# Challenges and Opportunities in Operationalizing Coupled Human and Natural Systems Research in the Chesapeake Bay Watershed


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HESI Human-Environment Systems Interactions, Impacts & Intelligence

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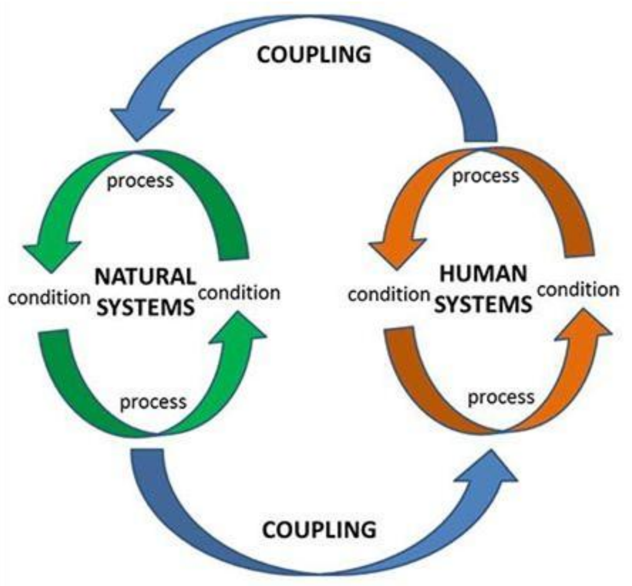
# Conceptual foundations of coupled systems thinking

CHANS, CAS, SES, and SETS

# <u>Some</u> common frameworks

## for reasoning about human-environment interactions



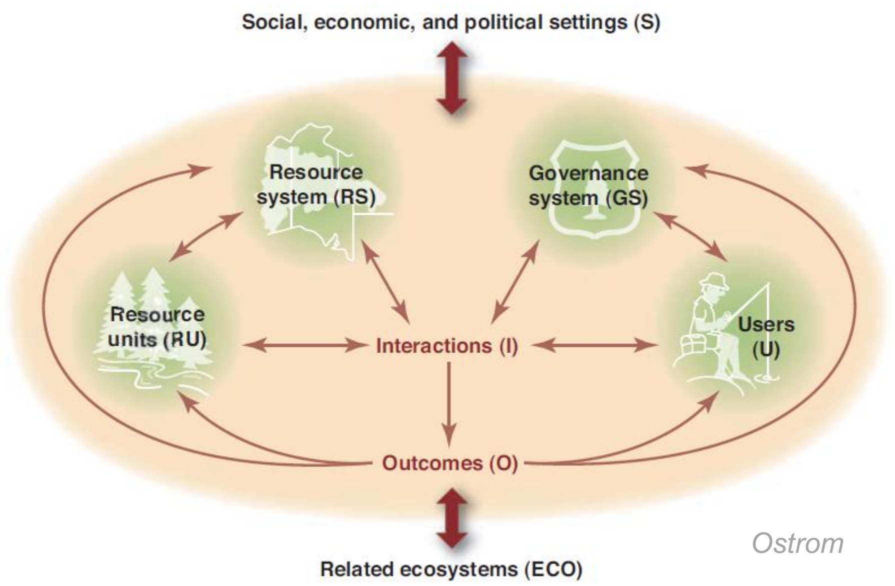
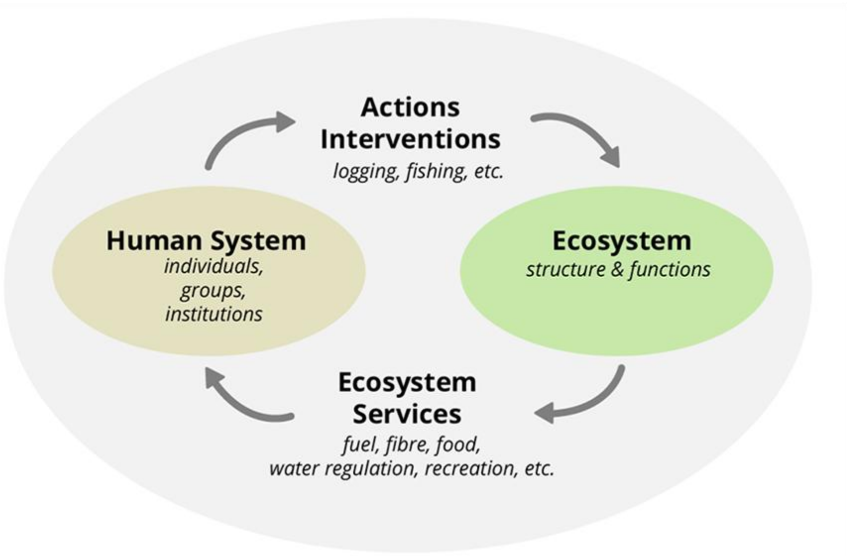




**Fig. 1.** The core subsystems in a framework for analyzing social-ecological systems.




*Social-ecological System*

*https://saras-institute.org/social-ecological-systems/*

**Human activity is NOT separate from ecosystem**

**Global change *results from <u>social</u> processes***

Problems transcend ***traditional disciplines***

# CHANS, CAS, and SES:

## Acronym soup of convergent traditions

### Complex Adaptive Systems (CAS)

*Holland 1995*

Systems where autonomous agents interact, adapt, and produce emergent outcomes that cannot be predicted from individual behavior alone

