

The importance of measurement uncertainty in ecological management

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A large school of fish, likely barracudas, swims in a dense, swirling mass against a dark blue background. The fish are silvery with dark stripes. In the distance, a few more fish are visible.

Managing fisheries is hard: it's like managing a forest, in which the trees are invisible and keep moving around

--John Shepard, from unpublished lecture at Princeton University, ca 1978



We've gotten much better at including
uncertainties in our models



It is time to include uncertainties in our decisions

A wide-angle photograph of a coastal landscape at sunset. The sky is filled with large, billowing clouds illuminated from behind by the setting sun, casting a warm orange and yellow glow. In the foreground, dark, silhouetted shapes of land or mountains rise from a body of water. The water is a deep blue-grey, with small whitecaps visible where it meets the shore.

Decision Theory



Decision Theory

Fischer et al (2009): *Integrating resilience thinking and optimisation for conservation.*

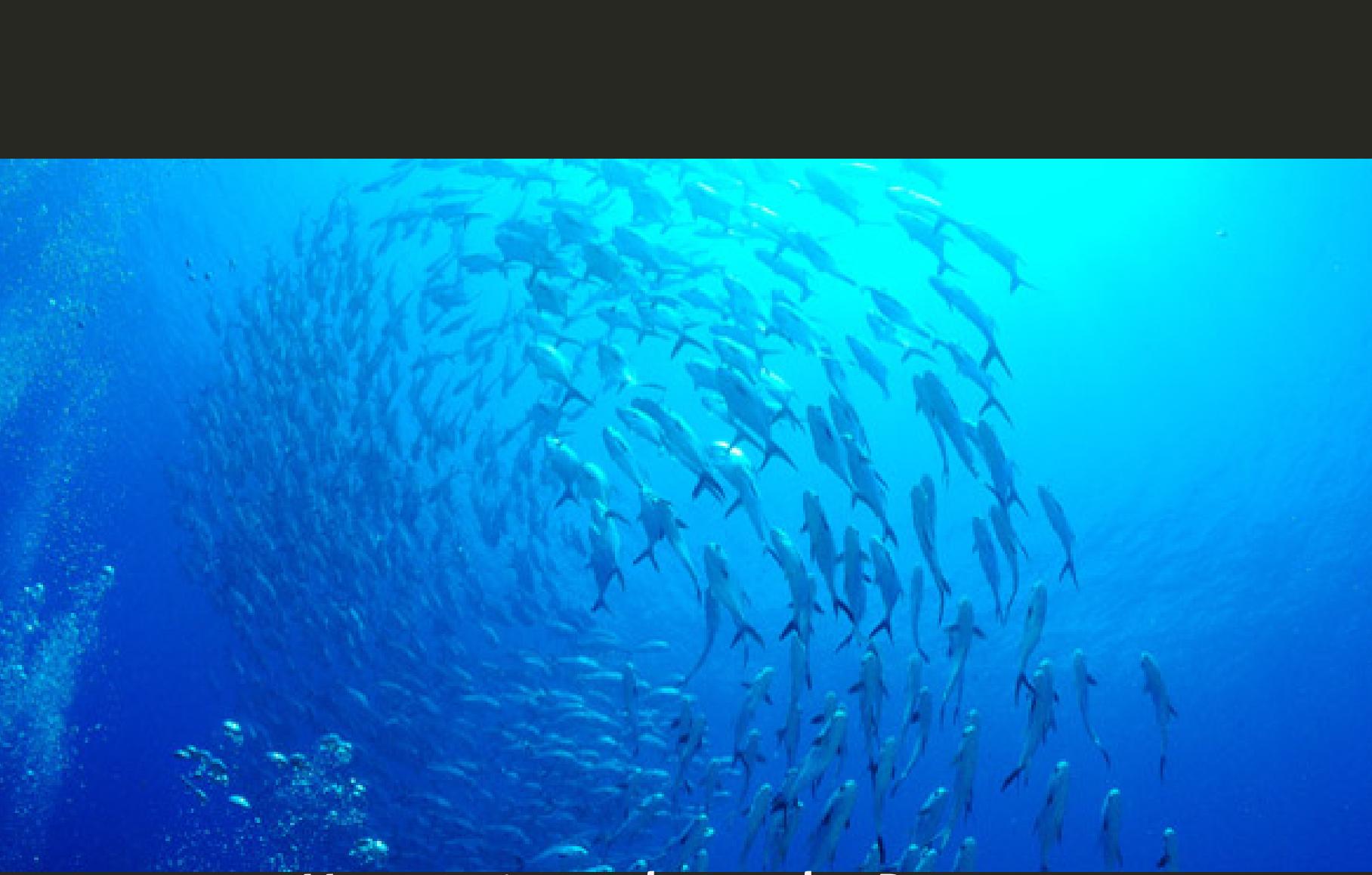
Polasky et al (2011): *Decision-making under great uncertainty: environmental management in an era of global change.*

