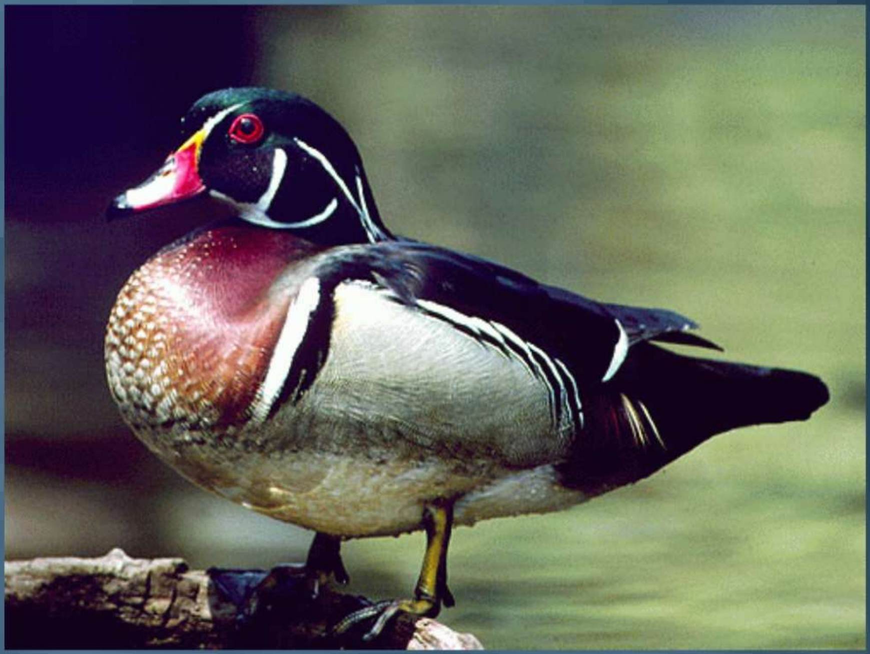
Modeling, Monitoring, and Adaptive Management

June 2023 STAC
Quarterly Meeting



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Modeling, Monitoring and AM

- Comments on modeling in AM
- Comments on monitoring in AM
- Integrating modeling and monitoring into AM

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5 General Points about Models

1. Every scientific investigation has an underlying model
   - that imbeds assumptions and highlights the hypotheses to be investigated
   - Were it not so, there would be no way to focus the investigation on key questions of interest
   - In fact, the whole field of experimental design can be seen as a highly structured exercise in scientific modeling.

General Points about Models

2. Every management strategy has an underlying model

   - that imbeds the manager’s understanding of the resource being managed
   - Were it not so, there would be no way to determine what to manage, or how
   - The model may not be explicit but it’s always there, guiding the manager’s expectations
   - Otherwise, management would be little more than a random coin toss.

General Points about Models

3. Models can take many forms
    - A simple diagram
    - A verbal description of the resource
    - A physical model
    - An intuitive concept of the resource
    - A formal mathematical model

Whatever its form, the model is used to

- Capture assumptions
- Express one's understanding about the system under investigation

General Points about Models

4. There is no “right” model
   - A model may be simple, or may be complicated
   - May be general, or may be specific to the resource system
   - May have lots of technical detail, or may not

Which kind of model and attributes to use come down to

- the nature and scale of the management problem
- the available knowledge about the management situation

