Using Machine Learning to evaluate ecosystem connectivity and biodiversity in marine ecosystems

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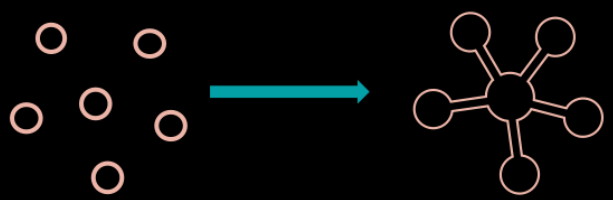
Ecoregions identification and Connectivity inference: the problem



- Management and species conservation, invasive species dispersal, MPAs, …
- CHALLENGING: **large-scale dispersal by ocean currents**, **data paucity** off-shore
- **Several approaches** (Taxonomic, Ecological, Taxo-Ecol.) , **shared limitation**: ocean fluid dynamics is not explicitly accounted for.

- **Connectivity-based: a necessary approach**

effects caused by oceanic currents on larval dispersal and on connection or isolation of ecoregions are accounted for.

Challenge in the Coral Triangle

Coral reefs have experienced severe mass bleaching as temperatures soared in the past few decades.

Anthropogenic stressors - climate change, pollution, overfishing … - threaten ocean biodiversity and ecosystem functioning

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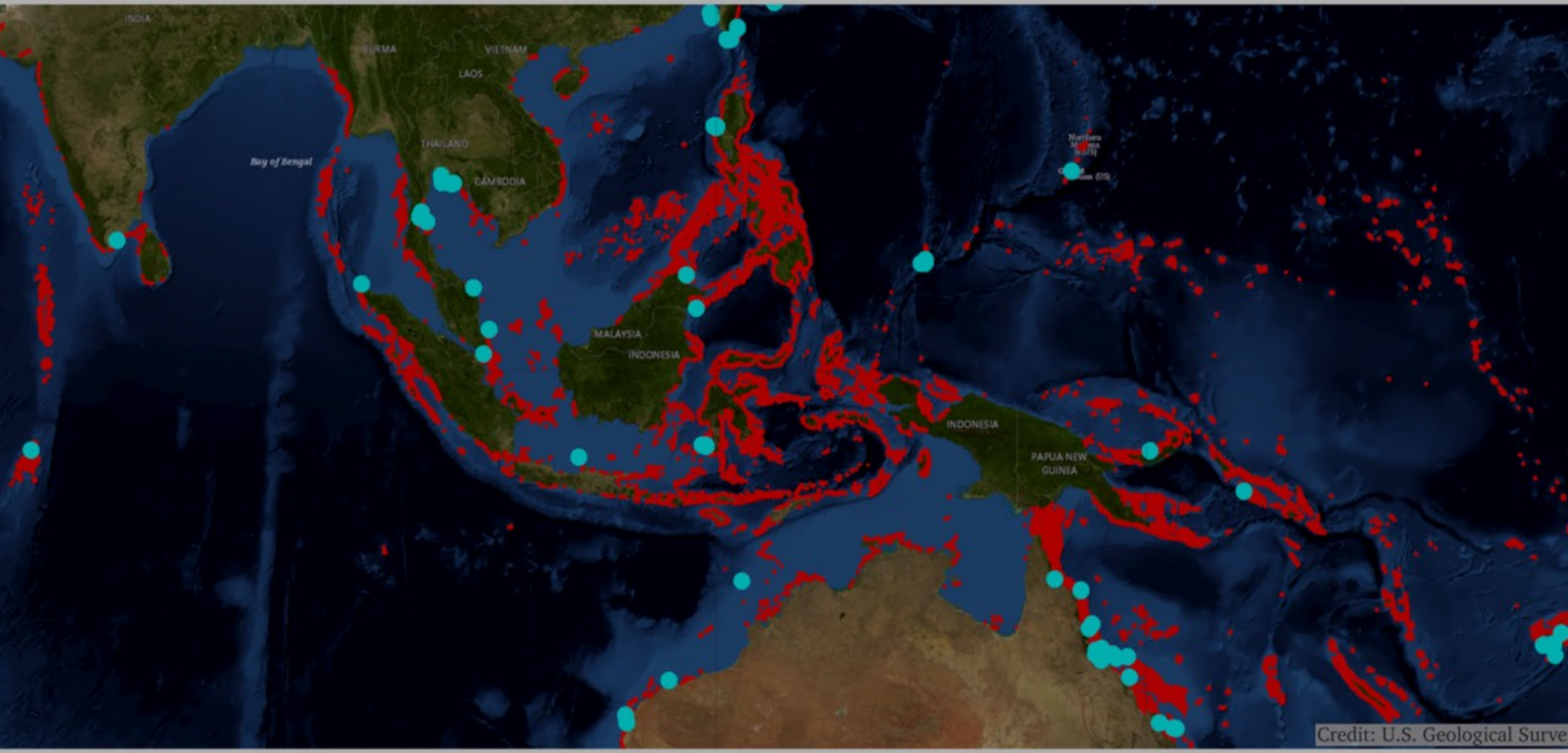
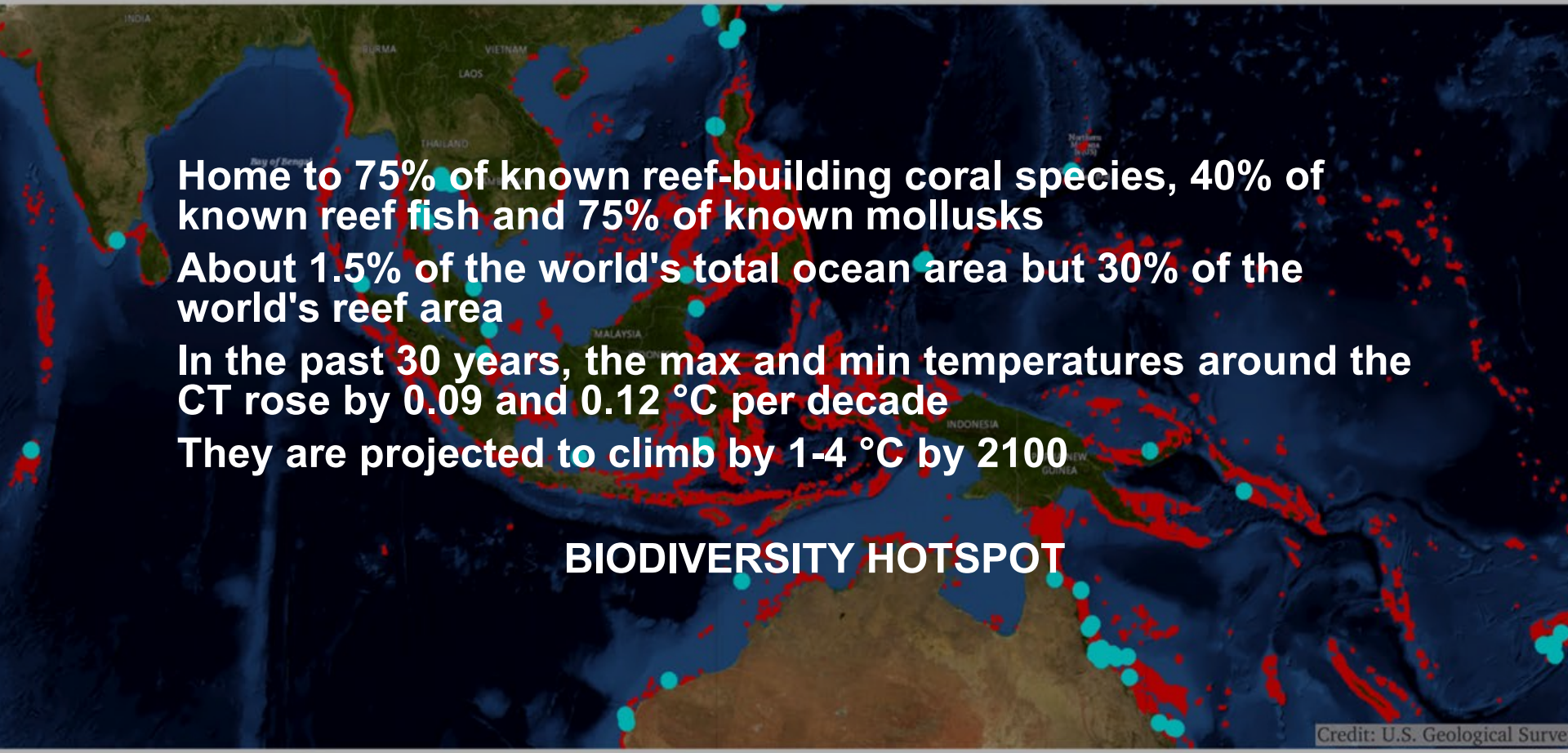
75% corals are nearing their collapse. Their survival is an urgent priority (SDG14)