Optimal Control

Resilience Thinking



Uncertainty about the Future

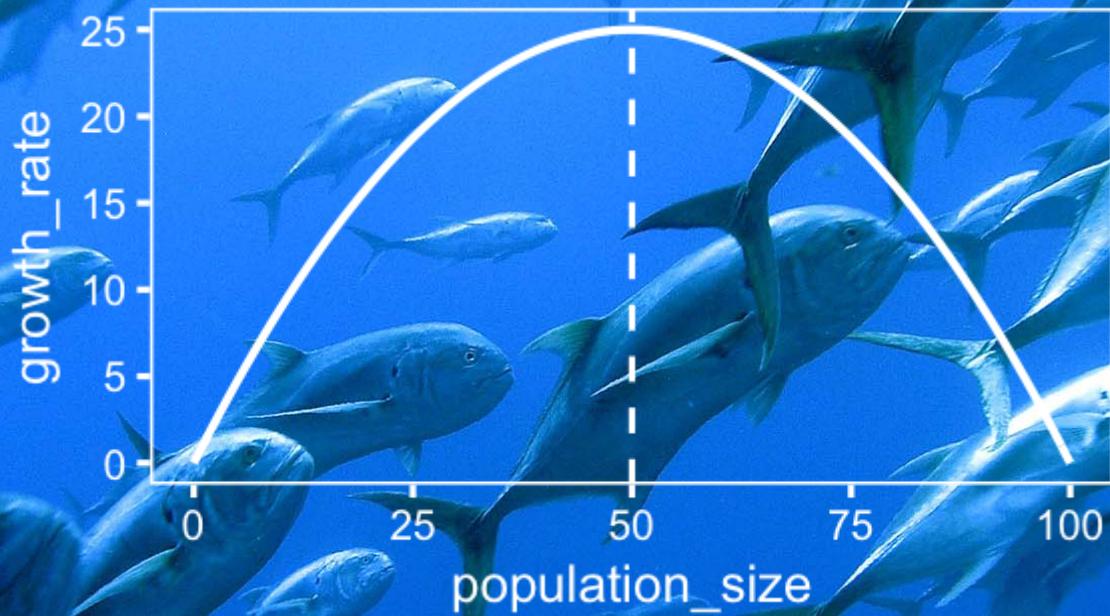


Uncertainty about the Present

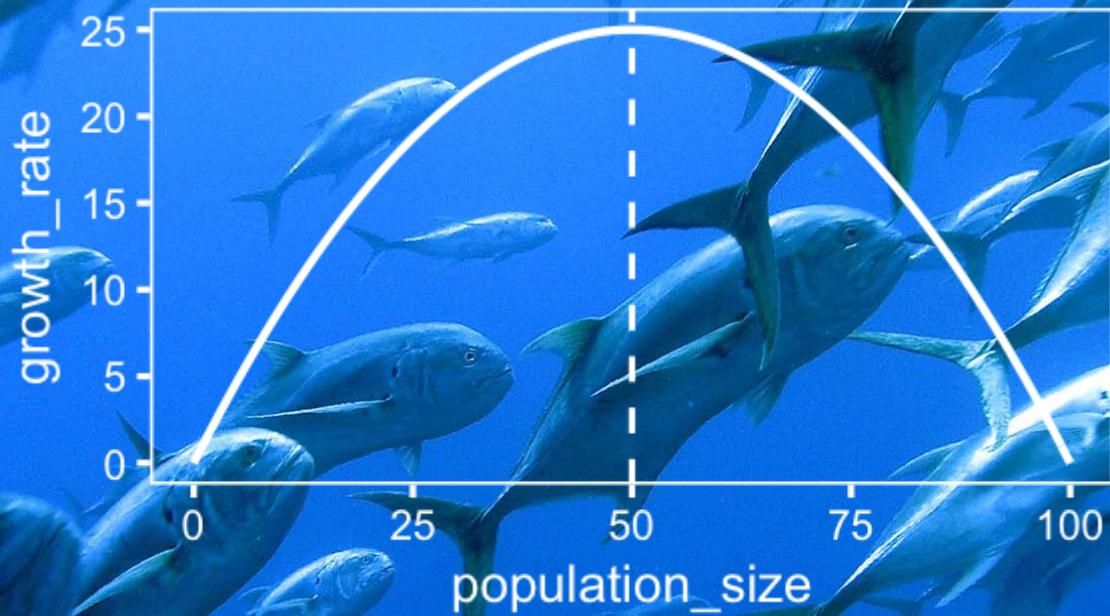


Stock assessment uncertainty

MSY: a sticky idea



MSY: a sticky idea



$$\frac{dN}{dt} = \underbrace{rN \left(1 - \frac{N}{K}\right)}_{f(N)} - H$$

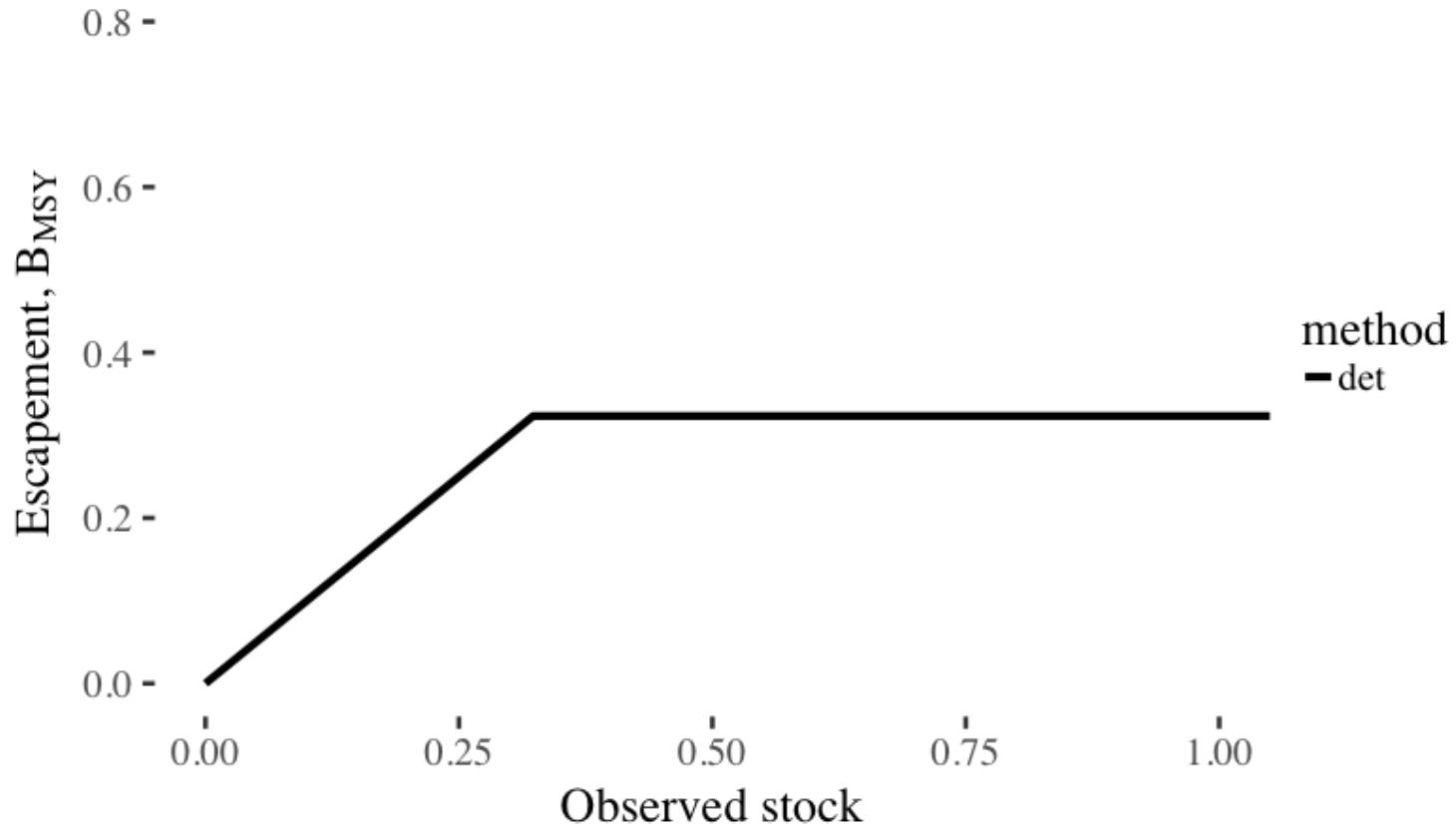
$$H_{\text{MSY}} = f(N) = rK/4, \quad B_{\text{MSY}} = K/2$$

Stochastic Models: Reed 1979

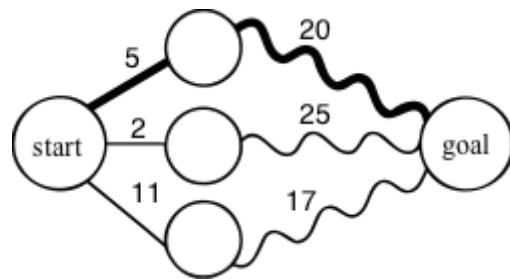
THEOREM 2. *Under the conditions of Theorem 1 if the level σ (at which the expected discounted annual growth in the immediate harvest value of the population is maximized) is self-sustaining then the optimal escapement is at σ (i.e., $S = \sigma$). If on the other hand σ is not self-sustaining then $S > \sigma$, (except in the trivial exceptional case when $S = \sigma = m$).*