General Points about Models

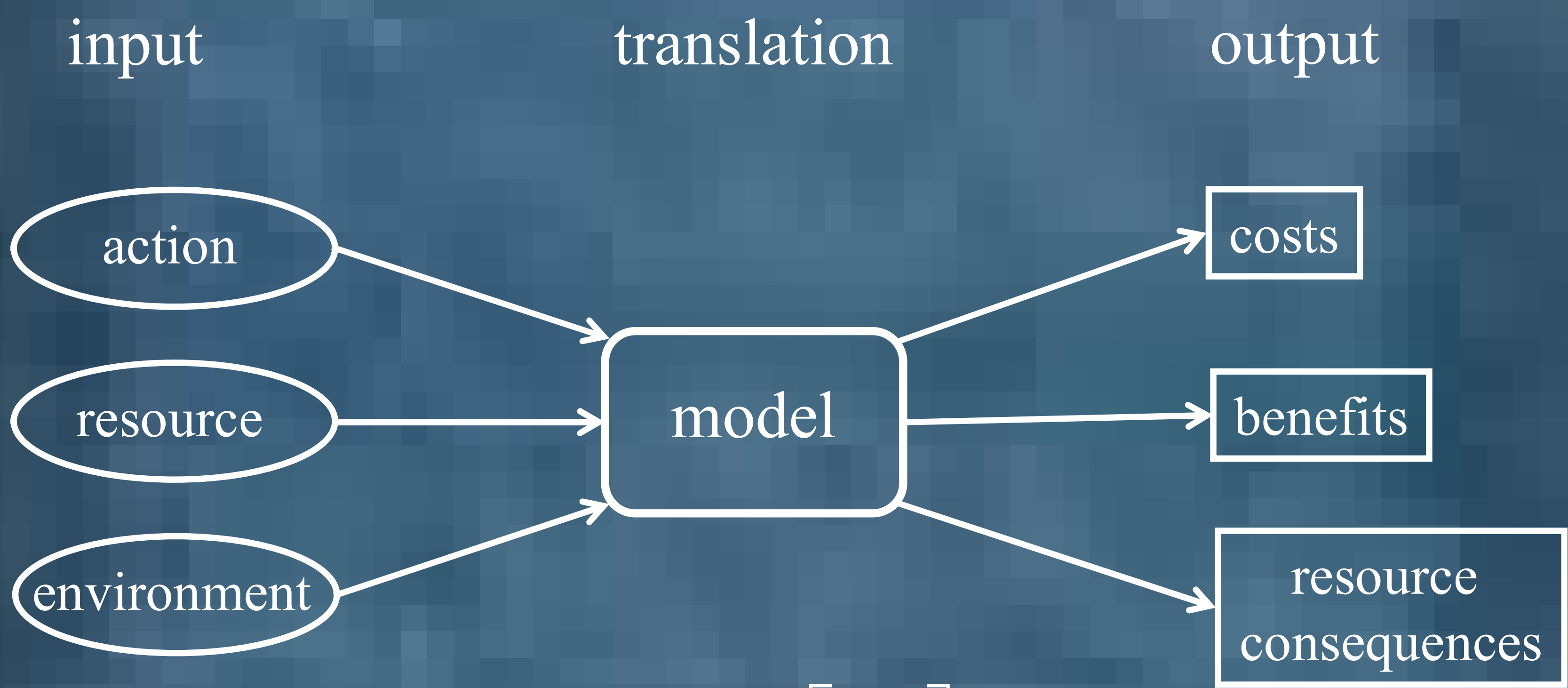
5. You use models every day
    - To help organize your thoughts about resource problems
    - To focus your attention on what needs to be done
    - To anticipate the results of your management actions
    - To recognize what's known, and what's not known but needed

The trick is to use models to help with decision making and not hinder it

5 General Points about Models

- Every scientific investigation has an underlying model
- Every management strategy has an underlying model
- Models can take many forms
- There is no “right” model
- You use models every day

AM Models: Linking Actions to Impacts



$$f(a_t, r_t, e_t) = \begin{bmatrix} c_{t+1} \\ b_{t+1} \\ r_{t+1} \end{bmatrix}$$

Model Features in AM

$$f(a_t, r_t, e_t) = \begin{bmatrix} c_{t+1} \\ b_{t+1} \\ r_{t+1} \end{bmatrix}$$

- Models characterize resource changes through time
- Management actions drive resource dynamics
- Environmental conditions and resource state influence dynamics
- Resource outputs become inputs next time

Uncertainty in AM

- There's almost always some uncertainty about the effect of actions
- That uncertainty (or disagreement) can be expressed by different hypotheses about how the system works
- Alternative models imbed the hypotheses and express that uncertainty

AM focuses on uncertainty and its reduction, through the use of management and monitoring

Models and Learning

- Alternative models in AM predict different outcomes from management
- Post-decision monitoring produces an observed outcome
- Comparison of predicted against observed outcomes helps to identify the most appropriate hypothesis
- Sequential decision making and monitoring promotes learning through time

Roles of Modeling in AM

- To make explicit one's assumptions about the resource system
- To predict management impacts based on those assumptions
- To allow testing of assumptions with monitoring data
- To address and reduce management uncertainties
- To improve management through learning

Modeling, Monitoring and AM

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Monitoring Point 1

At bottom, there are only two reasons to monitor natural resources

- To learn stuff
- To manage stuff

All the important monitoring issues revolve around how to promote one or both these goals

Monitoring Point 2

There is a very large number of ways to monitor any resource system

- In the combinations of target and sampled attributes
- In variations of methodology, e.g., stratification, clustering, probability-based etc
- The approach you use can give a different of view the system

Bottom line:

- The patterns you observe will be influenced by what you monitor, and how you monitor it

Monitoring Point 3

Natural resource systems are infinite-dimensional

- Regardless of how many attributes, parameters, processes, interconnections, scales you can identify, infinitely more could have been identified

- An exhaustive accounting of resource attributes would require unlimited amounts of money and effort

Bottom line:

- Every monitoring effort is limited, no matter how multivariate, how broad the scale, how detailed the frame, how many resources are expended

Monitoring Point 4

Three questions must be answered for effective and relevant monitoring:

- Why is the monitoring to be conducted? For what purpose are the data being collected, to answer what question?
- What monitoring data are to be collected? What attributes will be recorded?
- How will the data be collected? By what design?