Corals are foundational species. If corals disappear, biodiversity will reduce greatly together with the livelihoods for > 120 million people in the **coral triangle** region alone


LEGEND
Coral Triangle Scientific Area
Coral Triangle Initiative
PHILIPPINES
BRUNEI
MALAYSIA
INDONESIA
PAPUA NEW GUINEA
TIMOR-LESTE
SOLOMON ISLANDS
AUSTRALIA


INDIA
BURMA
VIETNAM
LAOS
THAILAND
Bay of Bengal
CAMBODIA
MALAYSIA
INDONESIA
INDONESIA
PAPUA NEW GUINEA
Credit: U.S. Geological Surve



Home to 75% of known reef-building coral species, 40% of known reef fish and 75% of known mollusks

About 1.5% of the world's total ocean area but 30% of the world's reef area

In the past 30 years, the max and min temperatures around the CT rose by 0.09 and 0.12 °C per decade

They are projected to climb by 1-4 °C by 2100

BIODIVERSITY HOTSPOT

Scientific Problem

Hypothesis: Large-scale larval transport and recruitment among distant reefs is key to biodiversity

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We can test it by

1. defining distinct domains that demark unique assemblages of species → **ECOREGIONALIZATION**

2. measuring **CONNECTIVITY** → the degree and directionality of propagules, larvae and juvenile dispersal among ecoregions

Ecoregionalization

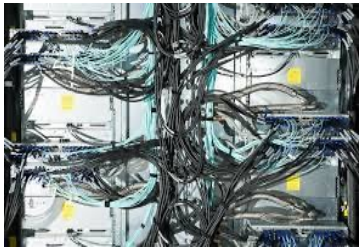
The identification of relatively homogenous areas in their ecosystem.