▼ *applied as* ▼

### Coupled Human and Natural Systems (CHANS)

*Liu et al. 2007*

Emphasizes **reciprocal interactions** and feedbacks between human activities and natural processes across scales. Includes economic, cultural, and institutional dimensions

### Social-Ecological Systems (SES)

*Ostrom 2009; Preiser et al. 2018*

Emphasizes governance, institutional design, and collective action in **managing shared resources**. Focuses on: resilience, adaptation, and regime shifts

***Core idea:*** *human and natural systems are reciprocally coupled through feedback loops across spatial and temporal scales*

# Five key properties of CHANS

## Nonlinearity

Small changes, disproportionate effects

## Feedback loops

Outcomes reshape conditions that produced them

## Heterogeneity

Responses vary across actors, places, and scales

## Adaptation & memory

Actors learn and change behavior over time

## Emergence

System-level patterns arise from interactions of individuals

# Nonlinearity

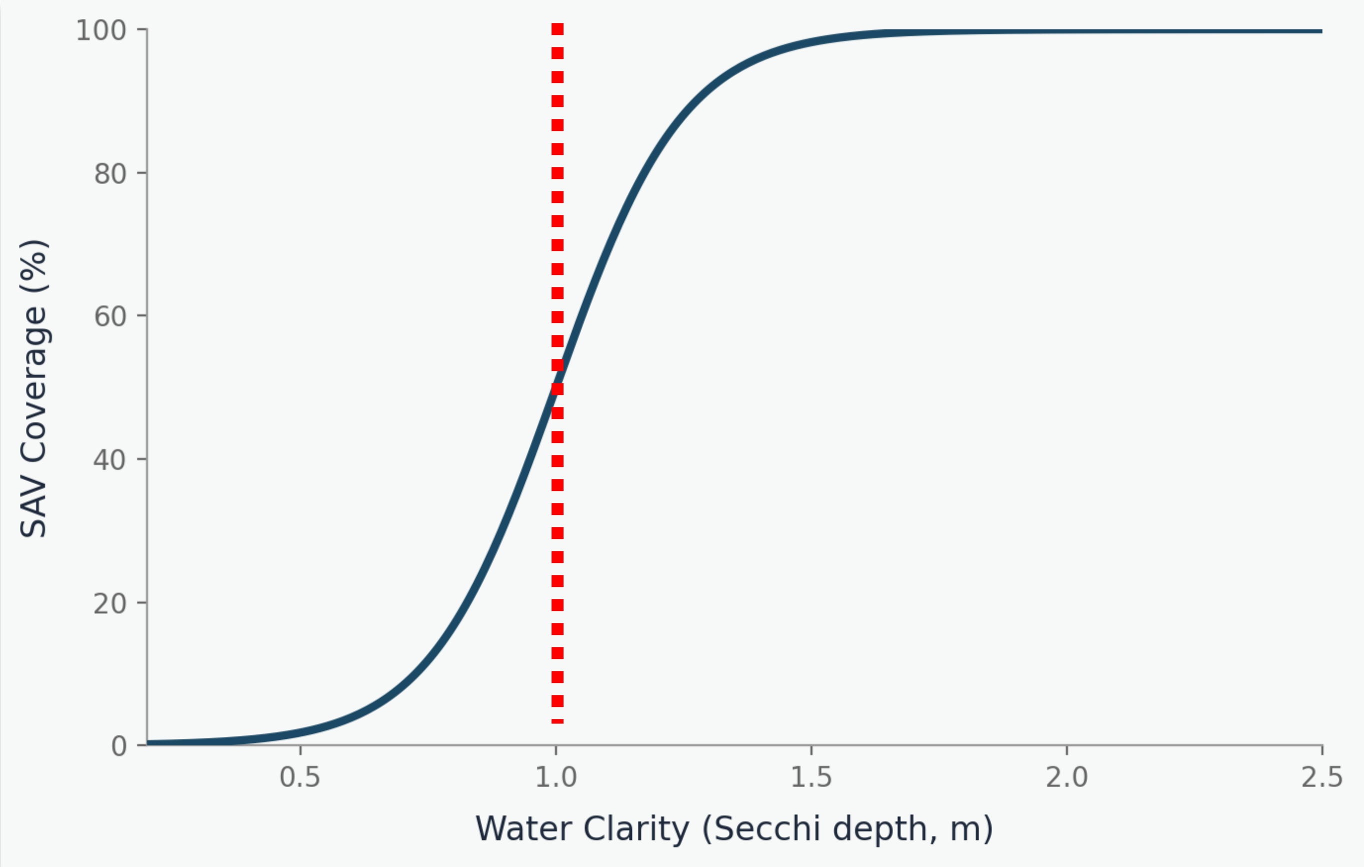
- Small changes in drivers can produce disproportionately large (or unexpectedly small) effects on system outcomes
- **Thresholds and tipping points**: relationship between cause and effect is rarely proportional

## IN THE CESR REPORT: TIPPING POINTS AND MUTED RESPONSE

- Nutrient load reductions have **not** produced proportional improvements in dissolved oxygen, particularly in deep-channel habitats
- **Tipping points** have been identified in subsystems (e.g., SAV recovery can accelerate nonlinearly once water clarity crosses a threshold, but gradual improvement below threshold can appear as "no response”)

