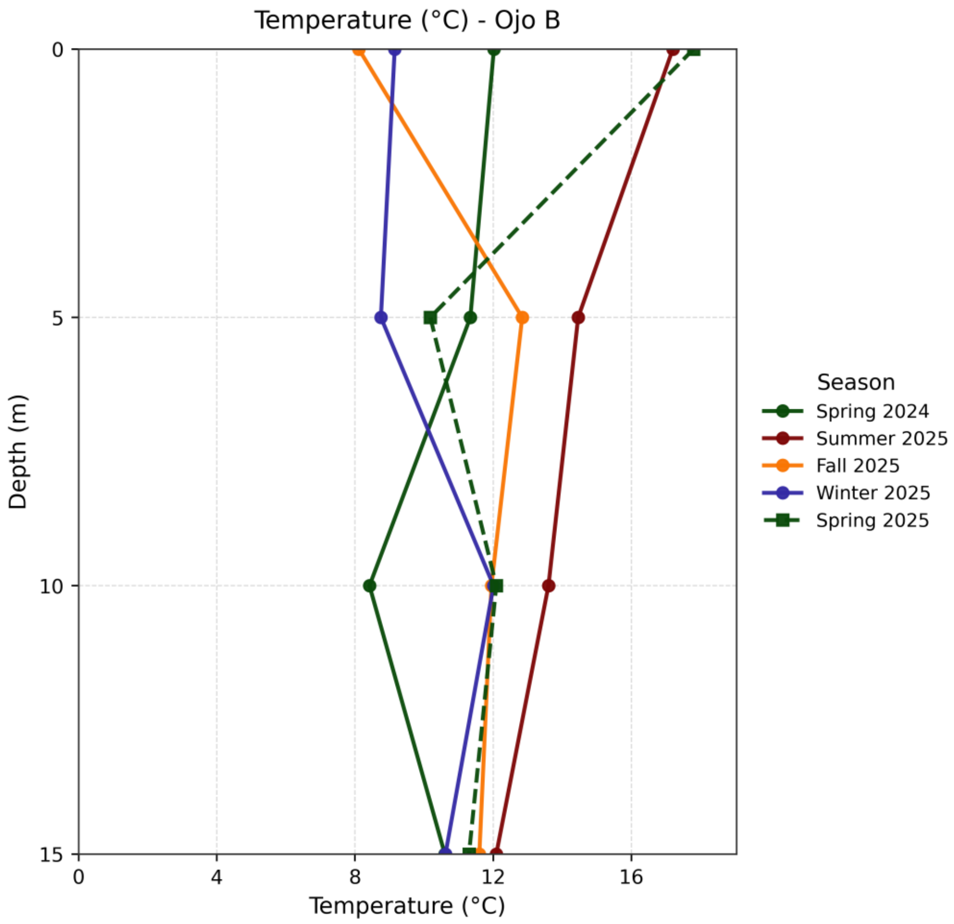
6.2. Technical Feasibility: Carbon-Based Thresholds