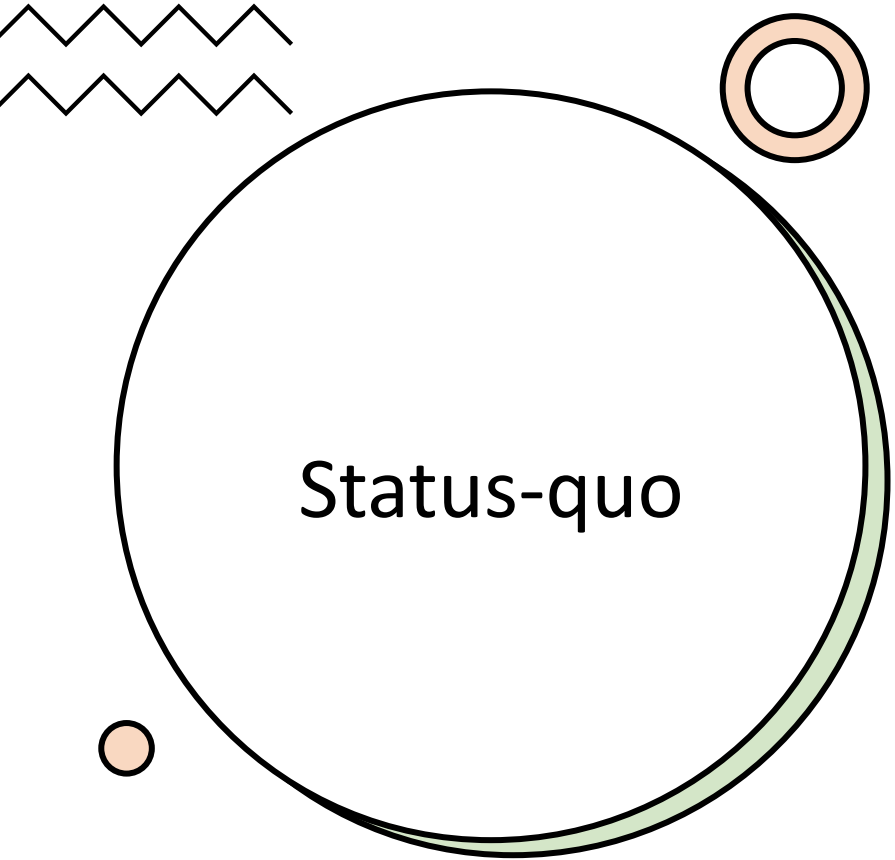
Key to environmental management and species conservation

4 approaches available:

- **taxonomic:** relies on species distributions and look for similar aggregations of species
- **ecological:** identifies areas by biogeochemical or physical features

- **taxo-ecological**: mix of the two above
- **connectivity-based:** quantifies the degree and directionality of propagules, larvae and juvenile dispersal (dynamical view)





Need for an ecoregionalization method that informs about ecosystem connectivity **at basin scales over decadal time scales**, with continuous spatial coverage and a meaningful resolution for ecosystem management purposes

- **Complex network tool** to identify **spatially contiguous** and **possibly overlapping** domains and their functional **connection**

δ-MAPS*

- **Domain:** spatially contiguous region with all grid cells **participating in the same dynamic functions**, and **sharing** a highly **correlated temporal activity**

- **Links between domains**: **functional network.**
  A weight is assigned to each edge to reflect the magnitude of interaction between any two domains

* *Fountalis, I., Dovrolis, C., Bracco, A., Dilkina, B. & Keilholz, S. **δ**-MAPS: from spatio-temporal data to a weighted and lagged network between functional domains. Appl. Netw. Sci. 3, 21 (2018).*

δ-MAPS

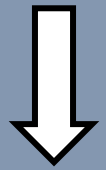
Machine learning algorithm to identify *domains* and their structural connection in any given field

Domain = spatially contiguous region with all cells participating in the same dynamic functions, with a highly correlated temporal activity

Links between domains define a functional network with a weight assigned to each edge to reflect the magnitude of interaction between any two domains

The sum of the absolute weights of all edges quantifies the strength of a domain

δ-Maps on SST_a



Connectivity and Ecoregions information

- SST anomalies are strongly coupled with the underlying horizontal oceanic currents: **there are dynamical links that relate SSTa to sea surface height (SSHa)** on spatial scales (mesoscale) and frequencies (interannual) pertinent to ecological dynamics (Leeuwenburgh and Stammer, JPO, 2001, https://doi.org/10.1175/1520-0485(2001)031<2340:TEOOCO>2.0.CO;2)

- Modulate habitability directly, as well as indirectly (solubility of oxygen and CO2)

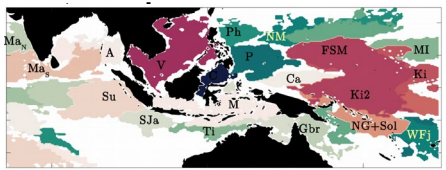
- Observed through satellites

Conceptual framework

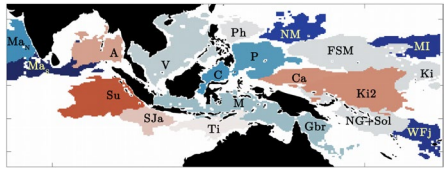
- Encode SSTa relationships and links

SSTa data

- Generate dynamically-aggregated ecoregions and connectivity



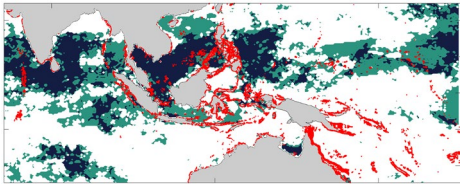
- Rank biodiversity role via centrality score