Proof. In the case when σ is self-sustaining we proceed by induction and assume

Constant Escapement vs MSY



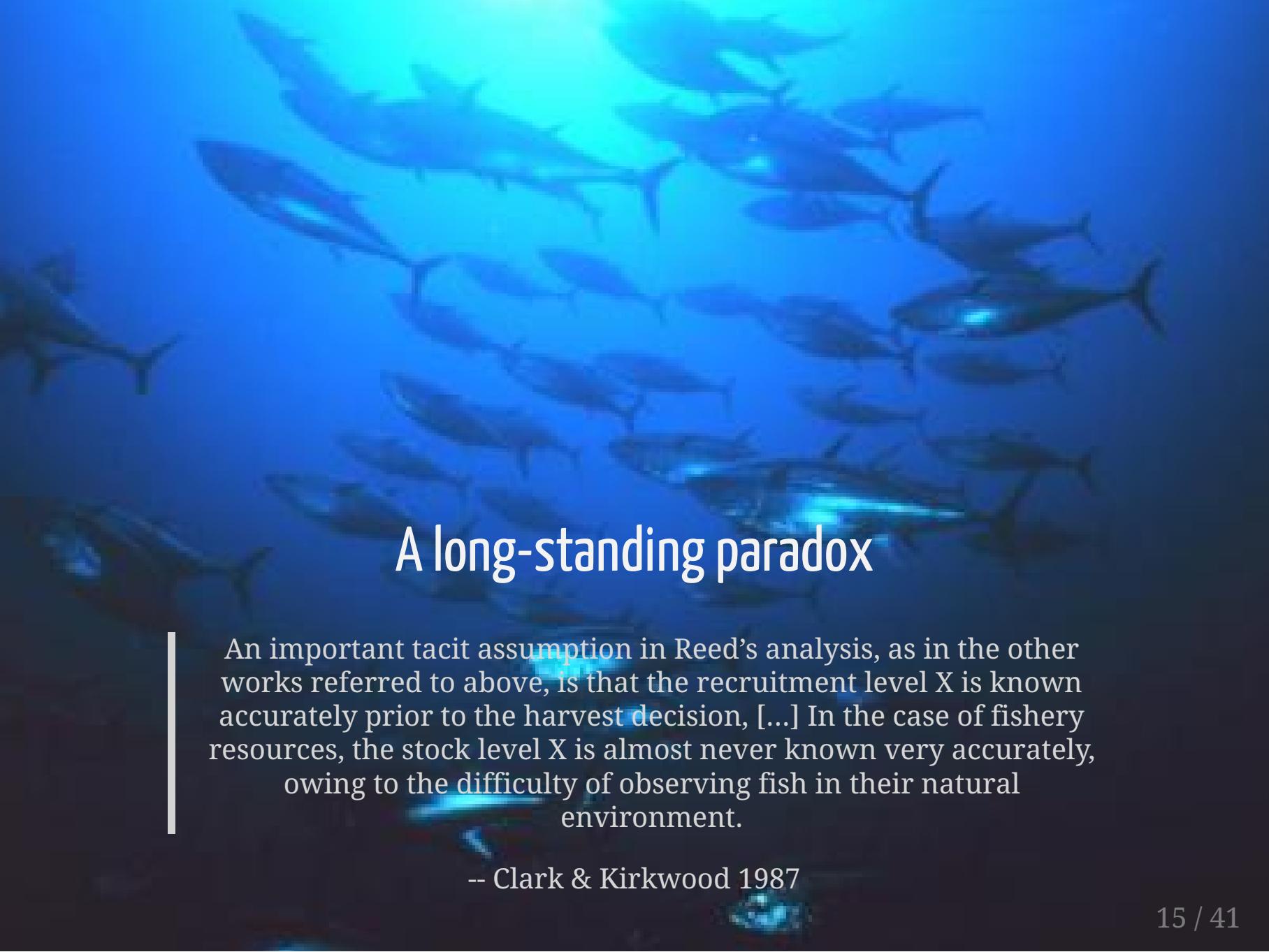
Sequential Decision problems: Dynamic Programming



Reed's legacy

We can ignore troublesome dynamic programming ...

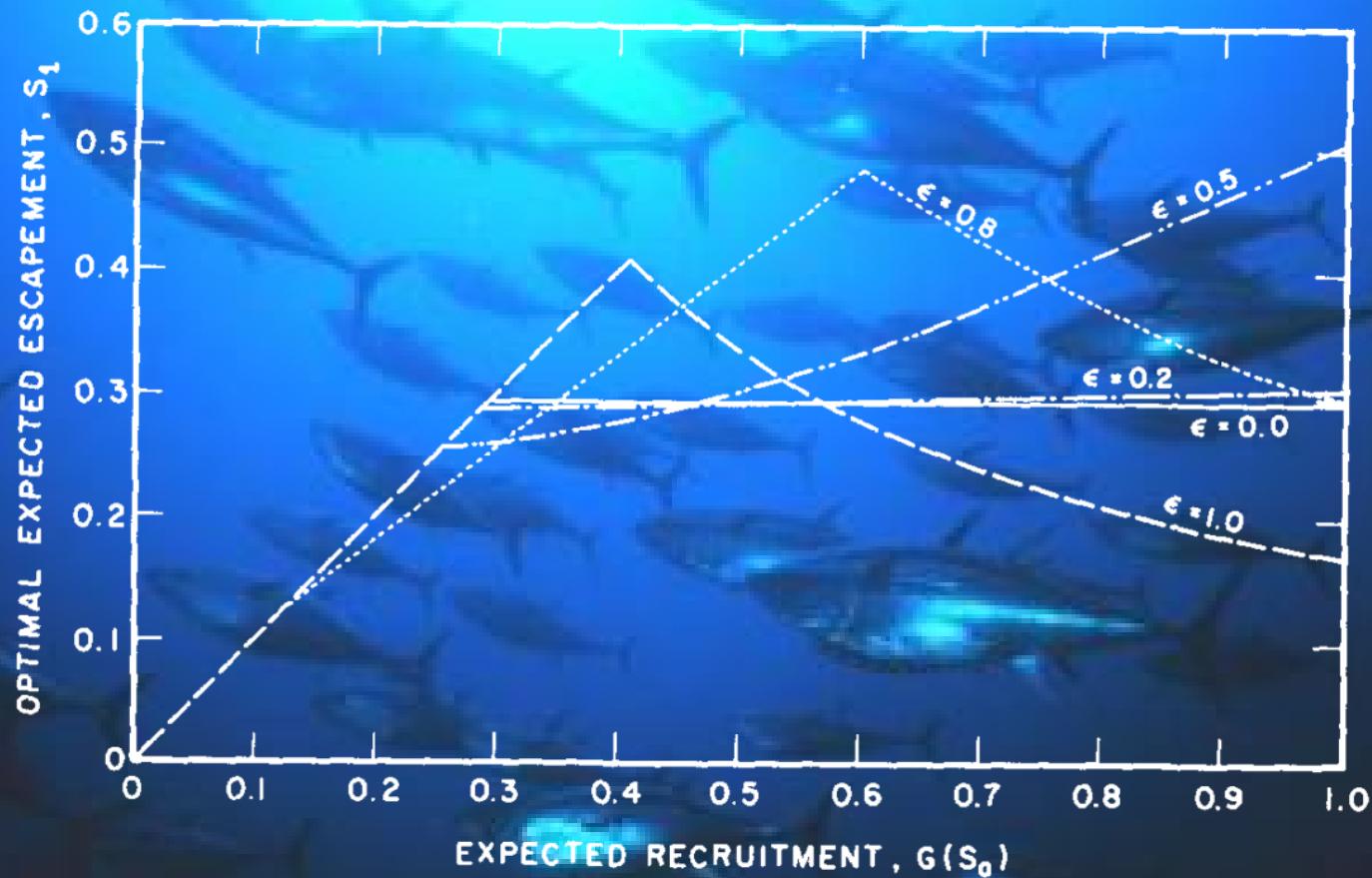
...and just stick with $s = B_{MSY}$ value from a model's deterministic skeleton

A large school of fish, likely tuna, swimming in a deep blue ocean. The fish are silhouetted against a lighter background, creating a sense of depth and movement.