# Nonlinearity

- Small changes in drivers can produce disproportionately large (or unexpectedly small) effects on system outcomes
- **Thresholds and tipping points**: relationship between cause and effect is rarely proportional



# Feedback Loops

Outcomes of system processes feed back to reshape the conditions that produced them

- **Positive** (reinforcing) feedbacks amplify change
- **Negative** (balancing) feedbacks dampen it

## IN THE CBW: FEEDBACK LOOPS

**Positive feedback example:**

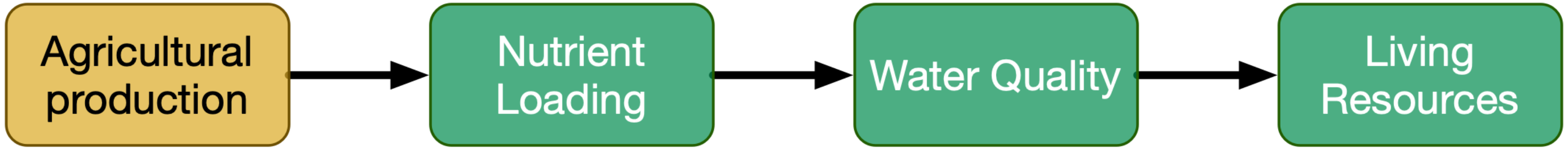
- Early adopters implement visible practices and see results →
- Visible improvement builds trust, which increases participation

**Negative feedback example (CESR):**

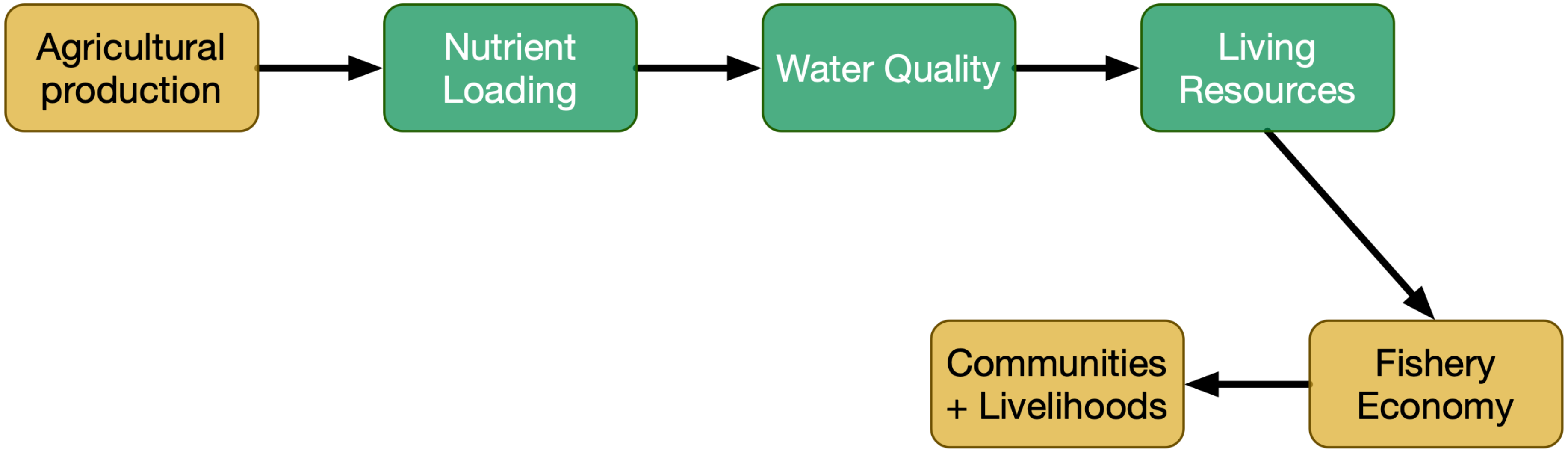
- If (or when) monitoring shows limited water quality response despite implementation effort →
- Political support for continued investment may erode: an "effort without visible reward" dynamic