- Identify high\low risk reefs

Additional information on bleaching

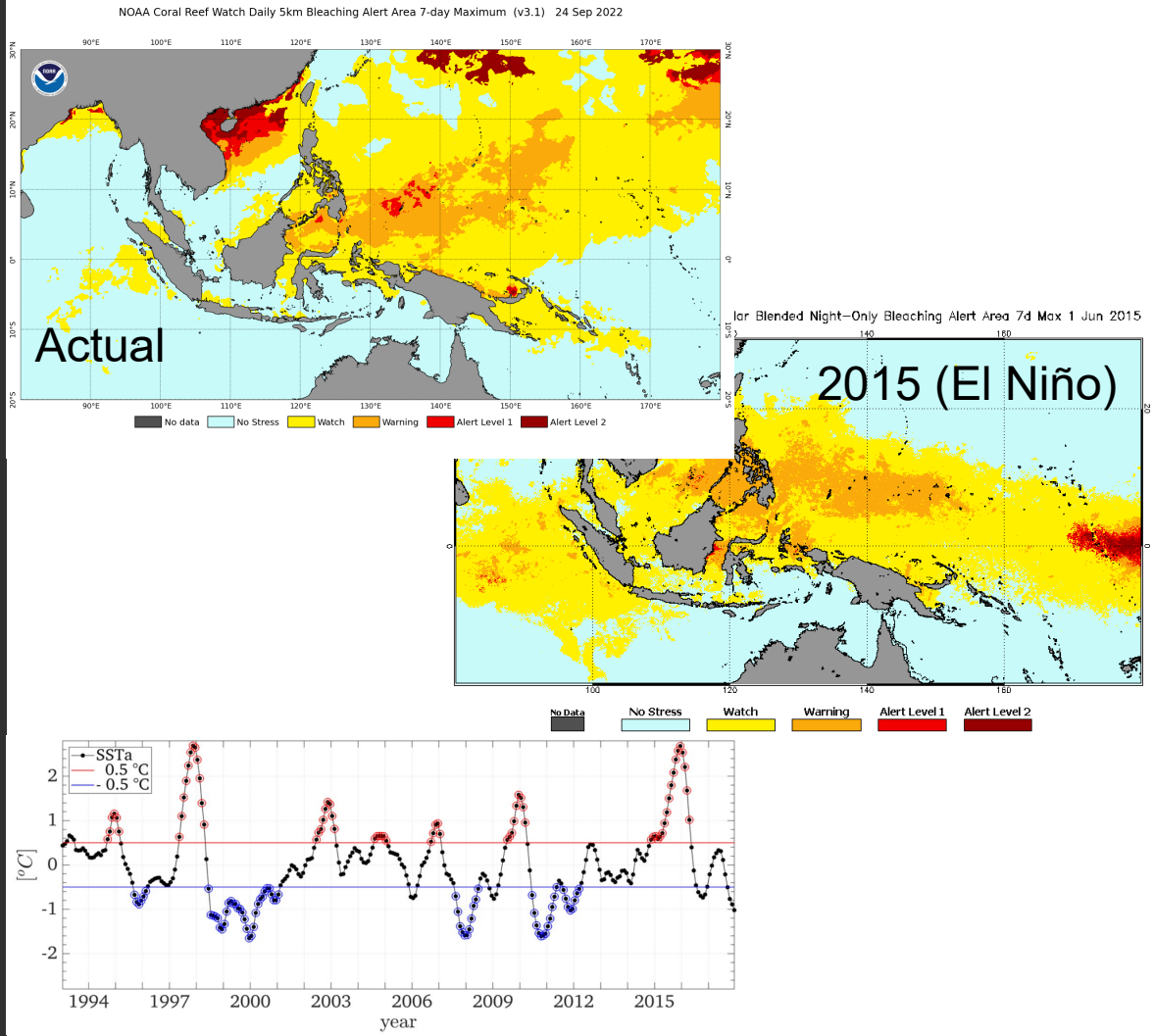
input



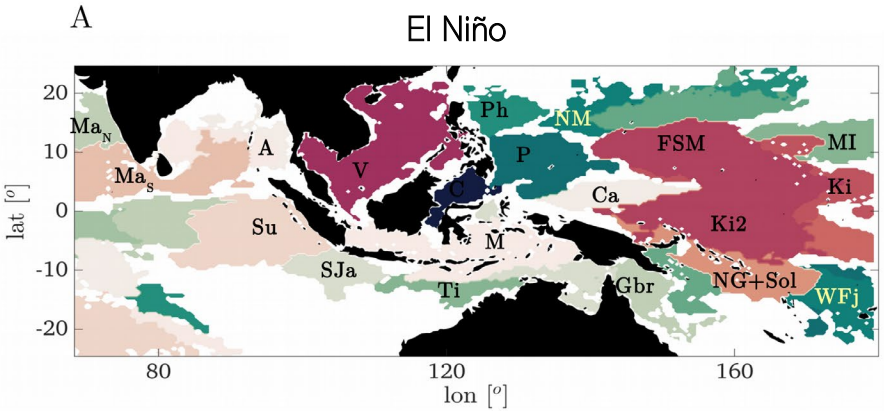
- Monitoring of highly-ranked reefs

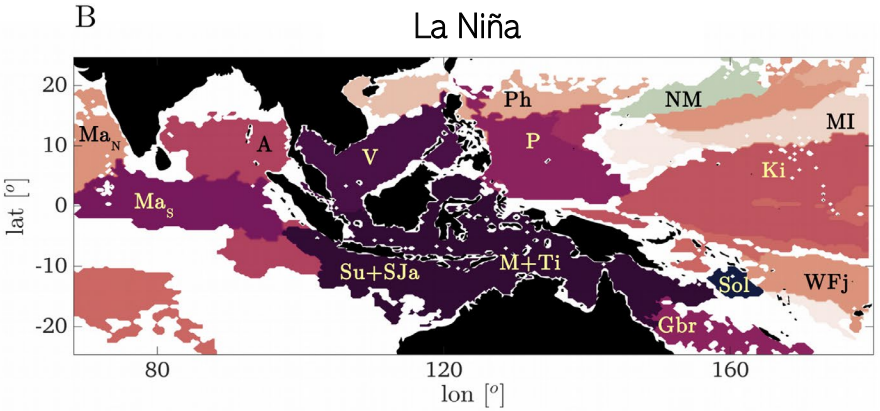
- Active\Passive reef restoration strategies