A long-standing paradox

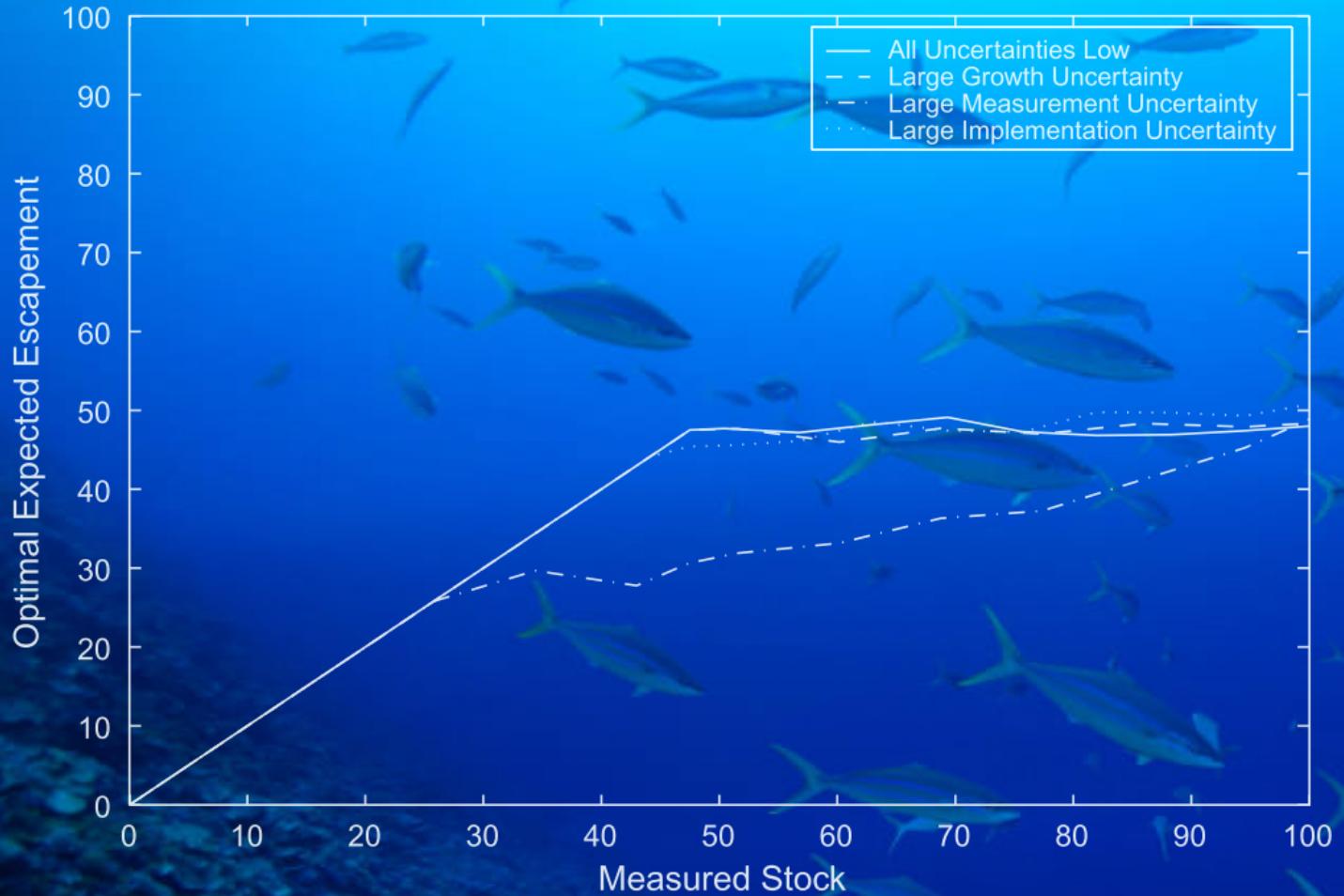
An important tacit assumption in Reed's analysis, as in the other works referred to above, is that the recruitment level X is known accurately prior to the harvest decision, [...] In the case of fishery resources, the stock level X is almost never known very accurately, owing to the difficulty of observing fish in their natural environment.

-- Clark & Kirkwood 1987



The above results appear to contradict the conventional wisdom of renewable resource management, under which high uncertainty would call for increased caution in the setting of quotas.

-- Clark & Kirkwood 1986



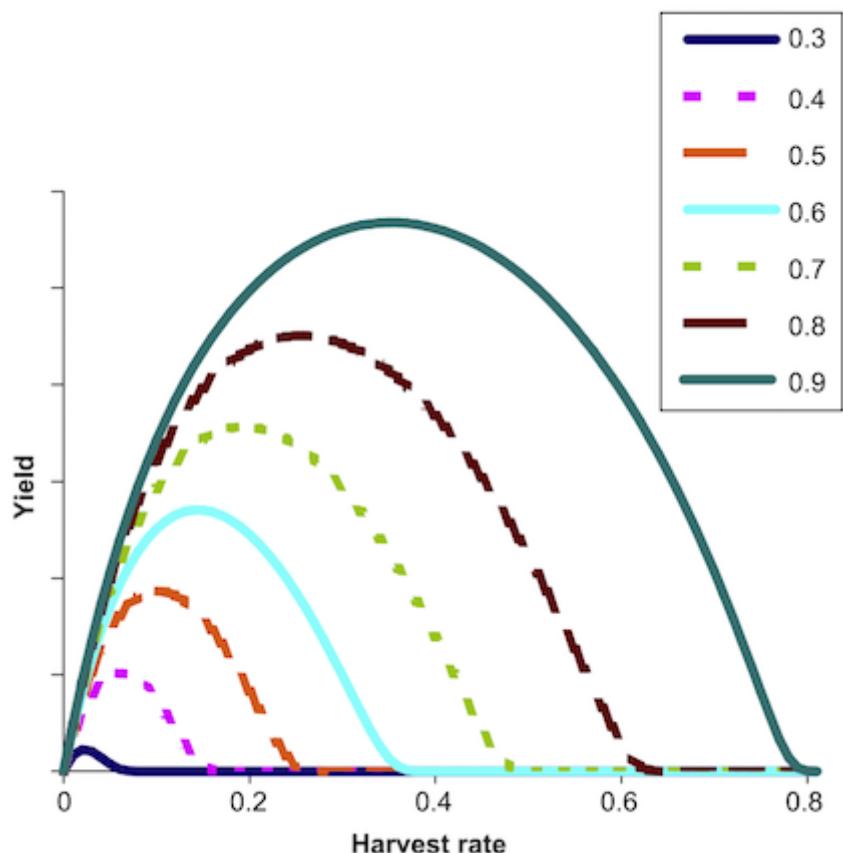
It may seem counter-intuitive that a measurement error causes lower expected escapements below the deterministic fishery closure threshold.

A large, dark fish, possibly a tuna, is caught in a fishing net, swimming towards the left. In the background, a scuba diver in a wetsuit and mask is visible, looking at the net. The water is a deep blue.

The uncertainty paradox:

More uncertainty = *Less precautionary?*

Pretty Good Yield (PGY)



A large, dark-colored fish, possibly a tuna or shark, is shown entangled in a fishing net. A scuba diver is visible in the background, observing the situation. The scene is set underwater, with blue light filtering through the water.

Measurement uncertainty -> Non-Markovian

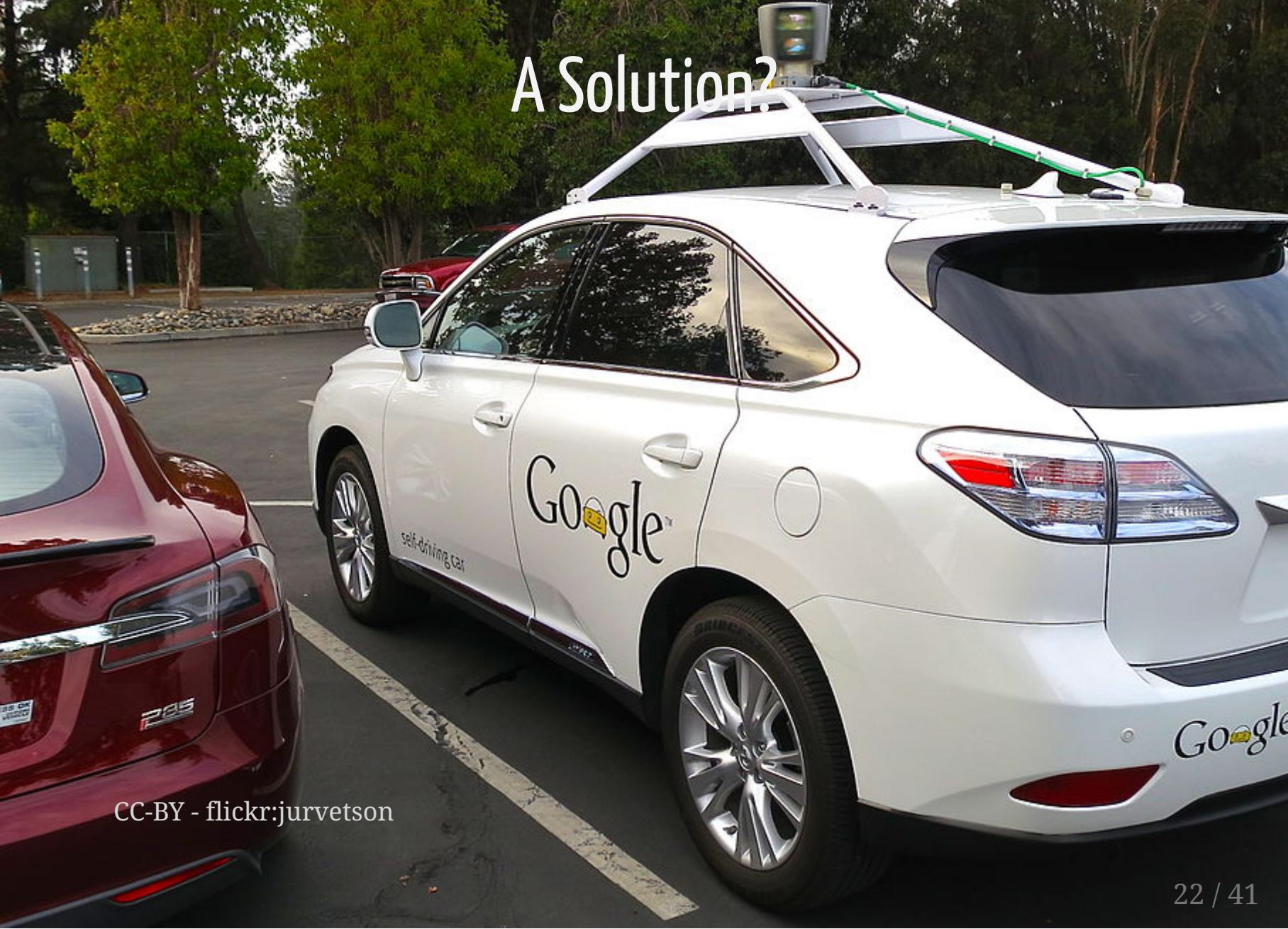
Previous work simply assumes the Markov property: prior history doesn't matter