Bottom line:

- What you monitor, and how you monitor it, should be conditioned on why you are monitoring in the first place
- Not thinking carefully about the why can lead to inefficient designs and a lack of support for the monitoring effort

Monitoring Point 5

The why, what, where, and how of monitoring are reflected in sampling design

- Specifying scale (spatial, temporal, ecological)
- Articulating accuracy requirements (bias, precision, etc)
- Focusing of monitoring targets (ecological attributes, status/trends, spatial pattern)
- Accounting for monitoring capacity (fiscal resources, field personnel, expertise)

Bottom line:

- Design is a critical and too often unmet need for monitoring usefulness, as well as continued support

Final Point on Monitoring

In monitoring, one size does <u>not</u> fit all

- Not in purpose
- Nor scale
- Nor focus
- Nor the need for accuracy
- Nor the need for standardization
- Nor the required capacity

Harder thinking about monitoring is needed at the outset of project planning

- Which is in turn promoted by a much greater focus on the <u>why</u>, as the key determinant of the <u>what</u>, <u>where</u>, and <u>how</u> of monitoring

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Adaptive Management Defined

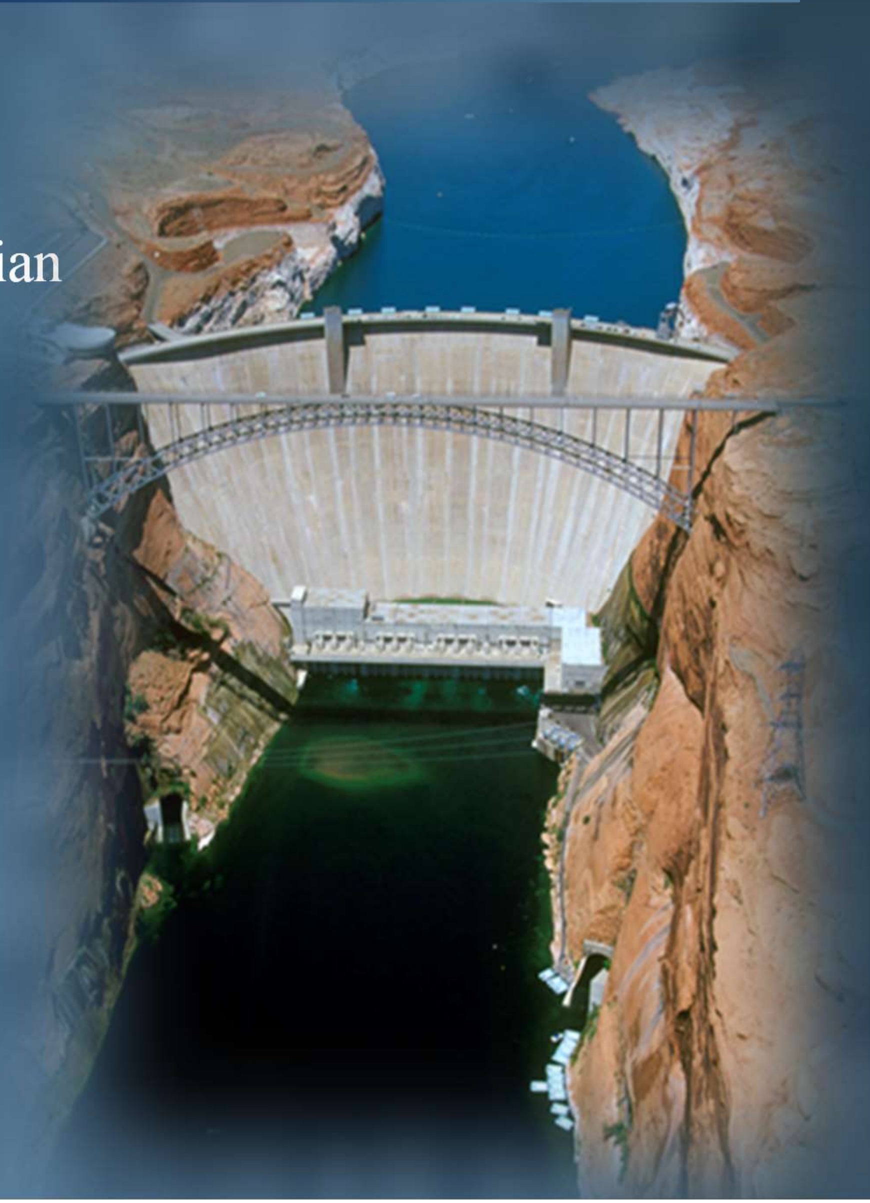
Learning through management, and adapting management based on what is learned

- Learning: the accretion of understanding through time
- Adaptation: the adjustment of management through time based on what's learned
- General AM goal: reducing uncertainty and improving management