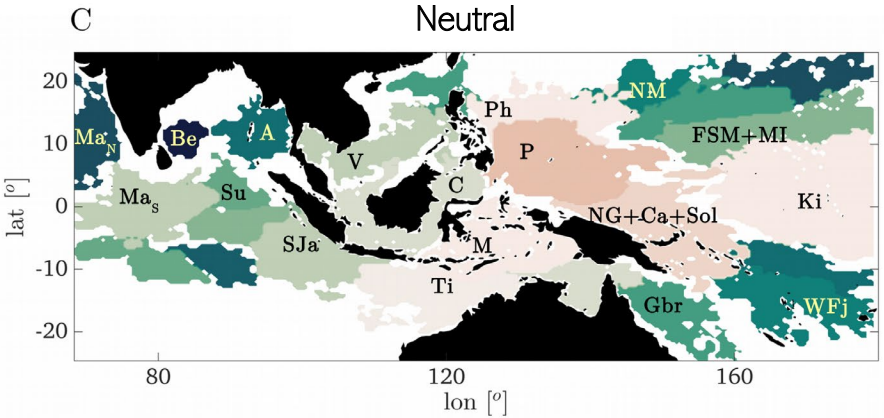
One more player in the CT: ENSO

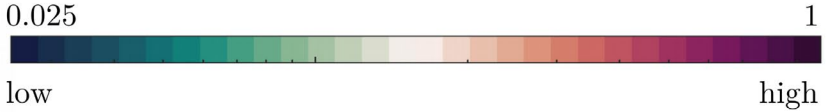


Ecoregions and normalized strengths



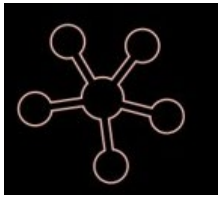






Connectivity-modulated biodiversity enhancement (Page Rank Centrality)

Network analysis: each ecoregion is a point of arrival of different connections



- **Hip: a domain has a higher connectivity-mediated biodiversity if it is reached by**

  (1) a lot of links from different ecoregions (which may or may not be individually biodiverse), or\and

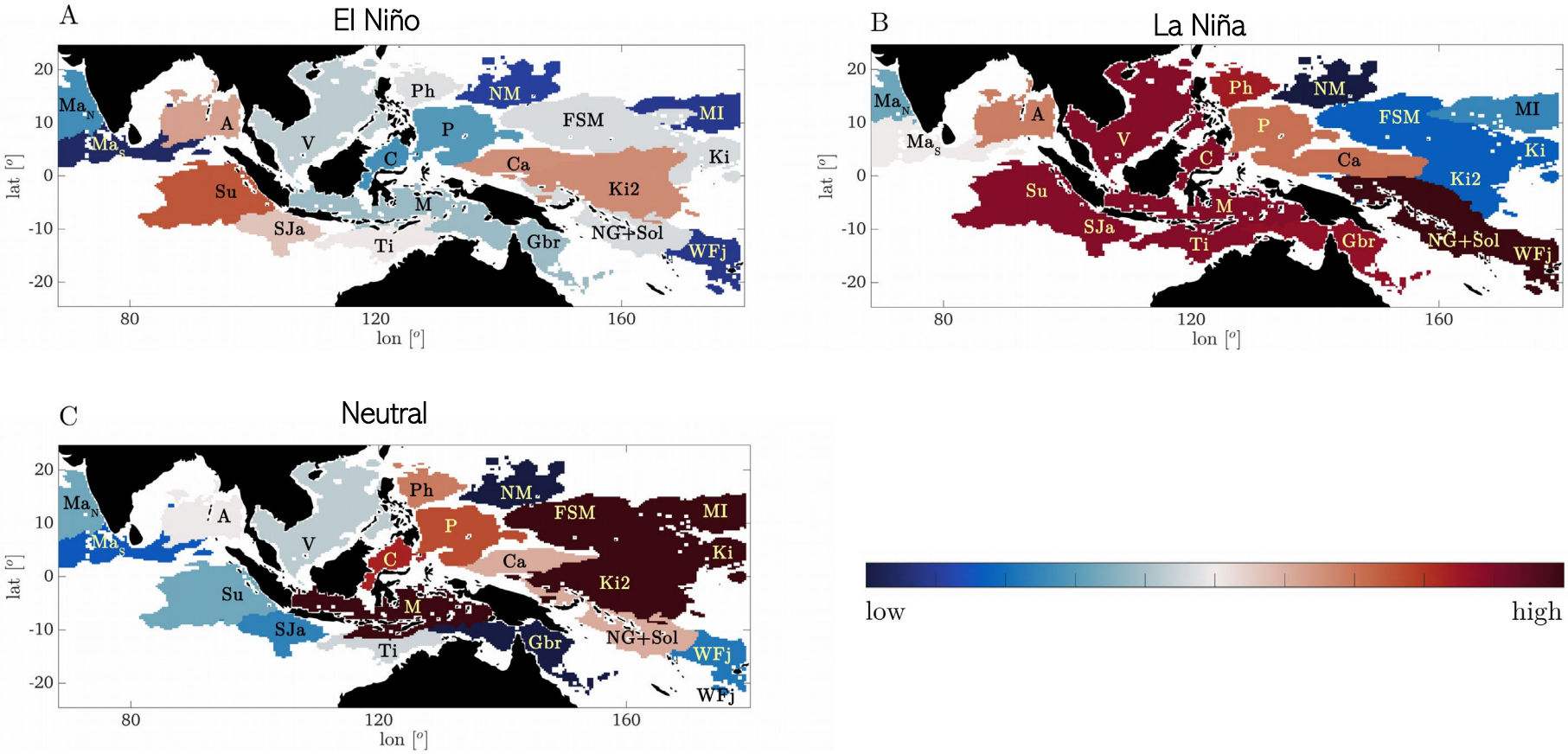
  (2) one\a few other highly-biodiverse ecoregion(s)

Page Rank Centrality (PRC): network-science algorithm that ranks websites according to their "popularity level".

(Roughly: it quantifies the likelihood to reach a webpage by randomly following the links on the internet. It results in high centrality computed for sites reached by a few others with high centrality scores or many low-centrality ones)

For each ENSO phase, the PRC in each domain is computed: estimate for the connectivity role in maintaining or enhancing the local biodiversity.