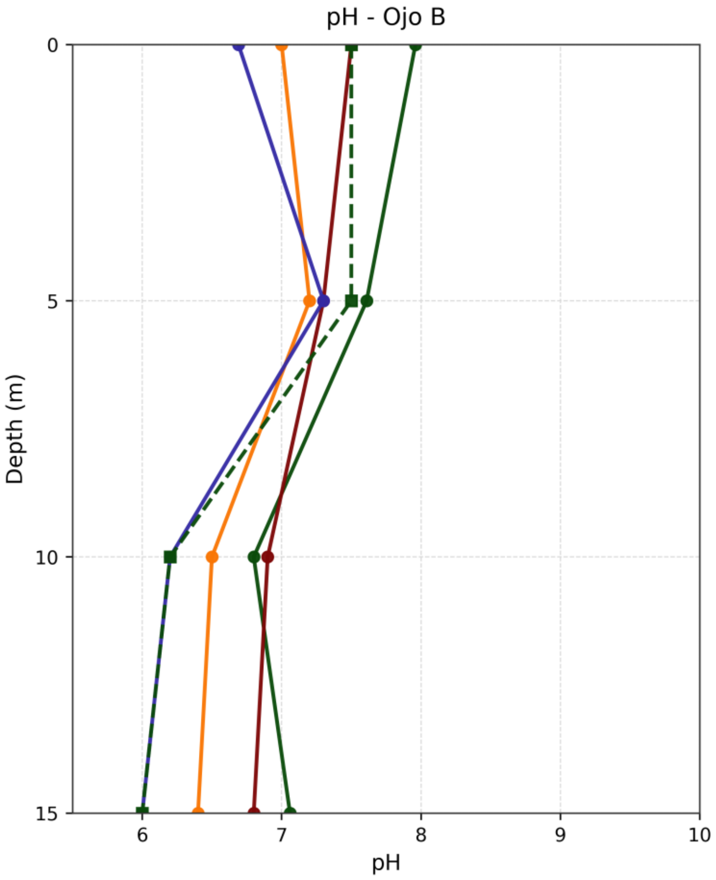
Evidence Line	Parameters & Indicators	Diagnostic Focus
Carbonate chemistry and modelling	Alkalinity, pH, Ca, **SI calcite, SI aragonite**	Carbonate equilibrium and buffering. Potential.
Normalized ratios	Ca/Cl, Alkalinity/Cl	Precipitation/dissolution, evaporation signals
Limnology - Primary production	Phytoplankton, chlorophyll-a, pigments, TP/TN, DIN/SRP	Biological production and organic matter generation. Tolerance threshold.
Redox / mineralization	NH_4, Fe, Mn	Mineralization and reducing conditions
Microbiology	EPS, biofilm, bacteria/archaea (CFU)	Microbial carbon processing and stabilization.
Physical structure	Depth, density, vertical deltas. Temperature, light penetration and dissolved oxygen profiles.	Stratification and functional gradients