Example 1: Management of water releases from a reservoir

- Uncertainty about
  - extremes in water levels
  - alteration of downstream aquatic and riparian vegetation
  - fish survival
  - interspecific competition

- Uncertainty limits the ability to achieve stakeholder agreement on the timing and amount of water to be released



Example 2: Management of grazing on rangelands

- Uncertainty about vegetation responses to grazing in terms of
  - future vegetation productivity
  - susceptibility to invasive plants
  - plant community succession
- Uncertainty limits the ability to design smart and acceptable grazing strategies

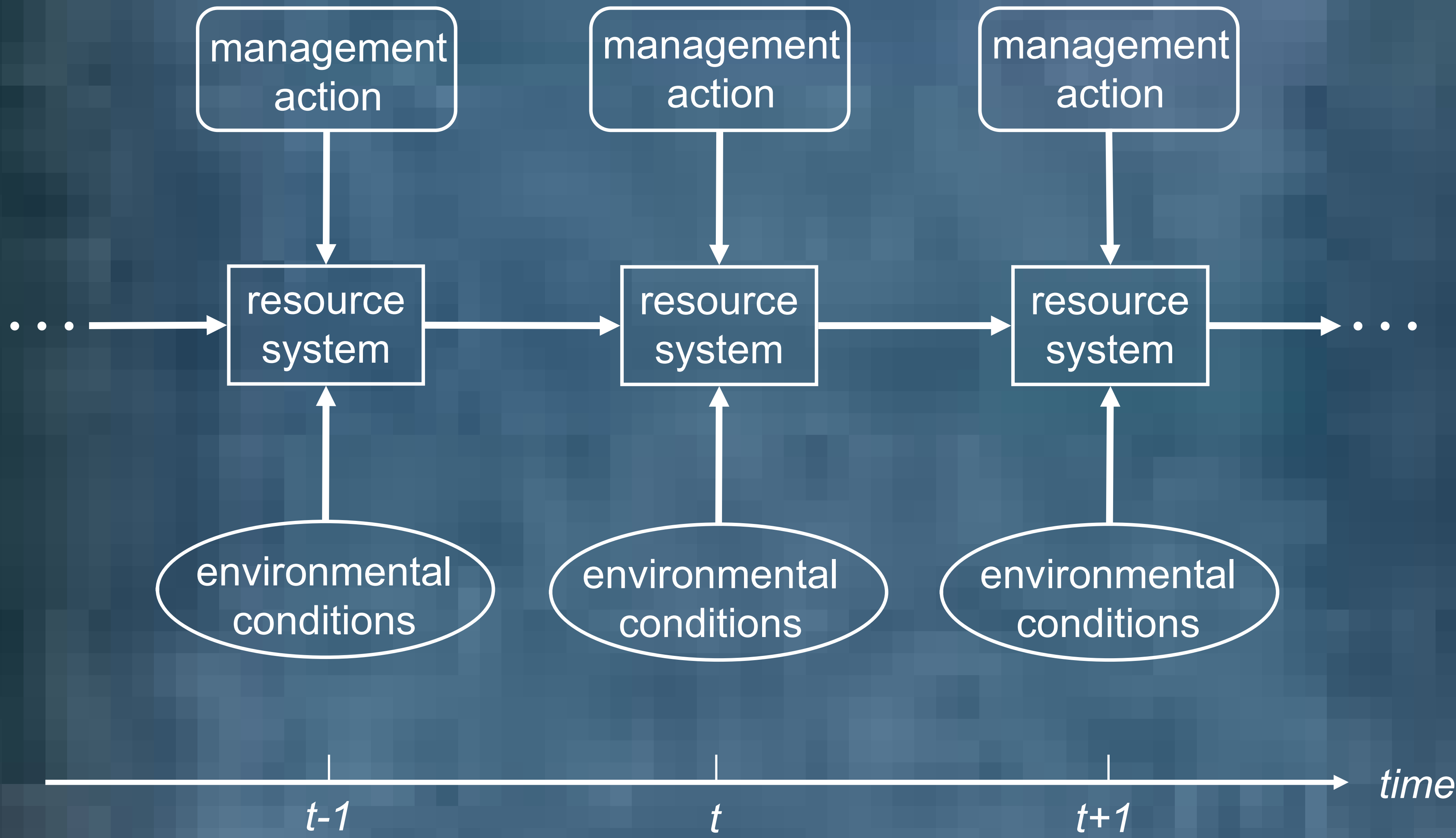
Example 3: Management of waterfowl hunting

- Uncertainty about
  - impacts of hunting on population survival rate
  - impacts of hunting on reproduction rate
  - impacts of hunting on behavioral adjustment of waterfowl
- Uncertainty limits manager’s ability to implement informed hunting programs