Connectivity-modulated biodiversity enhancement (Page Rank Centrality)



Connectivity-modulated bleaching resilience (CMBR)

- **Coral resilience and recovery capacity after widespread bleaching relies on external larval supply.**

- **Recovery potential estimated accounting for the combined effect of connectivity and time-cumulative bleaching**

- **"Degree-Heating Week" (DHW)** from The NOAA Coral Reef Watch (CRW) daily global 5km satellite product: Accumulation of the bleaching heat stress during the most recent 12-week period.

No-stress to possible bleaching **0 < DHW < 4** ⟹ **assigned class value: 2**

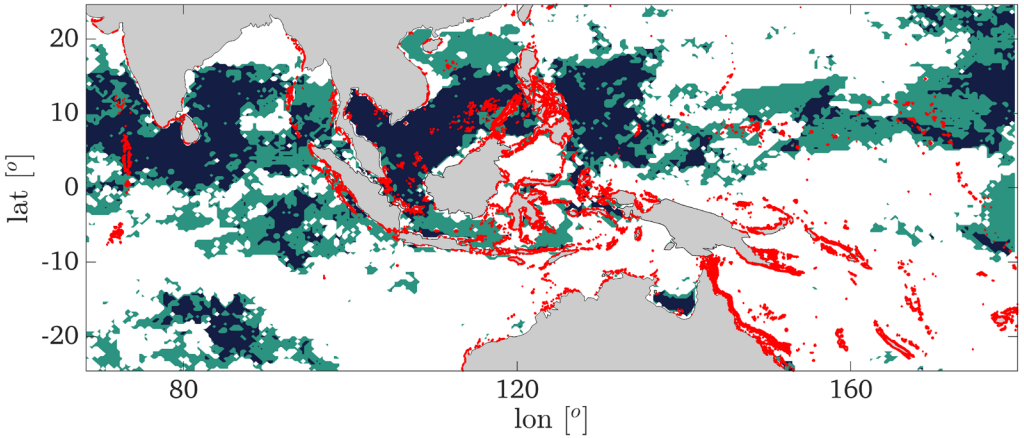
Significant bleaching **4 ≤ DHW < 8** ⟹ **assigned class value: 3**

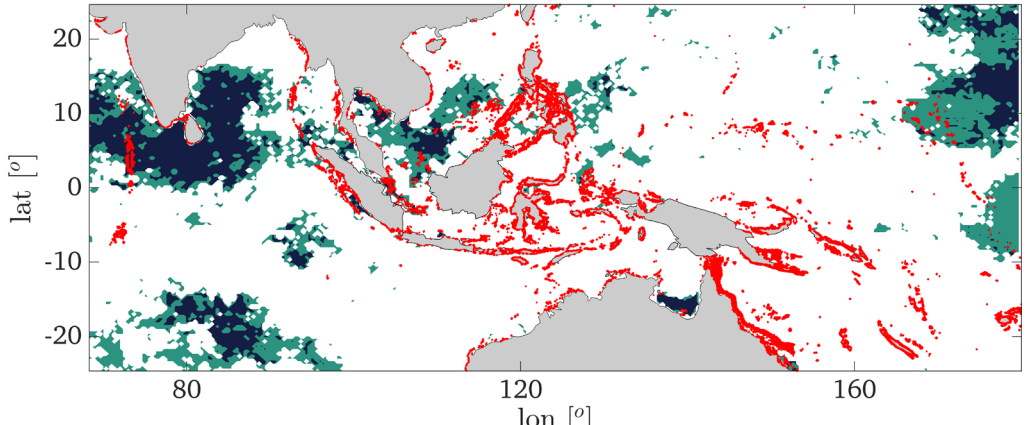
Severe bleaching and mortality **DHW ≥ 8** ⟹ **assigned class value: 4**

In each ENSO phase: CMBR = time cum. DHW / strength of positive connections with cc > 0.35. Put "1" at each pixel where CMBR < thr1 or DHW < thr2 (thr1, thr2: 25th prctiles in Neutral years). 0 elsewhere.

Sum the obtained three matrices = Recovery Potential Score (RPS)