A large, dark-colored fish, likely a tuna, is shown swimming through a fishing net. The fish is positioned diagonally across the frame, with its head towards the bottom right and its tail towards the top left. The net is made of a dark, mesh-like material and is partially visible in the lower right corner. In the background, a scuba diver wearing a mask and fins is visible, swimming towards the fish. The water is a deep blue color.

A Tough Problem

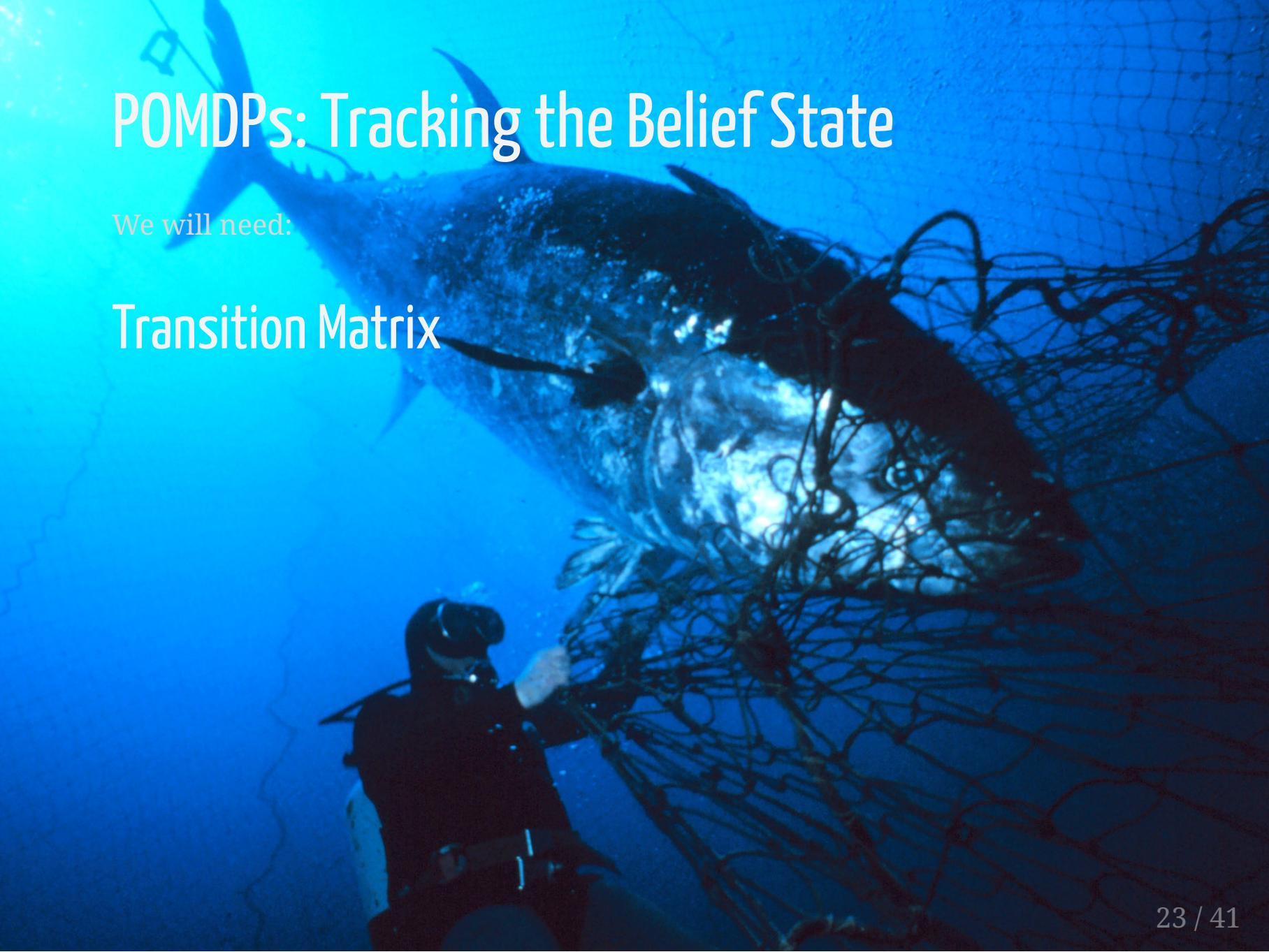
For reasons of tractability, we shall adopt the simplifying assumption that the escapement level S , is known exactly at the end of that period. (The mathematical difficulty of the problem increases markedly if this assumption is relaxed.)

A Solution?