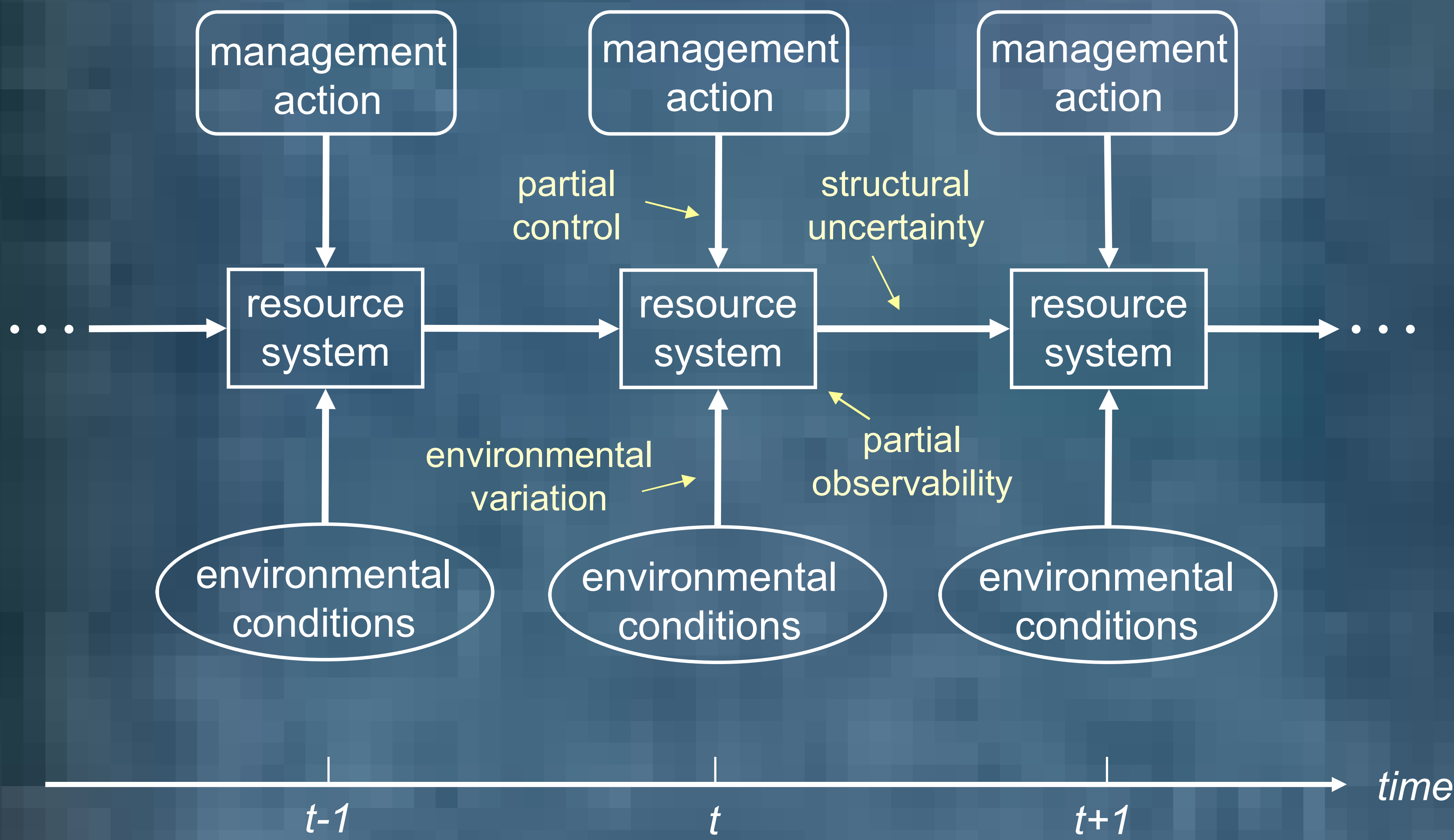
Commonalities in the examples

- Actions have future consequences for the natural resource system
- The consequences are not fully understood, i.e., are uncertain
- Lack of understanding gets in the way of making smart decisions
- Decisions have to be made anyway