Reefs Recovery Potential Score (RPS) over 1993-2017



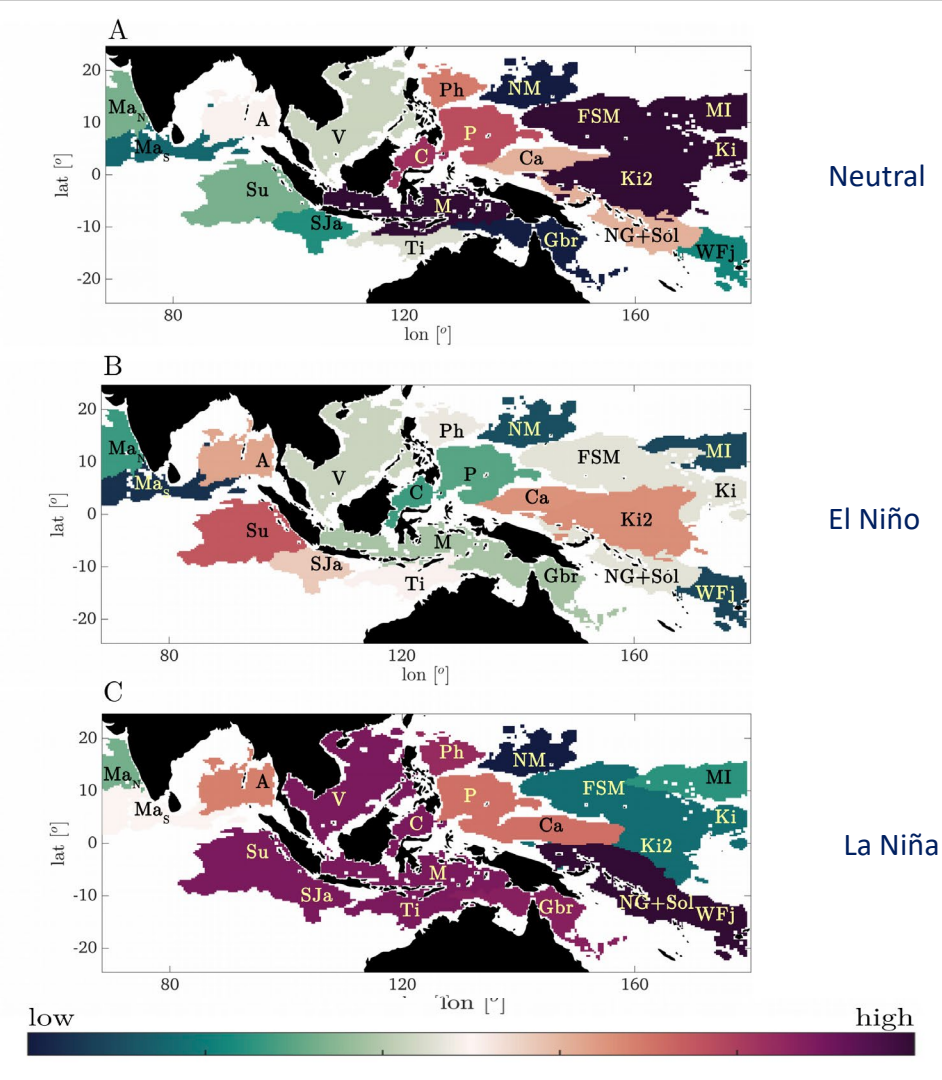


RPS = 3

RPS = 2

Accounting for connectivity

Only bleaching information



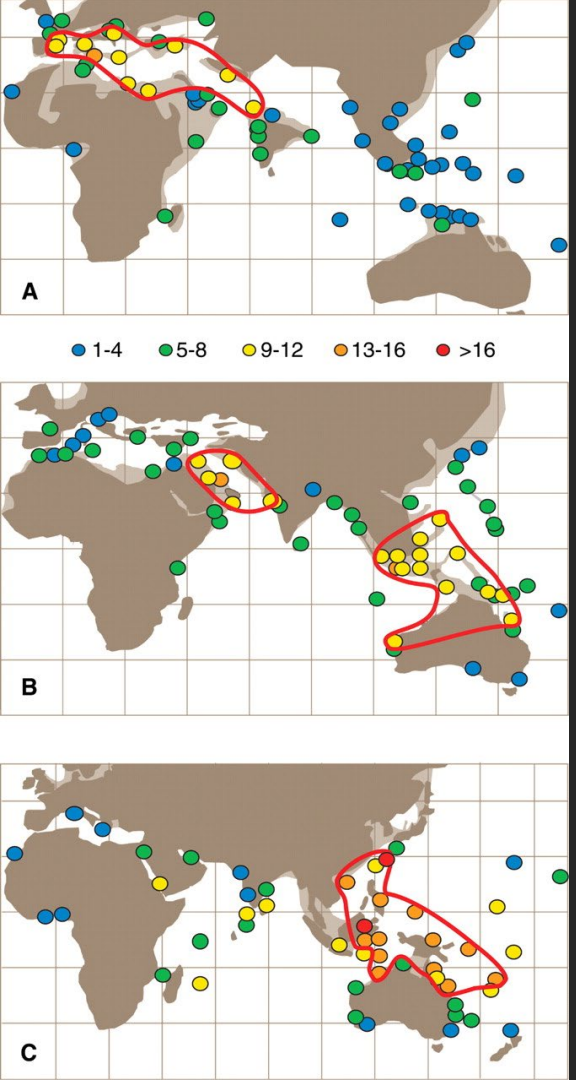
Neutral

El Niño

La Niña

ENSO variability modulates biodiversity.
The strengthening of ENSO through time likely created the hotspot we know today.