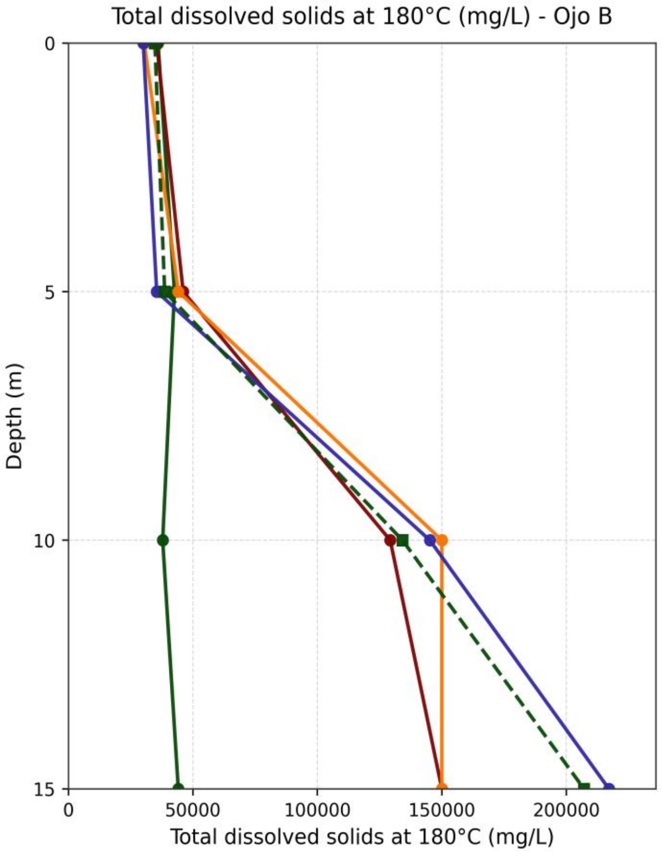


Spring
Summer
Fall
Winter
I
II
III
IV
V
VI
VII

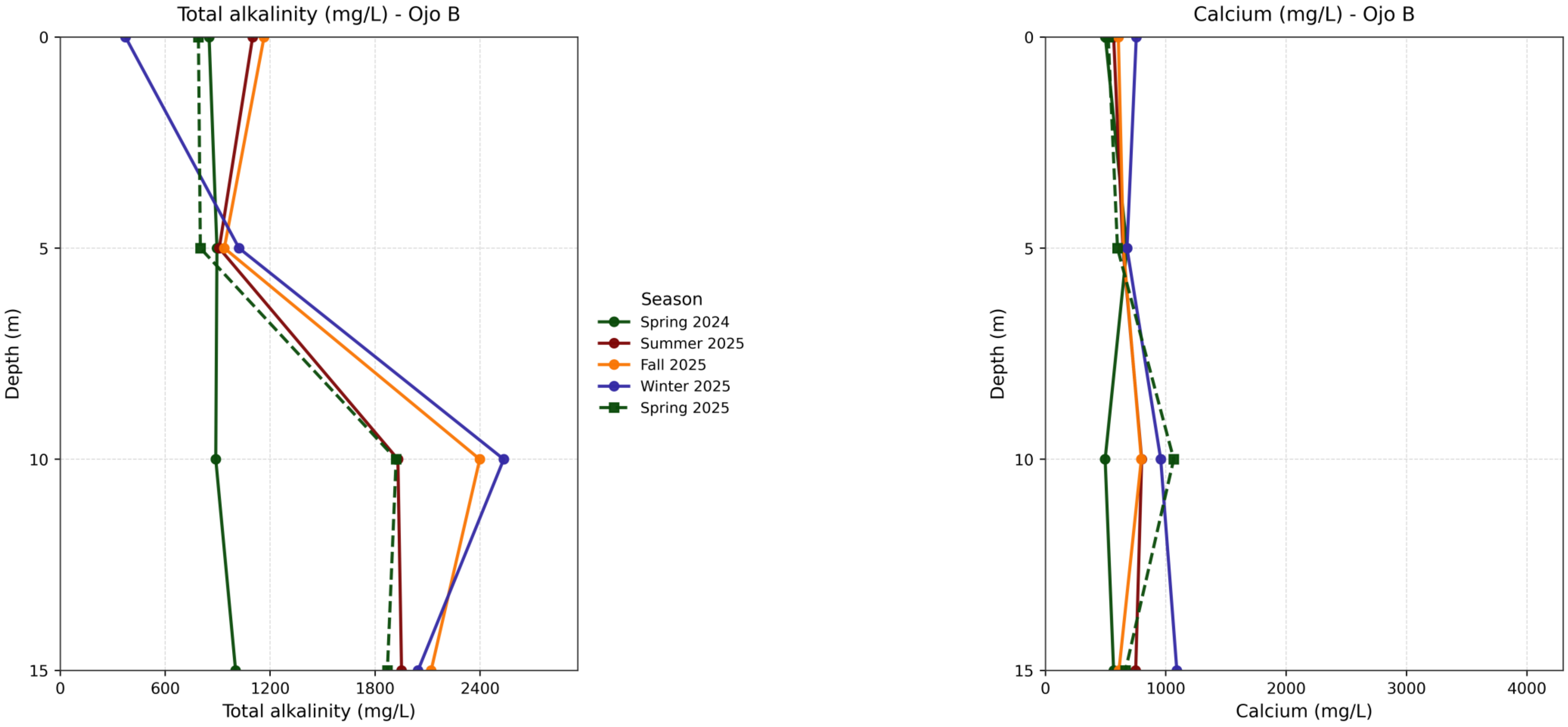
6.3. Technical Feasibility: Applied case