# The familiar forward path

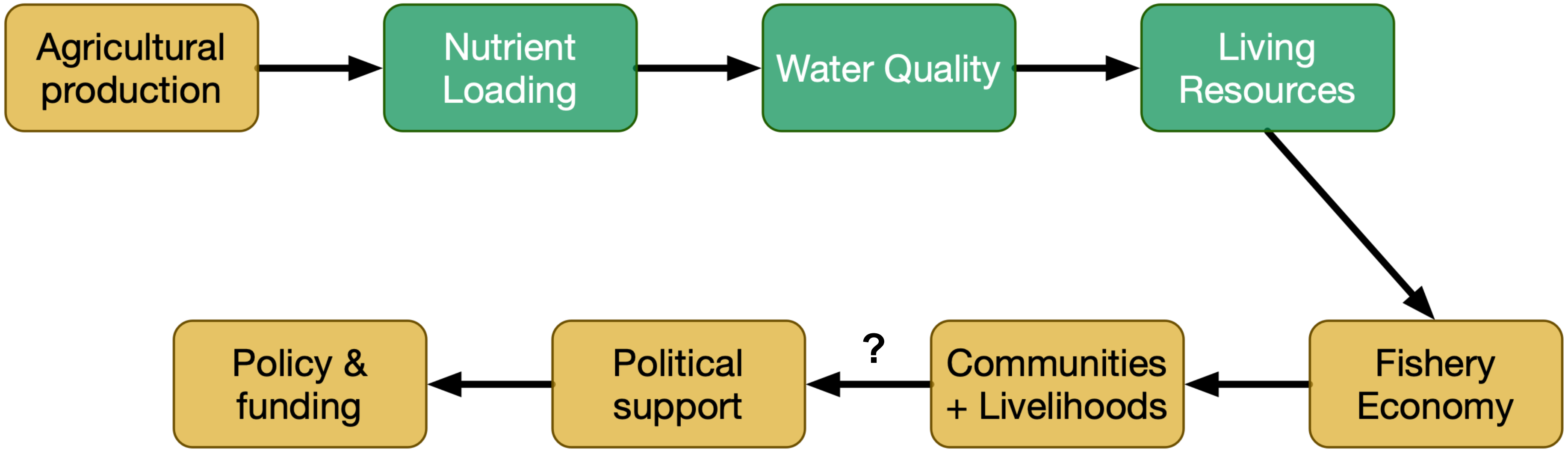
# A (simplified) ecological cascade



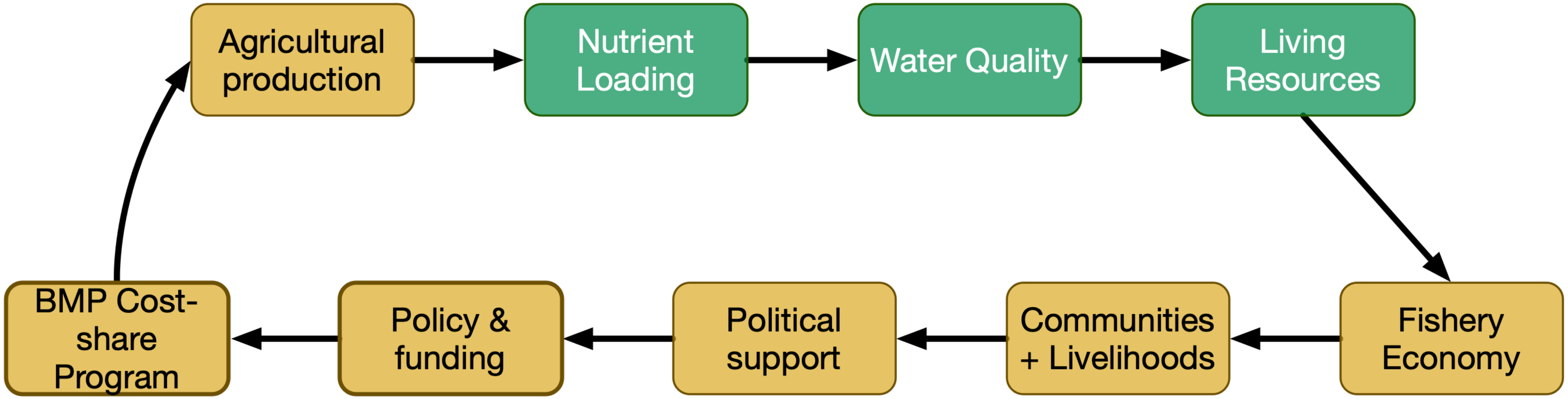
# Crossing the human-environment divide



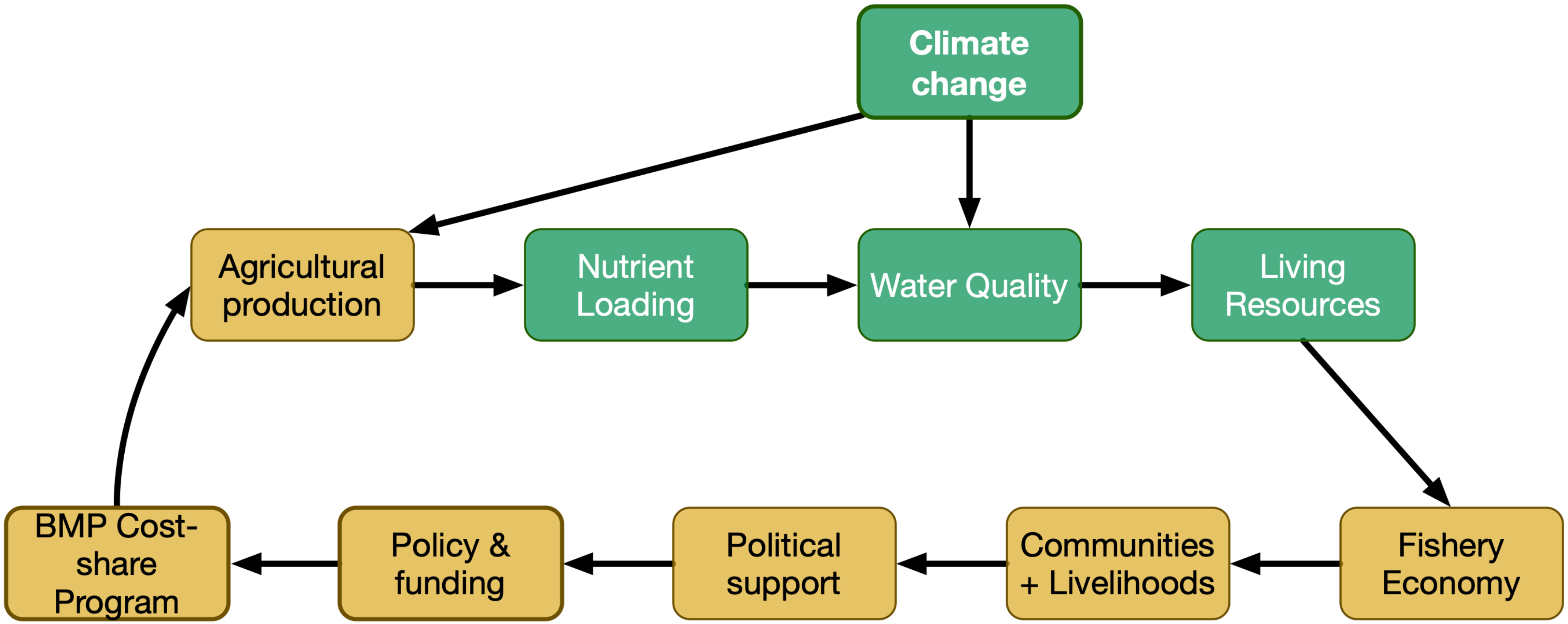
# The governance response



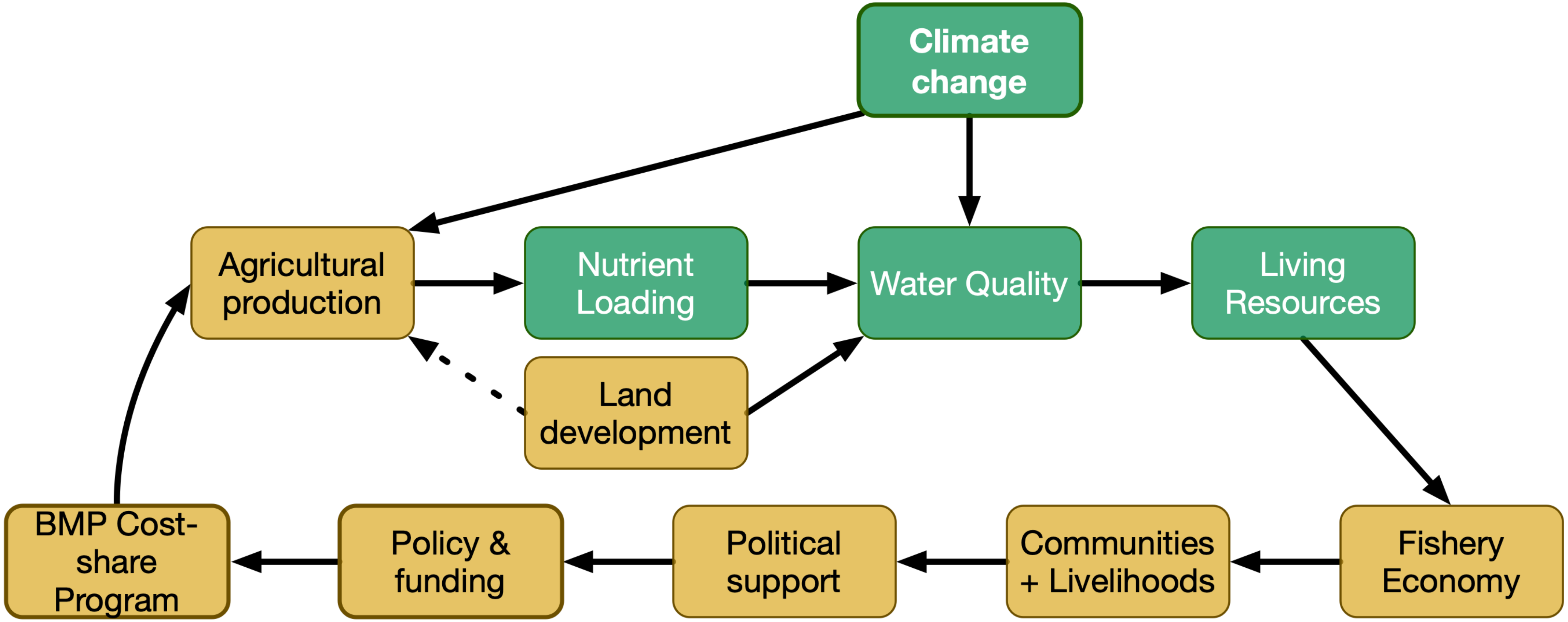
# The first feedback loop closes



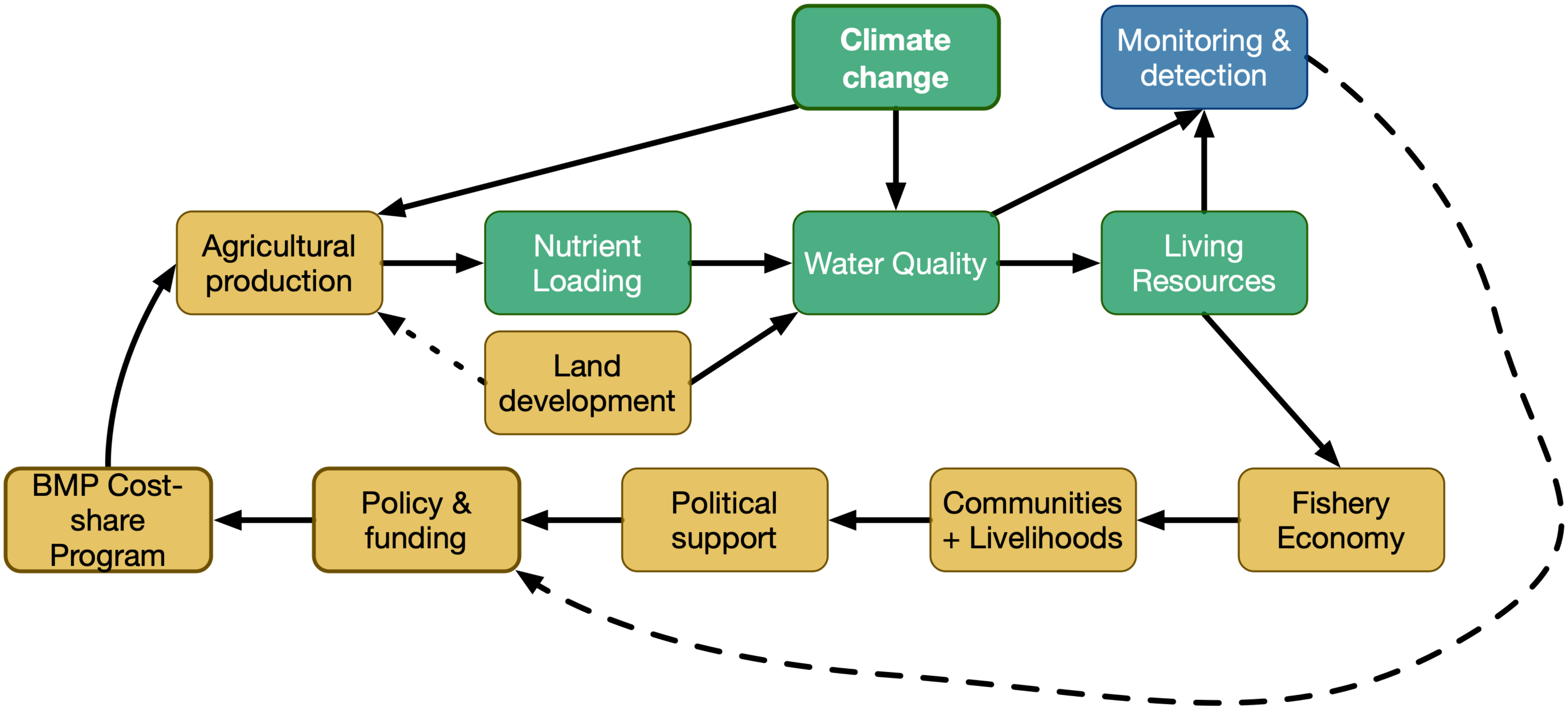
# External forcing



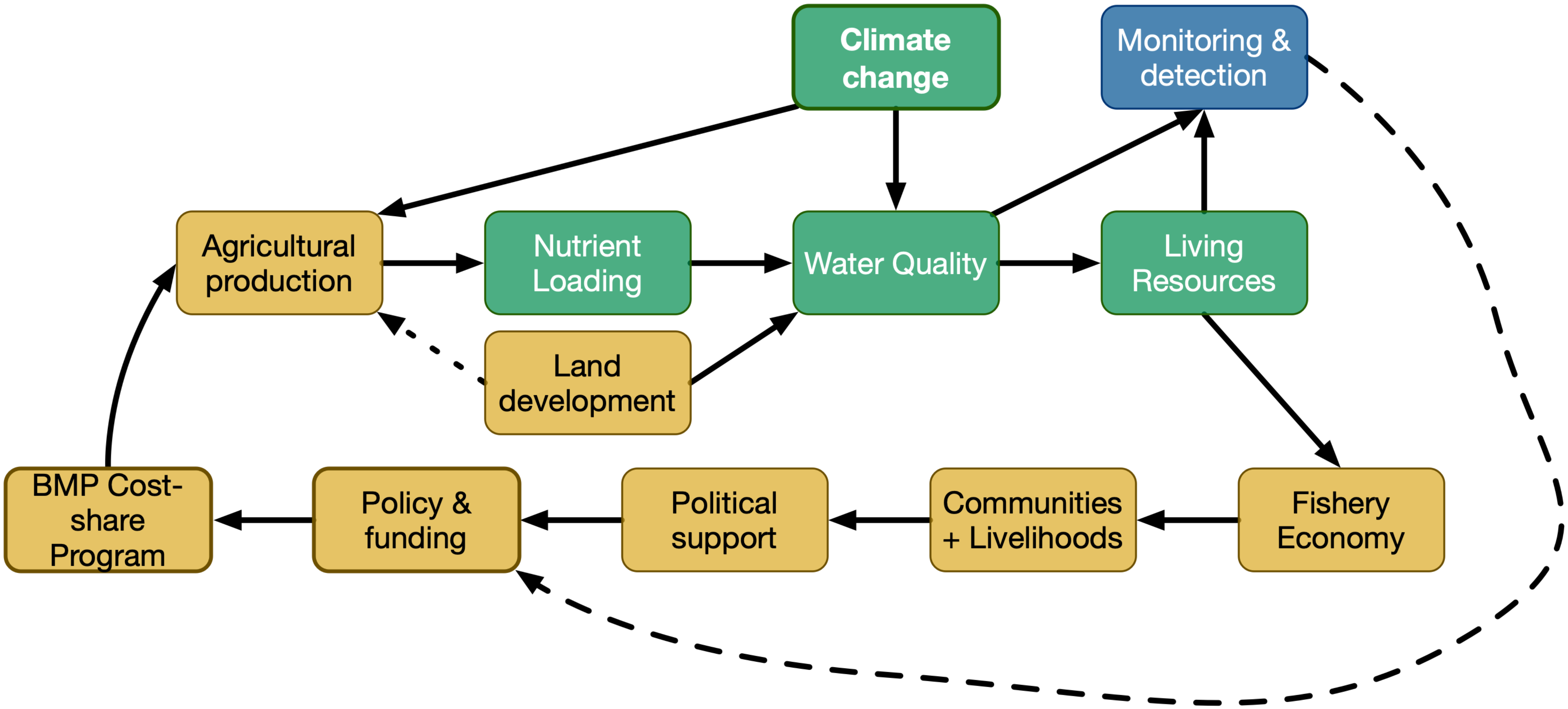