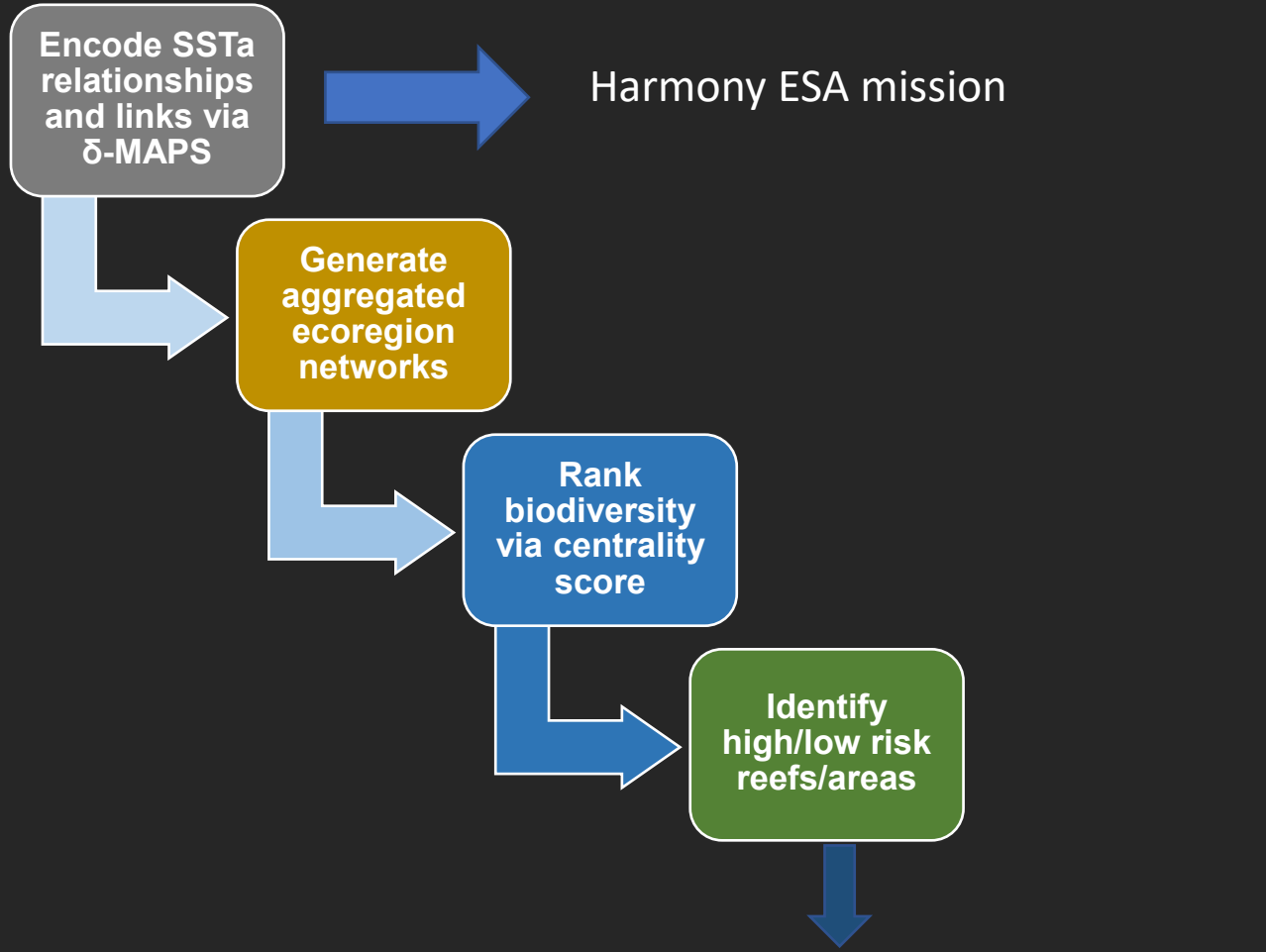
Biodiversity in the CT is dynamical and changes over space and time. We can now build upon this variability



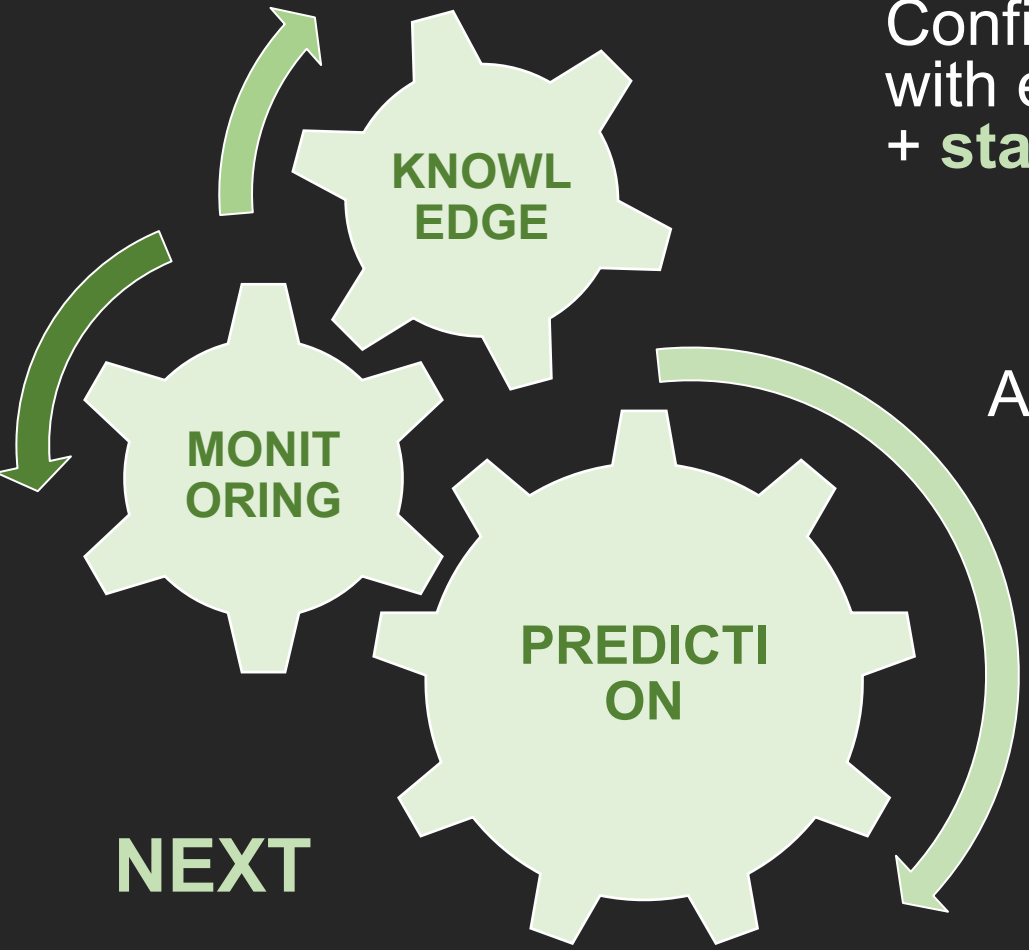
Generic α-diversity of large benthic foraminifera in (**A**) the late Middle Eocene (42 to 39 Ma), (**B**) the Early Miocene (23 to 16 Ma), and (**C**) the Recent

[Renema et al. 2008]

ENSO-like variability has been documented as early as at the Miocene-Pliocene transition [Thomas Weiss et al 2017]



- Monitoring of highly ranked reefs
- Passive and active reef restoration strategies



NEXT

Confirm inferred connectivity with ecological / taxonomic data + **stakeholder engagement**

Autonomous **monitoring** of reefs identified as conservation priorities

ENSO changes **in the future**