6.3. Technical Feasibility: Applied case



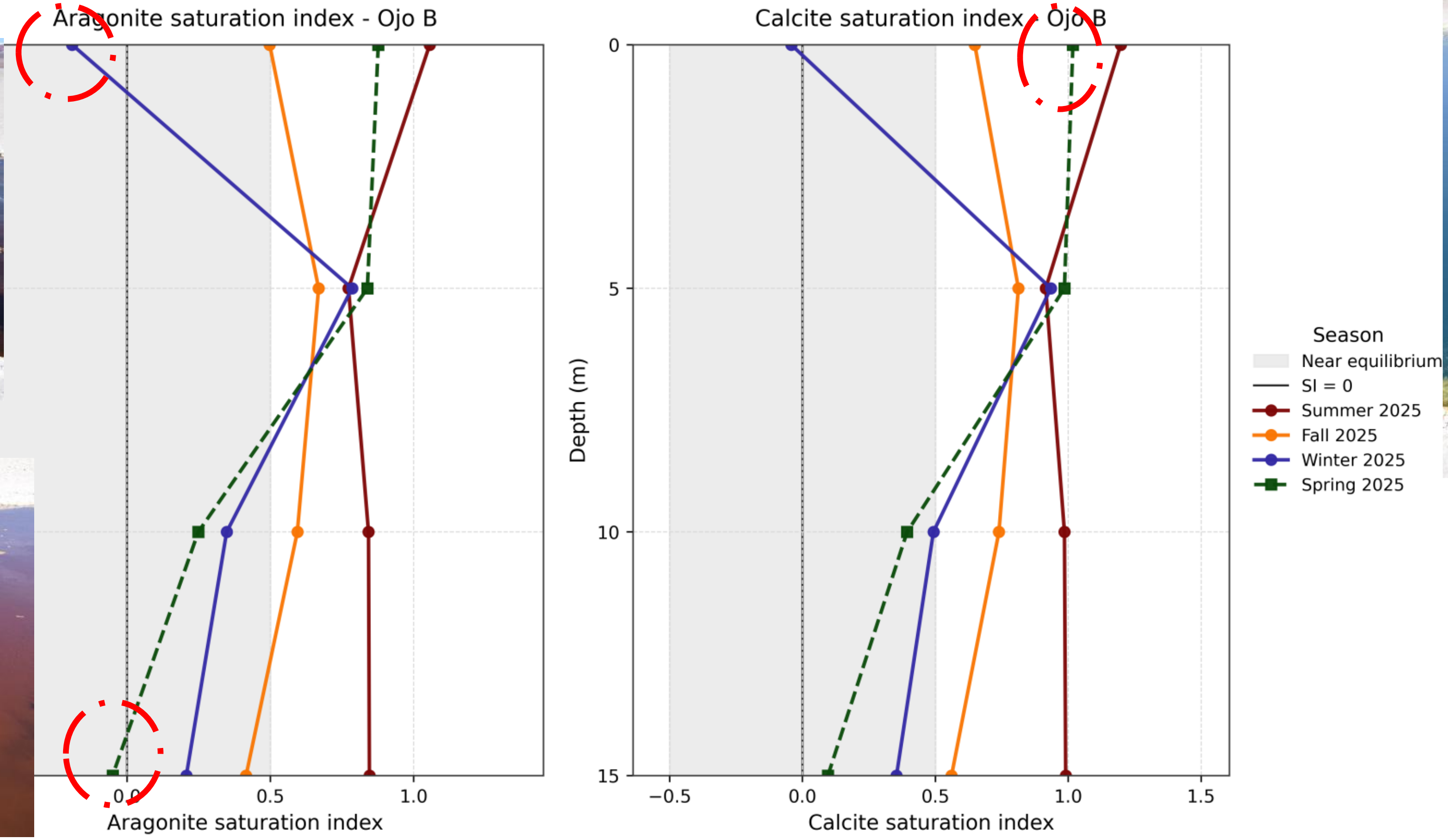
6.4. Applied case: SI calcite, SI aragonite

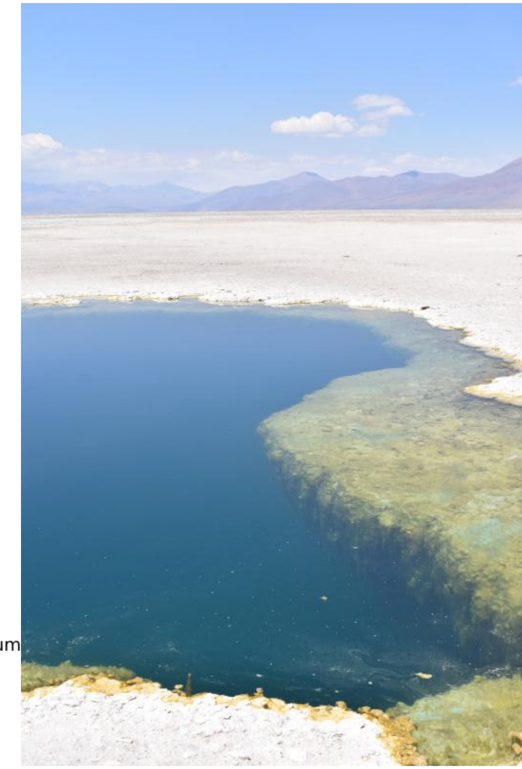
$$SI = log\left(\frac{IAP}{K_{sp}}\right)$$