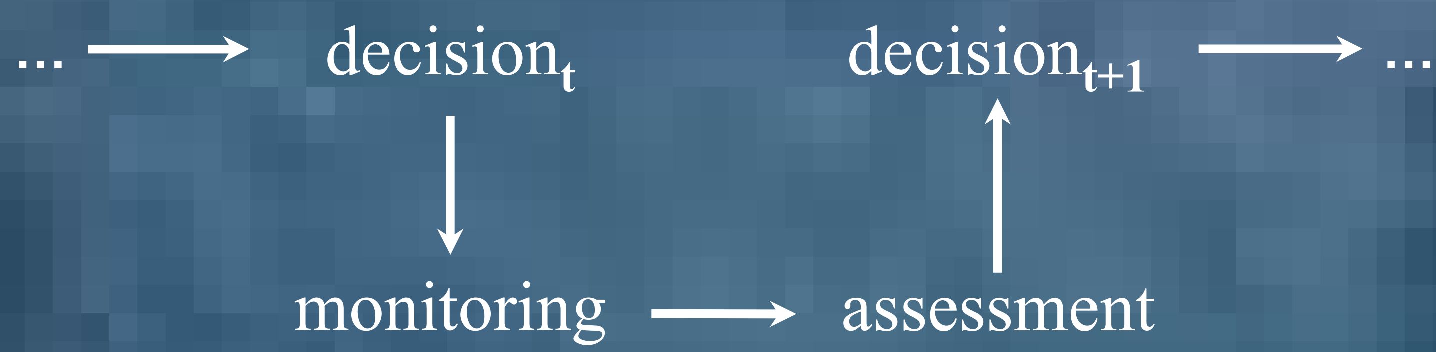
Resource Situation



Resource Situation



Sequential Decision Making



- Decisions guided by management objectives at each time
- Monitoring used to track system responses
- Assessment of monitoring data with previously collected information
- Subsequent decisions based on improved understanding

Adaptive Management

- Making decisions through time
- Keeping track of what you learn as you go
- Using what you learn to improve decision making
- Managing to promote learning, and learning to promote better management

AM process in two phases

Deliberative phase

Management framework

- Stakeholder involvement
- Objective(s)
- Potential management alternatives
- Predictions of consequences
- Monitoring protocols and plans

Institutional Learning

Iterative phase

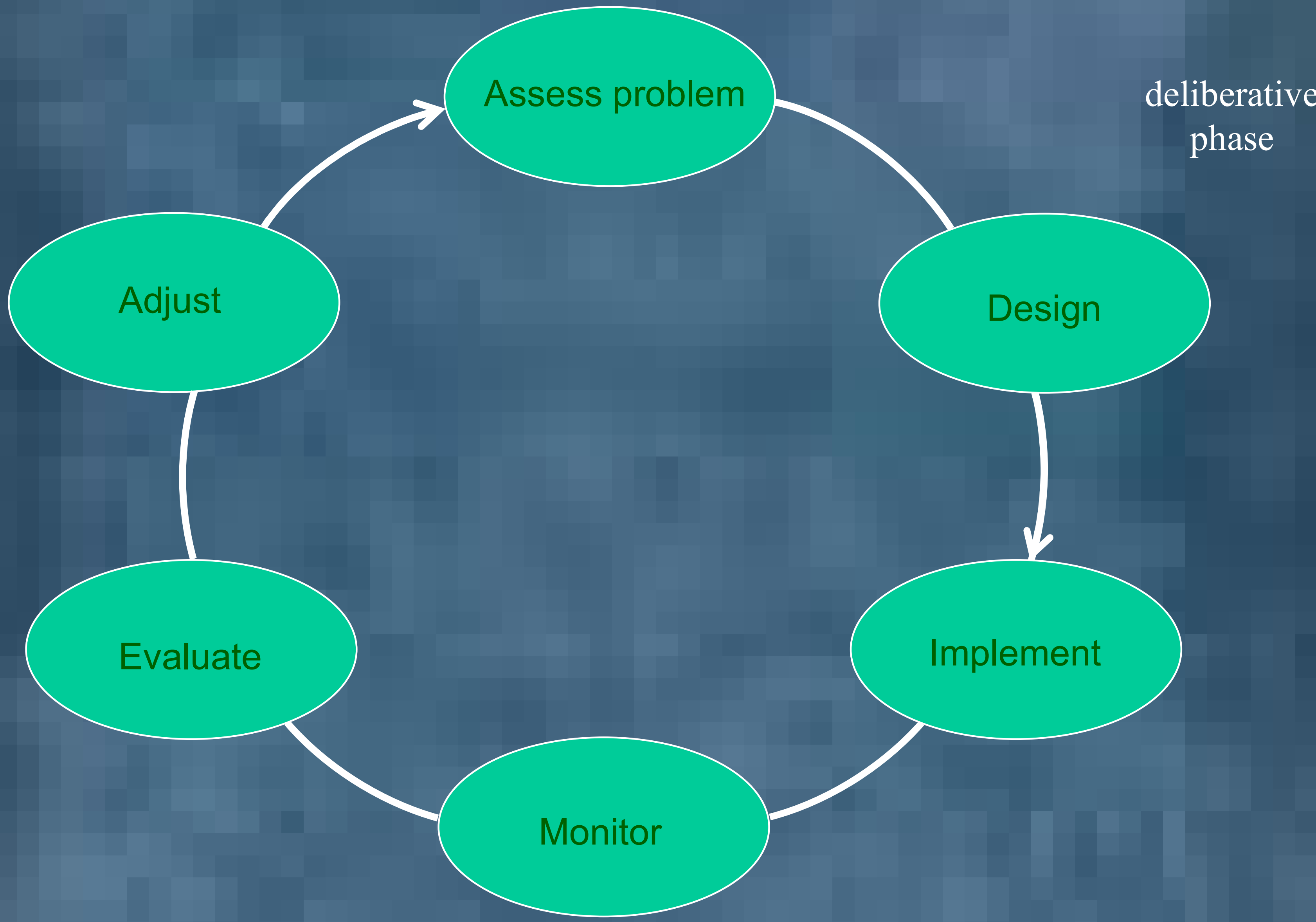
Feedback sequence (technical learning)