# Competing pressures



# An information pathway



# And yet… and incomplete story



# Heterogeneity

Actors, ecosystems, and institutions differ across

- Space
- Time
- Context

**THE CBW: 64,000 SQUARE MILES OF VARIATION**

- **Policy and political heterogeneity**: 7 jurisdictions
- **Land use heterogeneity**: intensive agriculture, rapidly urbanizing corridors around Baltimore and D.C., and rural forested headwaters.
- **Outcome heterogeneity**: increasing nutrient loads despite predicted declines

*Uniform policies applied to heterogeneous systems produce uneven results*

Recognized in 2025 Watershed Agreement's emphasis on **place-based approaches**

# Adaptation & Memory

- Actors **learn** experience and **adjust** behavior
- Institutional rules evolve
- Past decisions constrain future options (path dependence): legacy nutrients, established infrastructure, and institutional norms *all* carry forward

## IN THE CBW: INSTITUTIONAL MEMORY AND PATH DEPENDENCE

- TMDL's focus on deep-channel dissolved oxygen has organized the management system around a specific goal for 15+ years
- Creating path dependencies in:
  - monitoring design
  - model structure
  - political accountability

*History shapes the present system in ways that current-snapshot models may not represent*

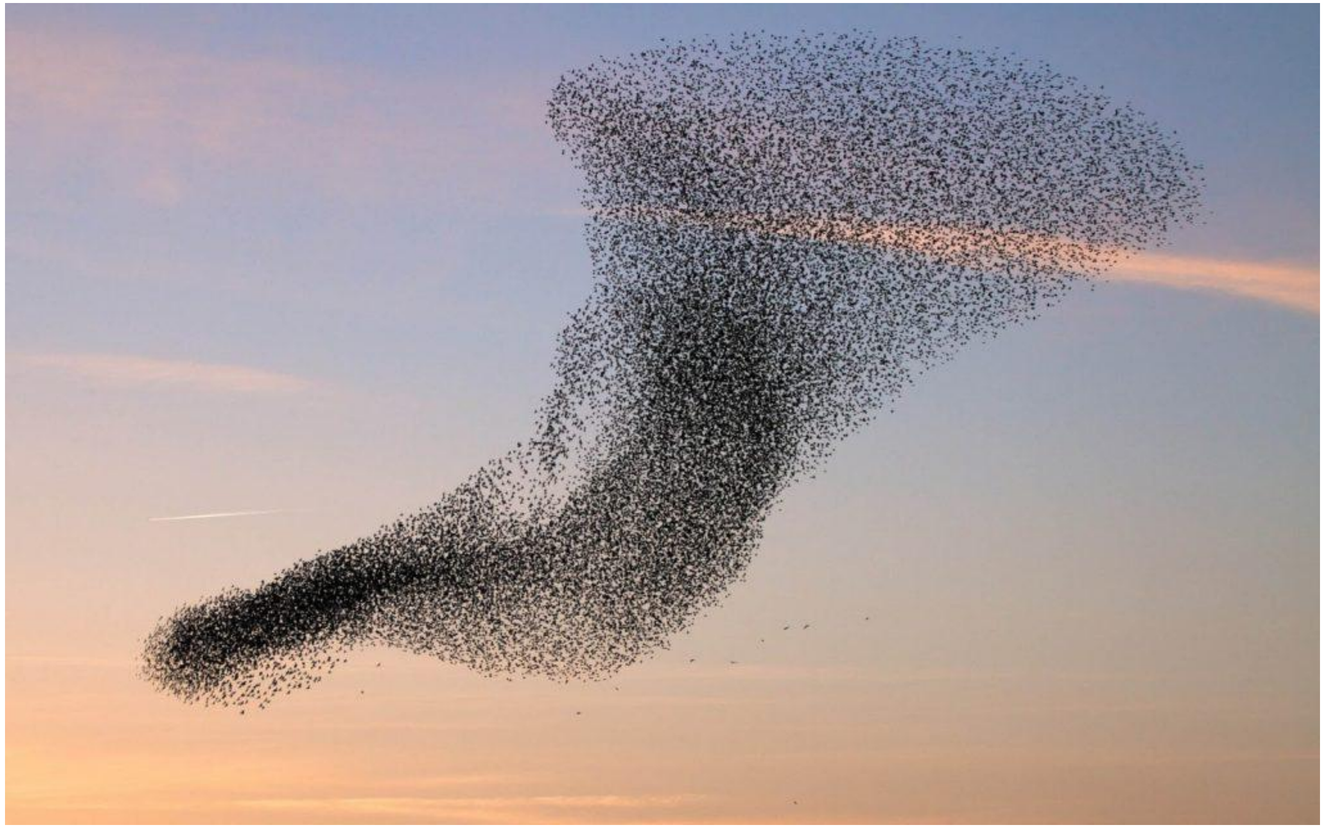
# Emergence

- System-level patterns and outcomes arise from the interactions among components *in ways that cannot be predicted from the behavior of any individual component alone*
- The whole is **different** than the sum of its parts