IAP = ion activity product
Ksp = solubility product constant

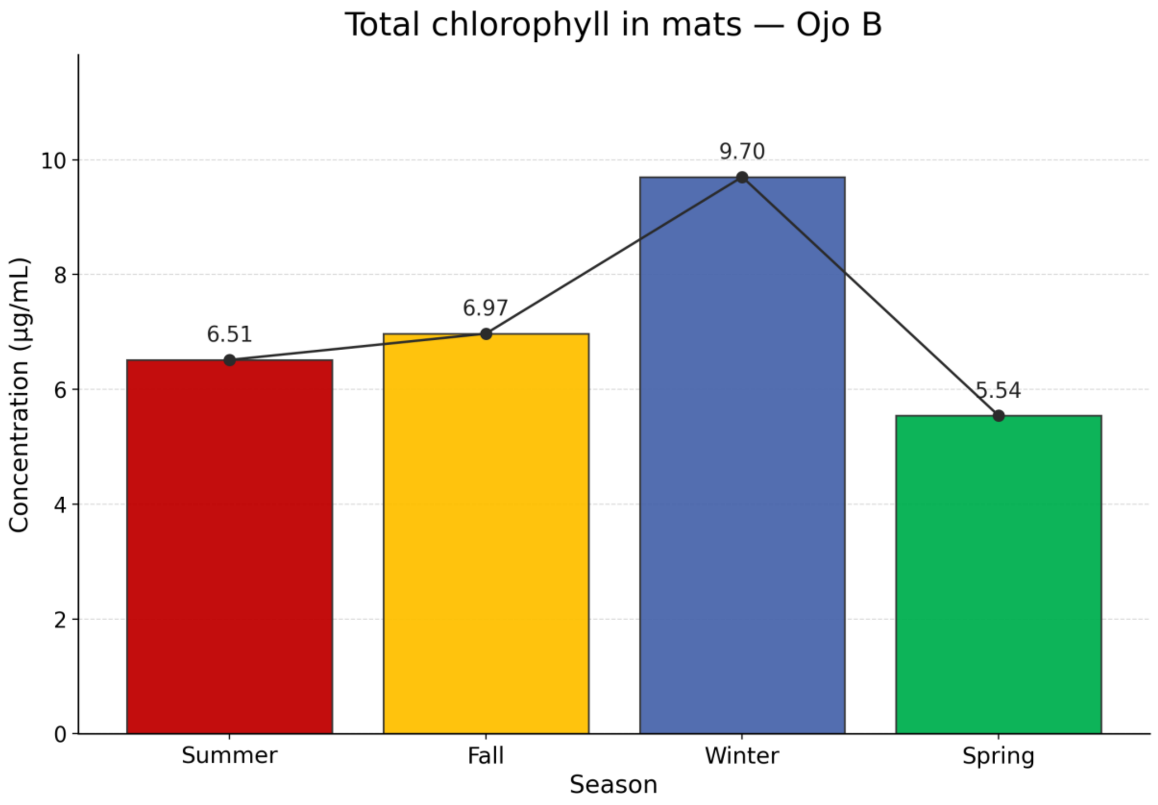
Saturation Index	Interpretation	Process favored
SI > 0	Supersaturation	Carbonate precipitation
SI = 0	Equilibrium	No net precipitation or dissolution
SI < 0	Undersaturation	Carbonate dissolution

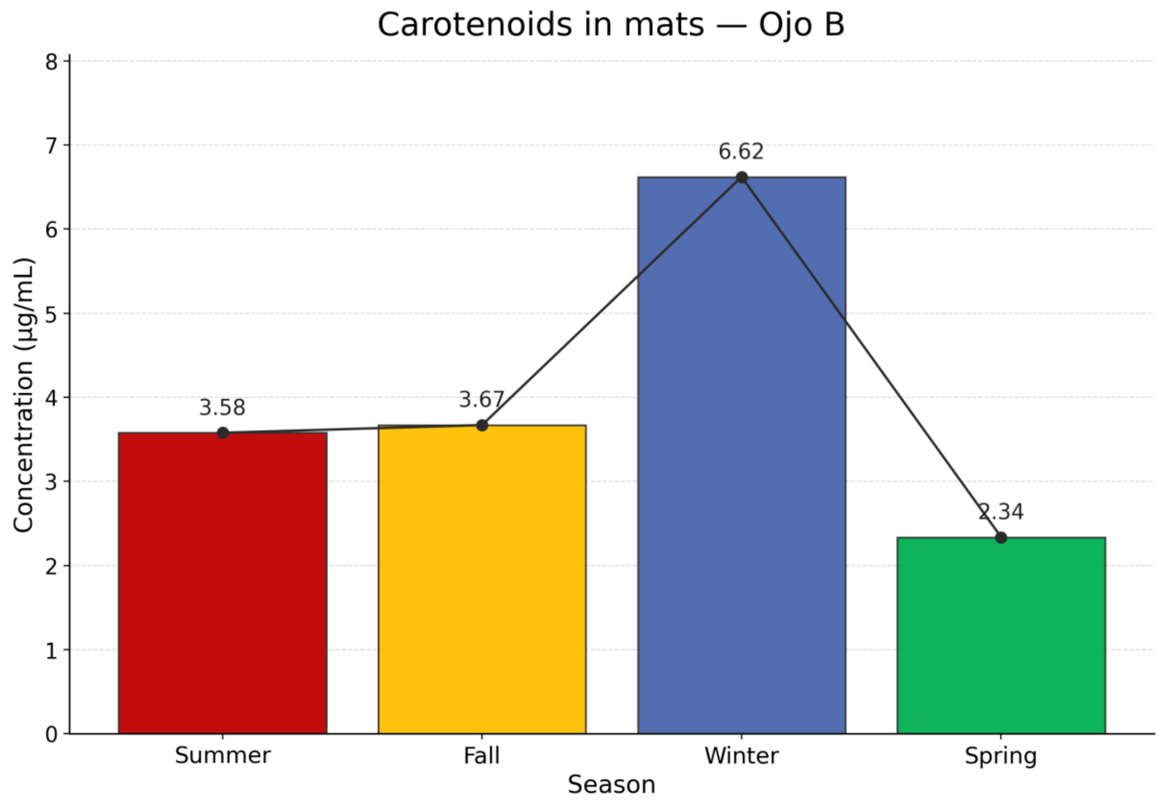
6.4. Applied case: SI calcite, SI aragonite