CC-BY - flickr:jurvetson

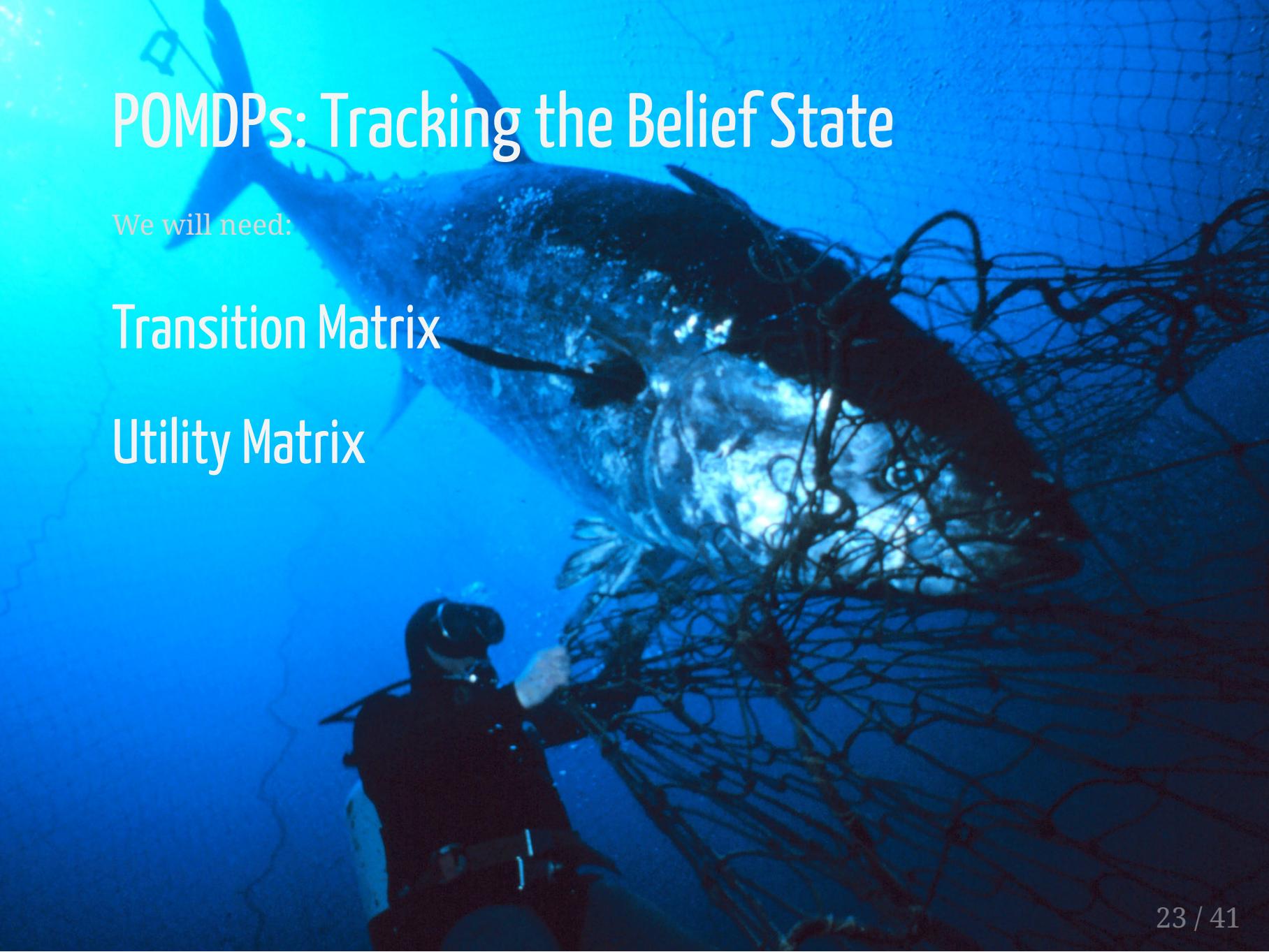
POMDPs: Tracking the Belief State

A photograph of a scuba diver in dark blue water. The diver is wearing a full scuba gear, including a mask, fins, and a wetsuit. They are reaching out towards a large fish, possibly a shark or a manta ray, which is entangled in a fishing net. The net is visible in the lower right foreground. The background is a deep blue, suggesting an underwater environment.

We will need:

Transition Matrix

POMDPs: Tracking the Belief State

A photograph of a scuba diver in blue water. The diver is facing away from the camera, towards a large fish that is entangled in a fishing net. The fish is dark-colored and has its mouth open. The net is visible in the lower right foreground. The background is a clear blue ocean.

We will need:

Transition Matrix

Utility Matrix

POMDPs: Tracking the Belief State

We will need:

Transition Matrix

Utility Matrix

Discount factor

POMDPs: Tracking the Belief State

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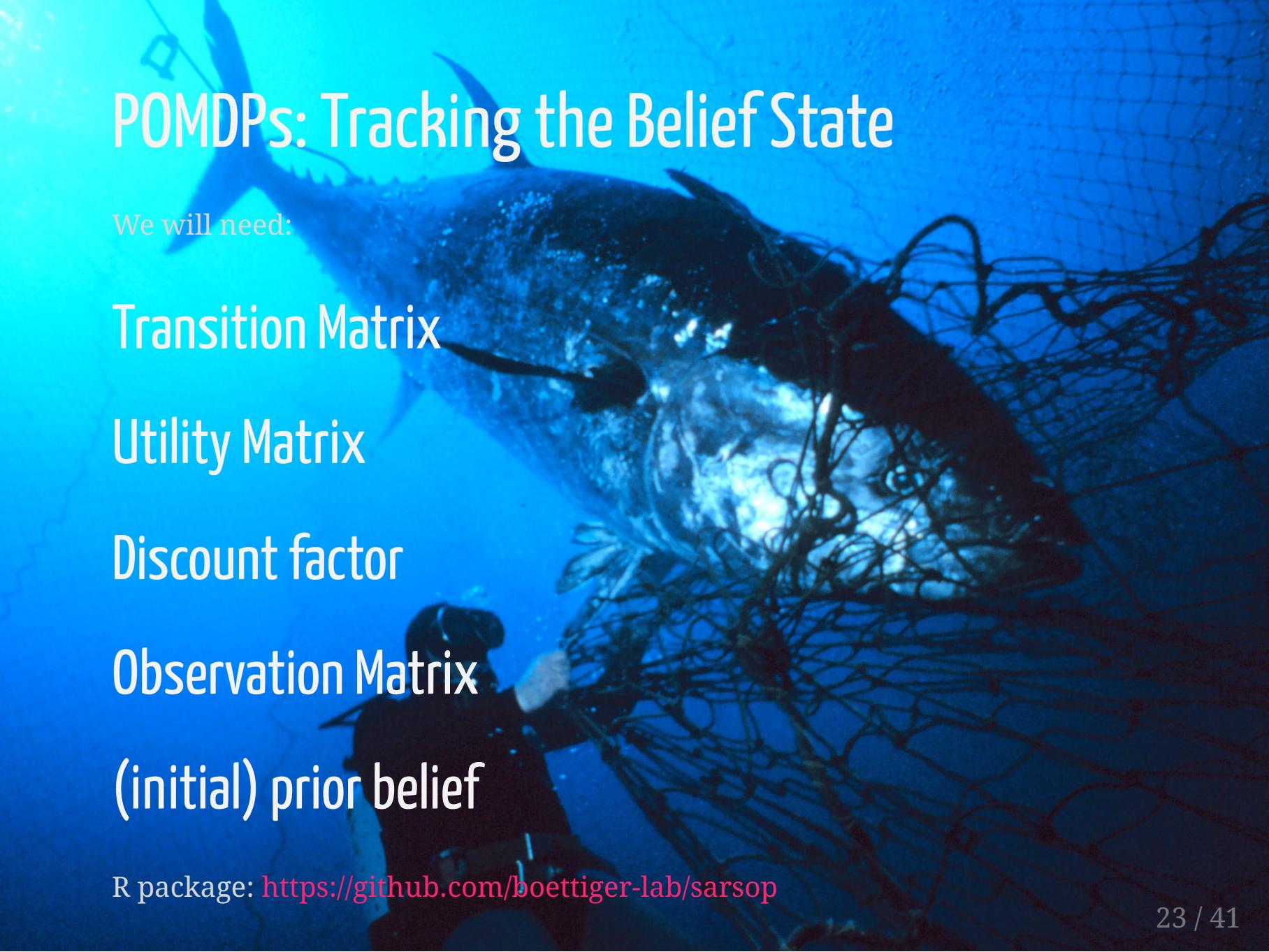
Utility Matrix

Discount factor

Observation Matrix

(initial) prior belief

POMDPs: Tracking the Belief State

A photograph of an underwater scene. A scuba diver in dark gear is visible in the lower-left foreground, facing away from the camera towards a large, dark fishing net that stretches across the frame. The water is a deep blue, and sunlight filters down from the surface in bright rays.

We will need:

Transition Matrix

Utility Matrix

Discount factor

Observation Matrix

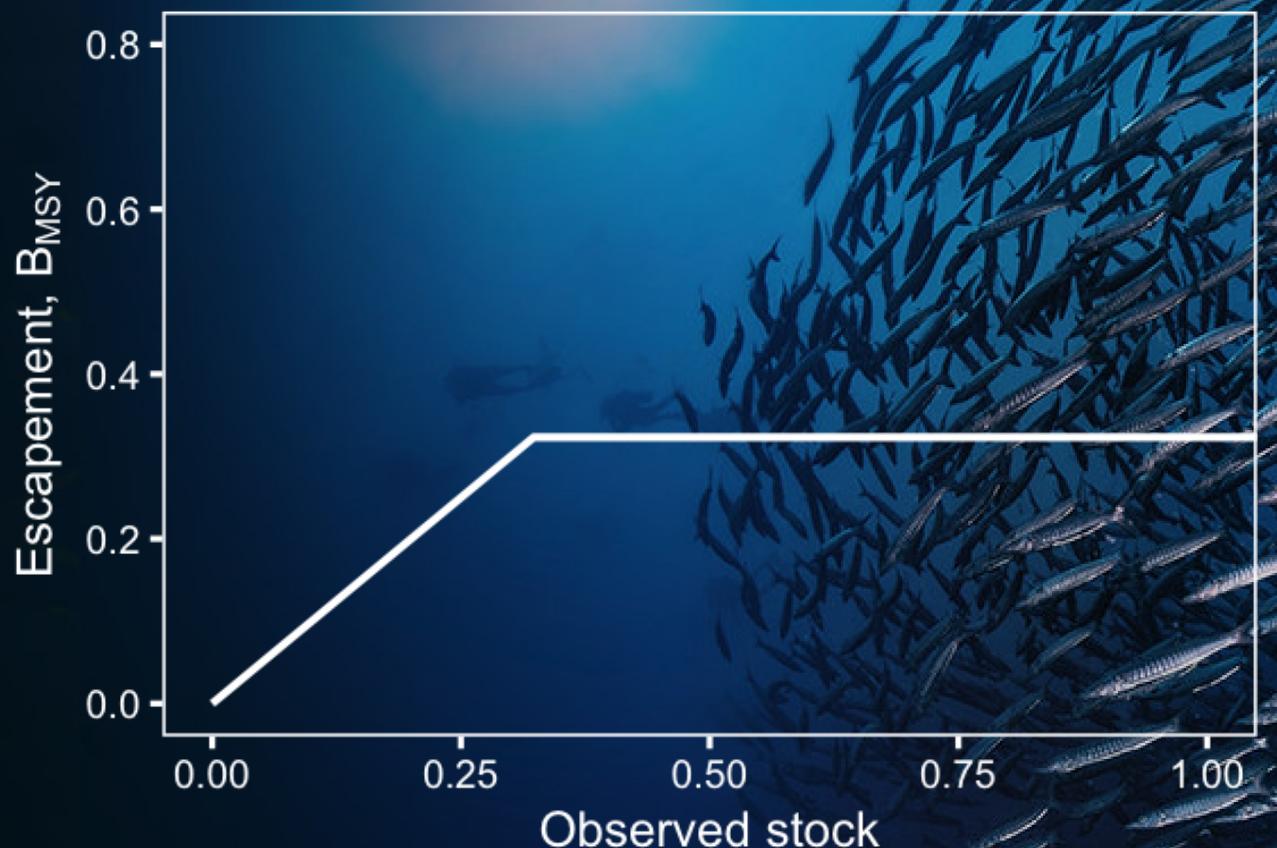
(initial) prior belief

R package: <https://github.com/boettiger-lab/sarsop>

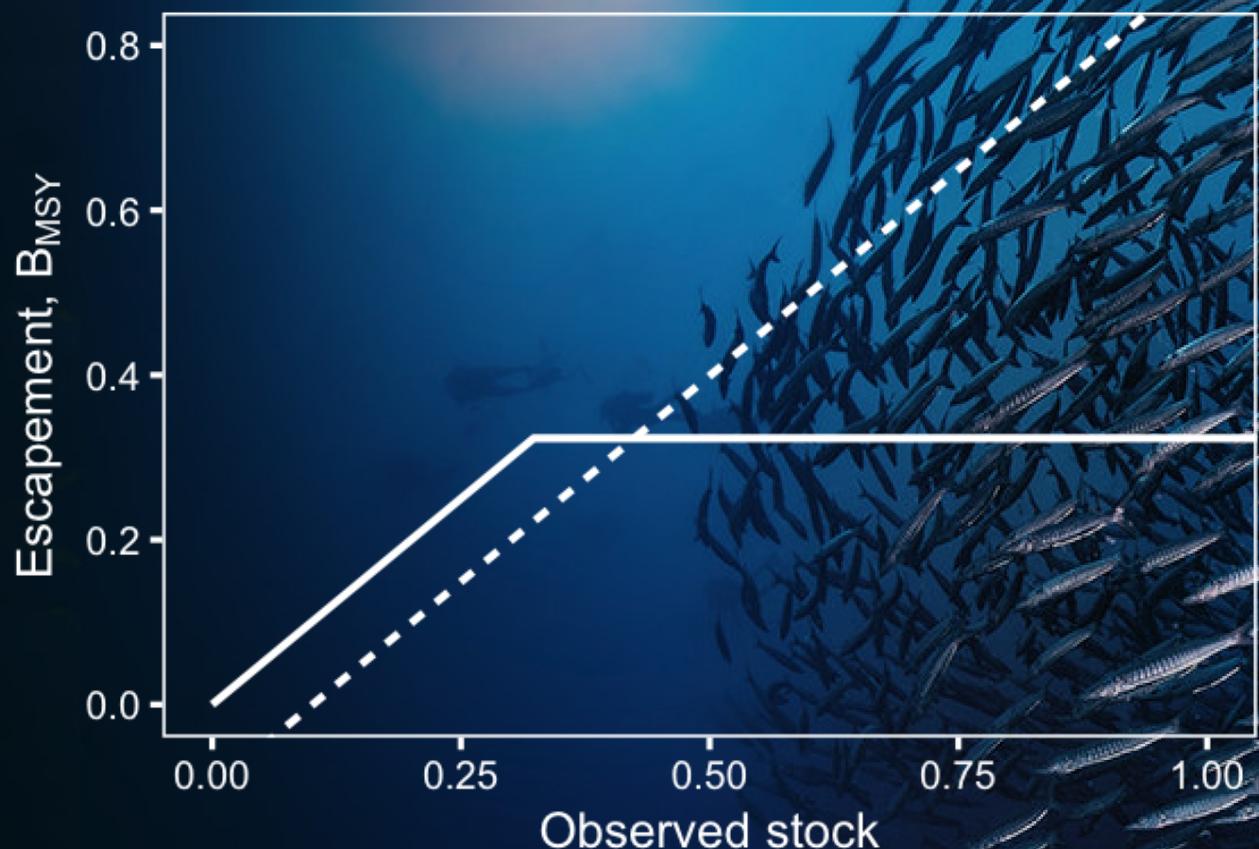