Decision making

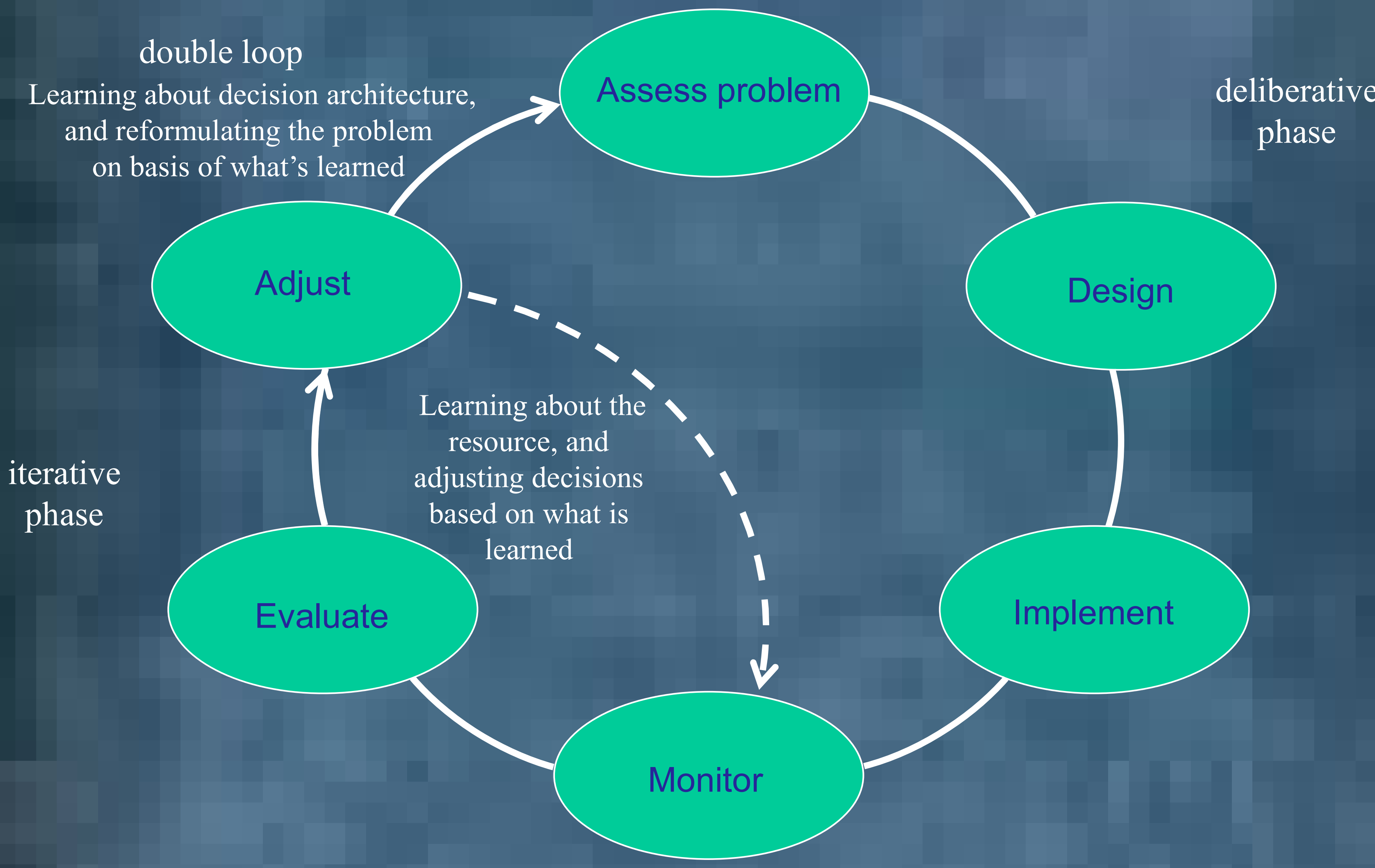
Monitoring

Assessment

Adaptive Management Cycle



Adaptive Management Cycle



Technical Description of AM

- Builds on a dynamic framework of actions taken and states responding
- With action at each time based on the state observed at that time
- With management value represented by accumulated returns through time
- And uncertainty expressed in terms of multiple decision models