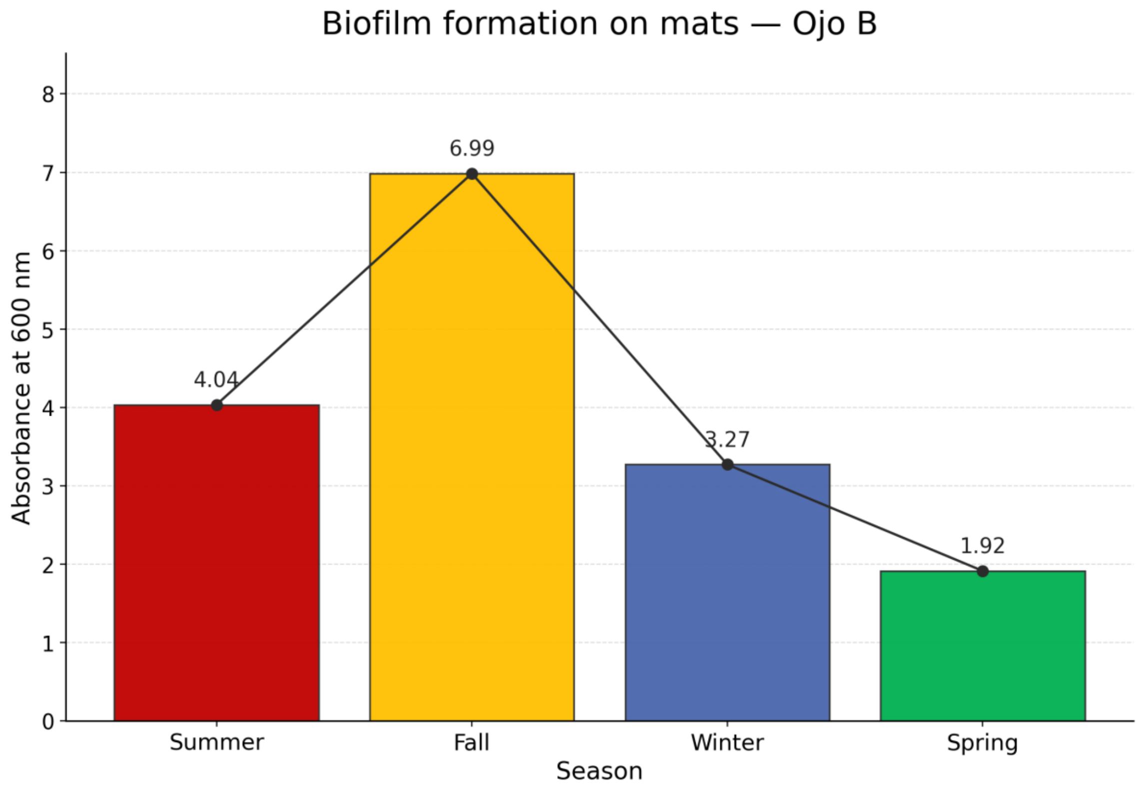


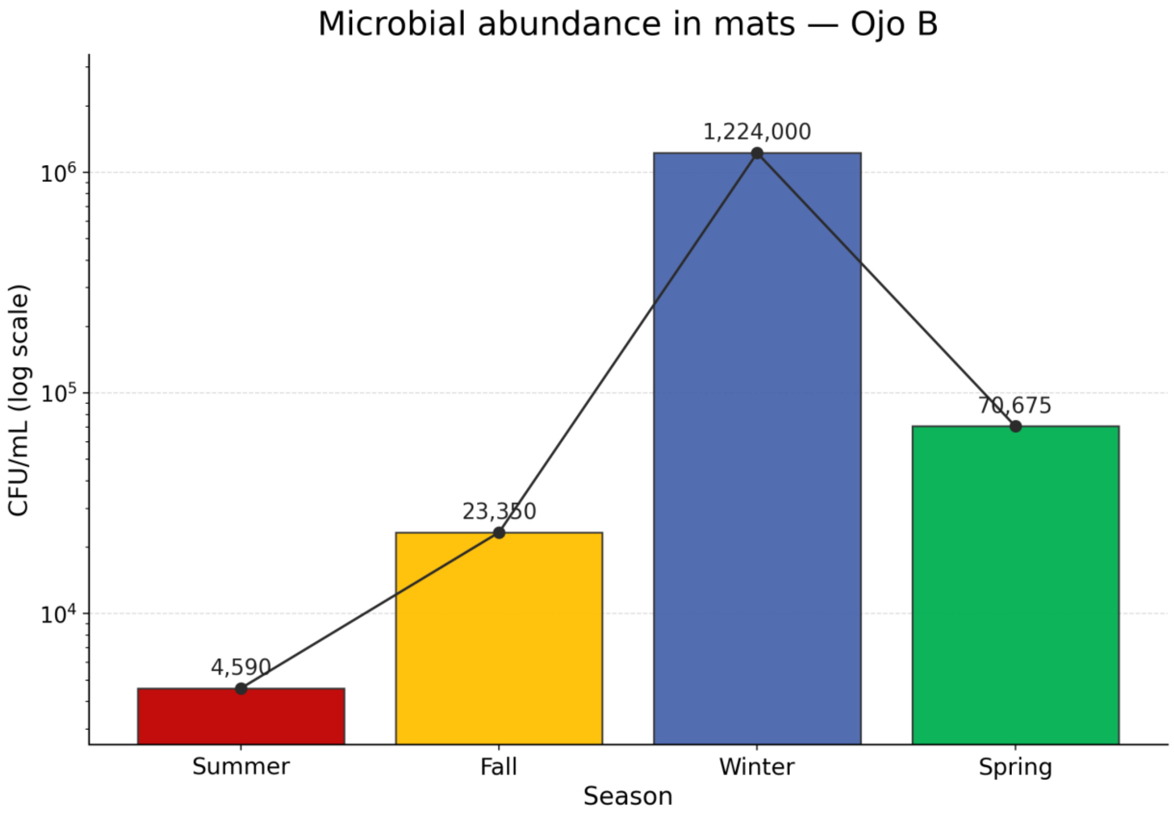


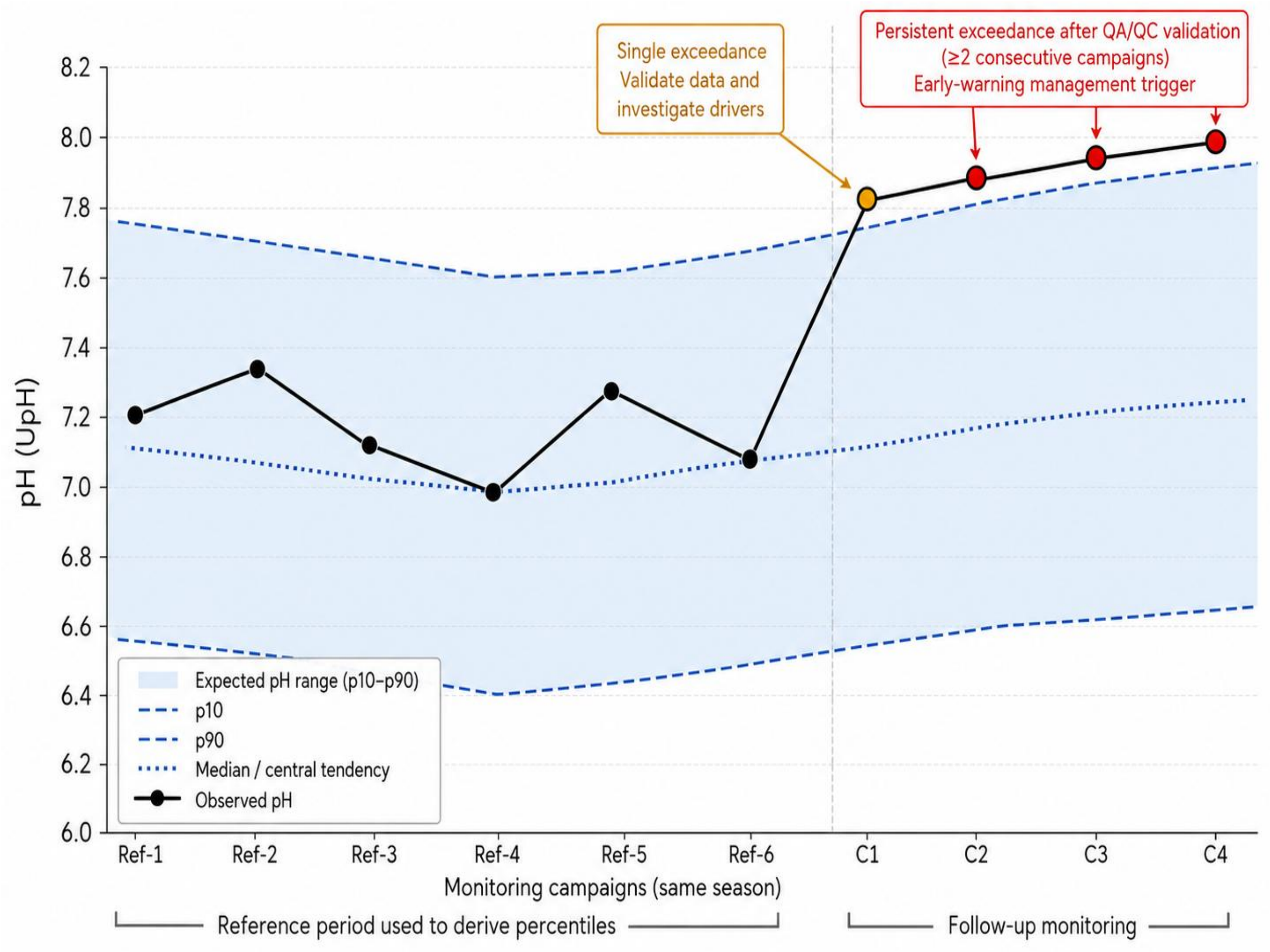
6.5. Biological Response






Biofilm formation on mats — Ojo B
Absorbance at 600 nm
0
1
2
3
4
5
6
7
8
4.04
6.99
3.27
1.92
Summer
Fall
Winter
Spring
Season


Microbial abundance in mats — Ojo B
CFU/mL (log scale)
10^4
10^5
10^6
4,590
23,350
1,224,000
70,675
Summer
Fall
Winter
Spring
Season



Single exceedance
Validate data and
investigate drivers
Persistent exceedance after QA/QC validation
(≥2 consecutive campaigns)
Early-warning management trigger
pH (UpH)
8.2
8.0
7.8
7.6
7.4
7.2
7.0
6.8
6.6
6.4
6.2
6.0
Expected pH range (p10–p90)
p10
p90
Median / central tendency
Observed pH
Ref-1
Ref-2
Ref-3
Ref-4
Ref-5
Ref-6
C1
C2
C3
C4
Monitoring campaigns (same season)
Reference period used to derive percentiles
Follow-up monitoring

7. Ecological Signals

- Dominance
- Evenness
- Sensitive Taxa
- Productivity Change
- Community Shift

8. Key Contributions to Environmental Assessment

Transparency: Converts complex monitoring data into traceable ecological meaning

Scientific credibility: Links monitoring evidence to process-based ecosystem interpretation

Early Warning: Detects functional change (Natural variability) before impacts become severe or irreversible

Adaptive management: Connects thresholds with proportional management responses/plans

Public engagement: more informed dialogue with communities, regulators, and decision makers

Countering misinformation: reduce misunderstanding and **build confidence** in environmental assessment

Better decisions: Makes BIA more predictive, communicable and actionable

Let’s continue the conversation!

Message me your questions or comments in the IAIA26 app.

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