**IN THE CBW: THE IMPLEMENTATION GAP AS EMERGENT PROPERTY**

- Not a failure of any single actor or program
- Emerges from the interaction of individually rational decisions:
  - farmers weighing costs against uncertain benefits
  - conservation districts prioritizing enrollments they can count
  - the modeling system treating adoption as exogenous
  - accountability framework that tracks practices installed rather than outcomes achieved

***No one designed the gap:*** *emergent outcomes can't be fixed by optimizing individual components. You must change the interactions*




https://netlogoweb.org/launch#http://netlogoweb.org/assets/modelslib/Sample%20Models/Biology/Flocking%20Vee%20Formations.nlogo

# State of the CHANS science

Or… “challenges and opportunities”

# Field has matured – if somewhat unevenly

- *From* conceptual frameworks *to* empirical and modeling applications
- Recent meta-analyses reveal both progress and persistent limitations:

### Schlüter et al. 2023 (PNAS)

- Empirical and modeling approaches **remain poorly integrated** – most studies use one or the other, rarely both
- Called for tighter coupling between field observation and computational modeling

### An et al. 2024 (Geography & Sustainability)

- Surveyed CAS science in the context of global sustainability crises
- Most applications remain at the conceptual or small-scale level - limited scaling to the management-relevant systems

### Elsawah et al. 2020 (SESMO)

- Identified **eight grand challenges** for socio-environmental modeling

# How coupled is coupled human-natural systems research?
(Shin et al. 2022)

**Typology of H-E dynamics:** **parallel (**side-by-side but not interacting); **one-way (**H→E or E→H); **bi-directional** (feedbacks explicitly represented)

***What improves bidirectional research?***

### Social science team members increase the likelihood of two-way linkages

- Teams with social scientists were significantly more likely to publish research displaying bidirectional coupling
- Attention to the human-response side that natural scientists often treat as exogenous.

### Physical/biological science members decrease this likelihood

- Teams dominated by natural scientists tend to produce one-way analyses (human→environment)
- Disciplinary training shapes what researchers see as endogenous vs. exogenous to the system

### Method matters: simulation models and conceptual frameworks enable coupling

- Essentially all articles with two-way linkages used either simulation models or conceptual-framework approaches
- Statistical methods alone rarely captured feedbacks

# Eight Grand Challenges in SES Modeling (Elsawah et al. 2020)

Interdisciplinary expert panel to identify **barriers** limiting the utility of socio-environmental systems modeling **for decision-making**:

1. Bridging epistemologies **across disciplines**
2. Multi-dimensional uncertainty assessment and management
3. Scales and scaling issues
4. Combining **qualitative and quantitative methods and data**
5. Furthering adoption and impact of SES modeling **on policy**
6. Capturing structural changes in systems over time
7. **Representing human dimensions** in SES models
8. Leveraging new data types and sources

***Which of these are the most significant for CBW management?***

# SETS: Technology as a System Component

***Technological and infrastructure systems as mediating components of the coupled system***

### Monitoring networks

What signals reach decision-makers? And what gets filtered out

### Modeling platforms

How system dynamics are represented; and what's omitted

### Decision-support tools

How information becomes actionable (or doesn't)

*CESR: Monitoring is oriented toward accountability (are criteria met?) rather than learning (why/not do we see desired outcomes?)*

# “Challenges and opportunities in operationalizing CHANS science in the CBW”

# Four processes, some convergence…

| | | |
|---|---|---|
| 2023 | CESR Report | Implementation and response gaps point to structural problems in ***how the management system handles environment → human feedbacks*** |
| 2024 | Beyond 2025 Report | Called for ***integrating social science into a systems-based approach*** to understanding decision-making across scales |
| 2024- | STAC Social Science Workgroup (SSWG) | Standing Workgroup established ***to integrate social science perspectives into CBP's work*** |
| 2025 | Watershed Agreement | Commits to ***integrating social science holistically*** and to adaptive management informed by the best available science |

# …and a timely opportunity

*2025 Watershed Agreement establishes commitments directly relevant to what this workshop addresses*

## SOCIAL SCIENCE INTEGRATION

*"Integrate social science holistically throughout the partnership to support adaptive management, more effectively engage with communities and incentivize individual and collective behaviors that support partnership goals."*

## INTERCONNECTEDNESS PRINCIPLE

*"All aspects of the ecosystem are connected"*

## ADAPTIVE MANAGEMENT COMMITMENT

*Apply adaptive management informed by the best available science, adjusting strategies as understanding improves*

*Understanding how feedbacks shape Bay restoration is directly relevant to how these commitments get implemented*