Framework for a Known Resource System

- Observed resource state $x \in \{x_1, x_2, ..., x_N\}$
- Action $a \in \{a_1, a_2, ..., a_M\}$ taken in response to system state
- Model transitions $x' = F(x, a, e) \Longrightarrow P(x' | x, a)$
- Reward $r(a | x)$ produced by action a when the process is in state x
- With information triples (x_t, a_t, r_t) repeated through time
- Policy $\pi : (x) \Rightarrow a$ describing state-based actions
- Goal is to find a policy with maximum value

Valuation for a Known System

- Value function

$$V_\pi(x) = E\left[\sum_{\tau=t}^{\infty} \lambda^{t-\tau} r(a_\tau \mid x_\tau) \mid x_t = x\right]$$
$$= r(a \mid x) + \lambda \sum_{x'} P(x' \mid x, a) V_\pi\left(x'\right)$$

- Value optimization

$$V\left[x\right] = \max_a \left\{ r(a \mid x) + \lambda \sum_{x'} P(x' \mid x, a) \max_\pi V_\pi\left(x'\right) \right\}$$
$$= \max_a \left\{ r(a \mid x) + \lambda \sum_{x'} P(x' \mid x, a) V\left[x'\right] \right\}$$

- Optimal policy

$$a^* = \arg\max_a \left\{ r(a \mid x) + \lambda \sum_{x'} P(x' \mid x, a) V\left[x'\right] \right\}$$

Process Uncertainty

- Limited understanding of resource dynamics
  - Uncertainty about which of several transition models is most appropriate
  - Uncertainty about parameters (e.g., survivorship, reproduction) that control transitions

- Expressed here with K models of resource dynamics, each with a model likelihood $q(k)$ in a model state $q = \{q(k) : k = 1, \ldots, K\}$

It is the accounting for model uncertainty, and the influence of decision making on it, that is definitive of adaptive management

How to Add Uncertainty to get AM

By including multiple models, each predicting a different response to management, each with its own likelihood of being the most appropriate model

- Resource states $x \in \{x_1, x_2, \ldots, x_N\}$ and actions $a \in \{a_1, a_2, \ldots, a_M\}$
- Resource state transitions $x' = F_k(x, a, z) \Longrightarrow P_k(x' \mid x, a)$
- Model state $q = [q(1), q(2), \ldots, q(K)]$
- Model state transitions $q'(k) = \dfrac{q(k) P_k(x' \mid x, a)}{P(x' \mid x, a, q)}$

with $P(x' \mid x, a, q) = \sum_k q(k) P_k(x' \mid x, a)$

Adaptive Management Valuation

- Model-specific rewards $r_k(a \mid x)$
- Average reward $r(a \mid x, q) = \sum_k q(k) r_k(a \mid x)$
- Model-specific value functions $V_\pi^k(x) = r_k(a \mid x) + \lambda \sum_{x'} P_k(x' \mid x, a) V_{\pi_{t+1}}^k(x')$
- Average value function

$$V_\pi(x,q) = r(a \mid x,q) + \lambda \sum_{x'} P(x' \mid x,a,q) \sum_k q'(k) V_\pi^k(x')$$
$$= r(a \mid x,q) + \lambda \sum_{x'} P(x' \mid x,a,q) V_\pi(x',q')$$

- Value optimization $V[x,q] = \max_a \left\{ r(a \mid x,q) + \lambda \sum_{x'} P(x' \mid x,a,q) V[x',q'] \right\}$

Bottom Line

There is a well-developed theoretical and operational basis for adaptive management in conservation

- Involves decision making though time that accounts for uncertainties as to the consequences of actions
- Considers policies of state-specific actions that vary in conservation value, as measured by accumulated discounted returns
- Provides a process of value iteration (dynamic programming) to determine policies that optimize value while reducing uncertainties through time

Ongoing Work on Adaptive Management

- Passive and active AM
- Multi-loop learning
- Accounting for key sources of structural uncertainty
- Pattern analysis for adaptive policies and valuations
- Computing approaches
- Stakeholder engagement
- Partial observability
- Non-stationary dynamics
- Lags between actions taken and returns recorded
- All manner of natural resource applications
- Etc

Challenges with Adaptive Management

- Resistance to the acknowledgment of uncertainty
- Belief by managers that everything important is already known
- Mistaken belief that AM is already being used
- Risk aversion by decision makers and managers
- Focus on management in the short term (myopia)
- Resistance to meaningful stakeholder involvement
- Resistance to focused and effective monitoring
- Lack of an effective decision making infrastructure
- Belief that AM is too expensive compared to alternatives
- etc

Closing comments

- Lots of talk (but limited action) about adaptive, learning-based management of natural resources
- Many challenges in actually doing adaptive management
- Many natural resource problems are pre-adapted for an adaptive approach
- There are many variations of AM - one size doesn’t fit all