XSEDE Jetstream Cloud

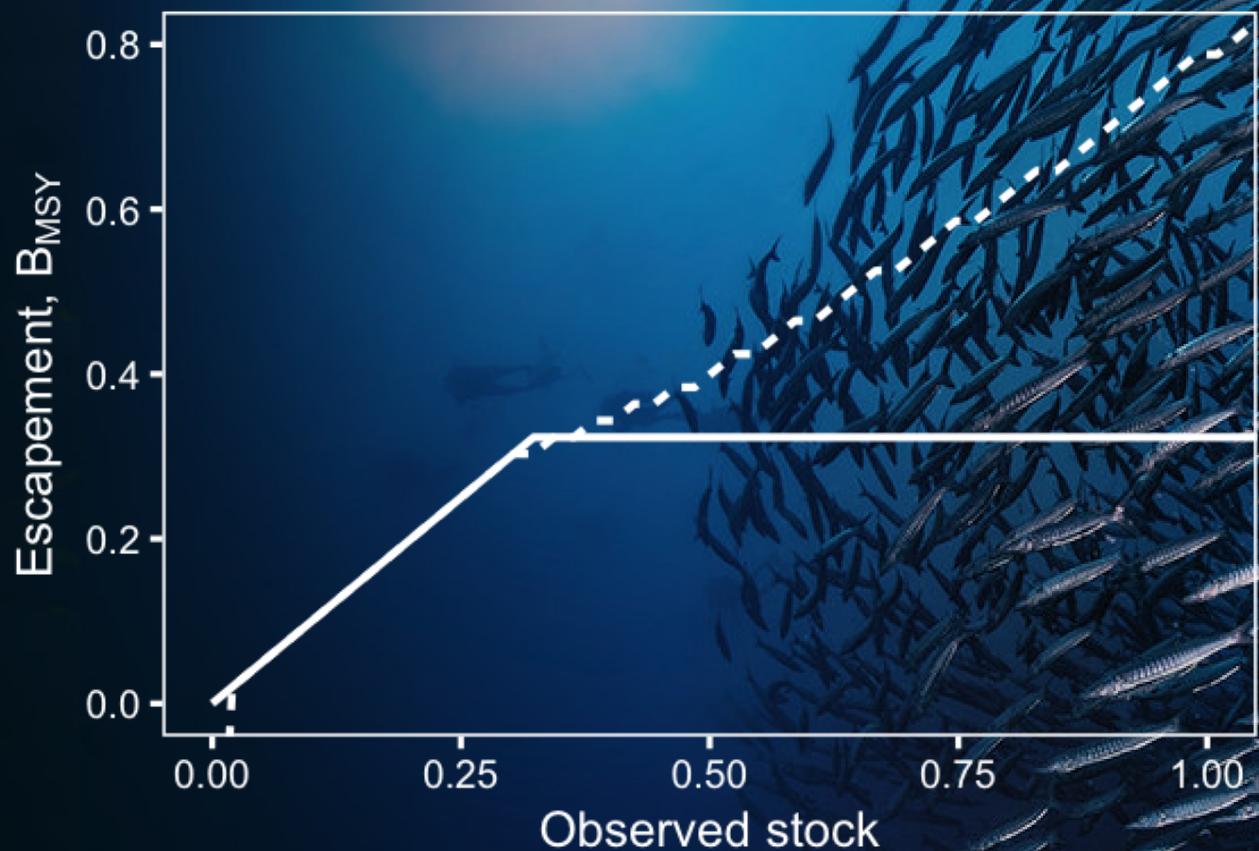
HPC for the rest of us



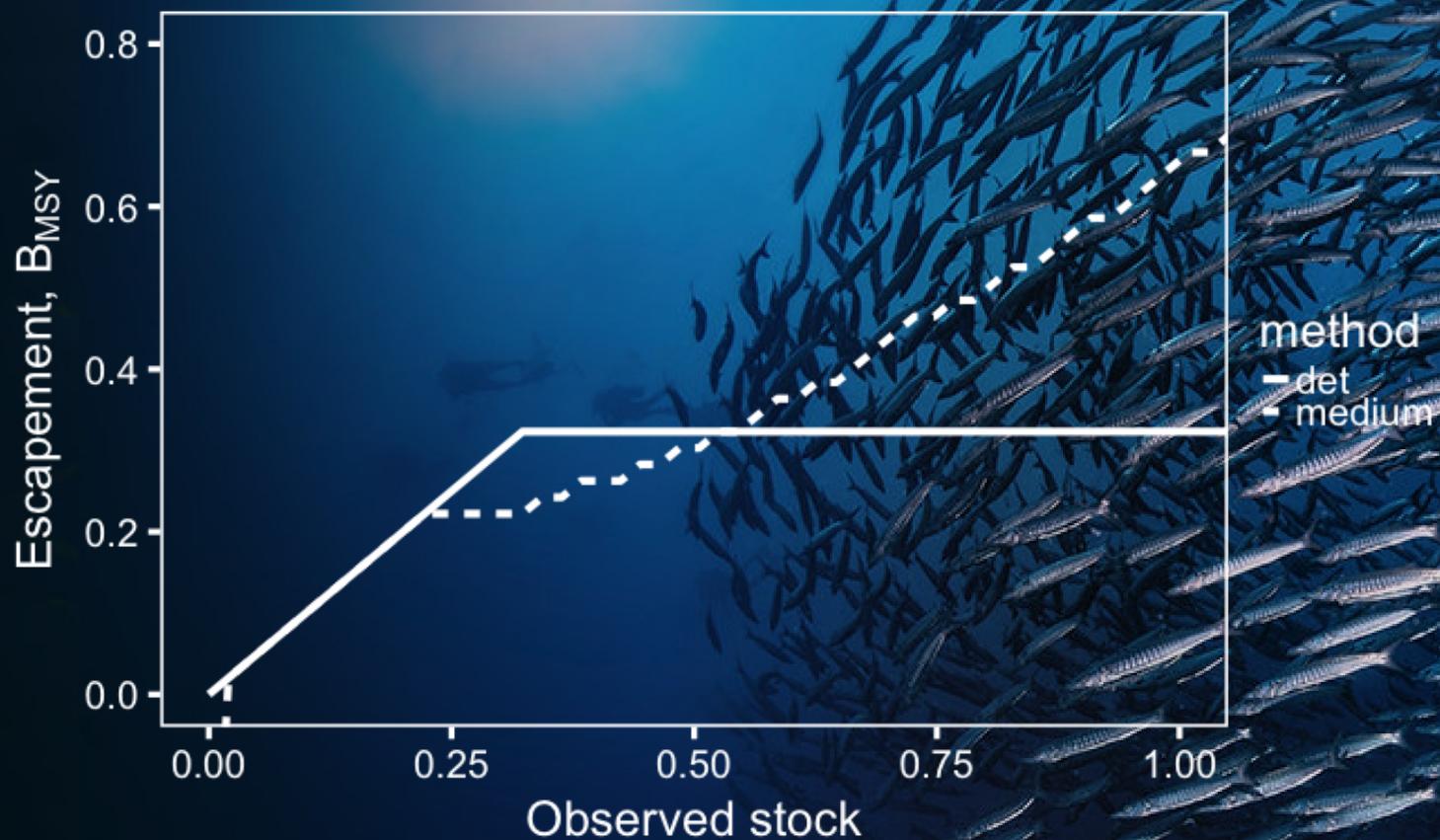
Deterministic Solution



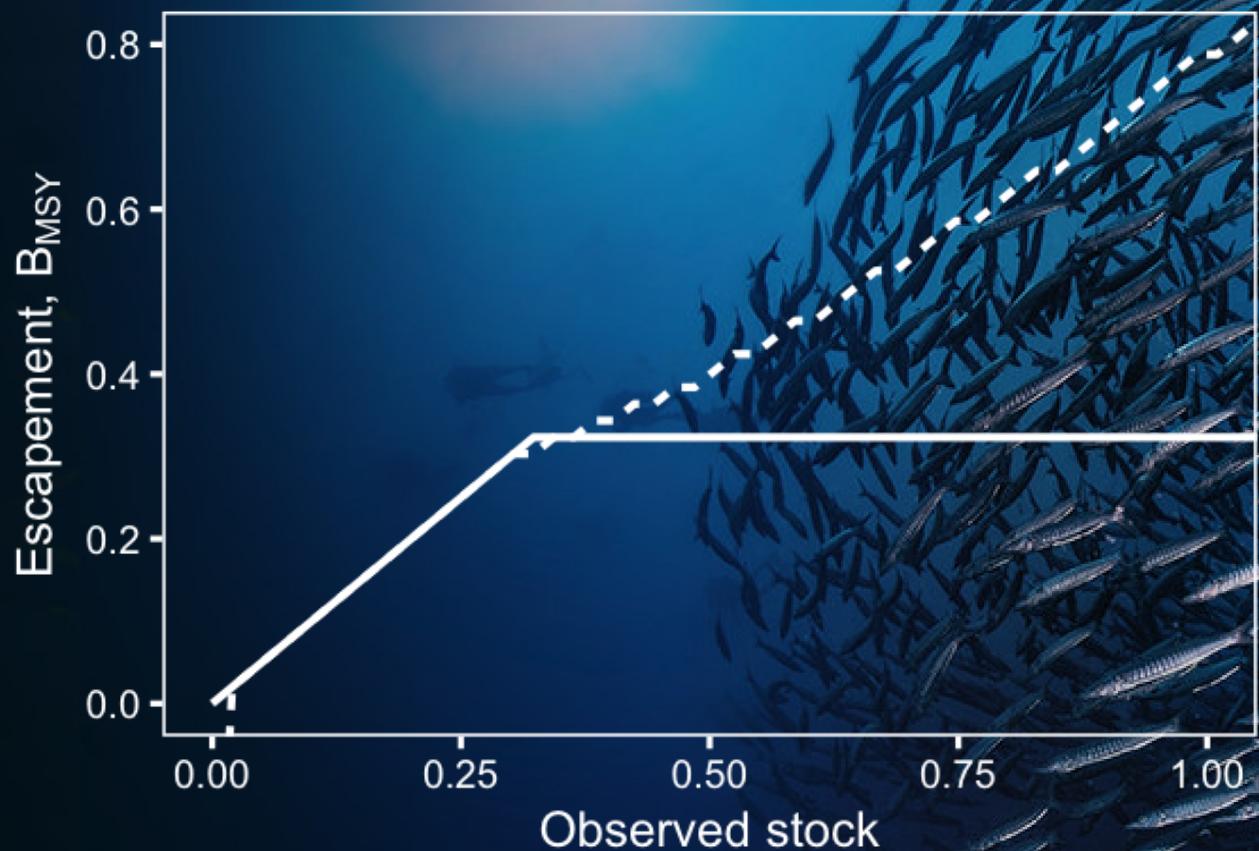
Pretty Good Yield



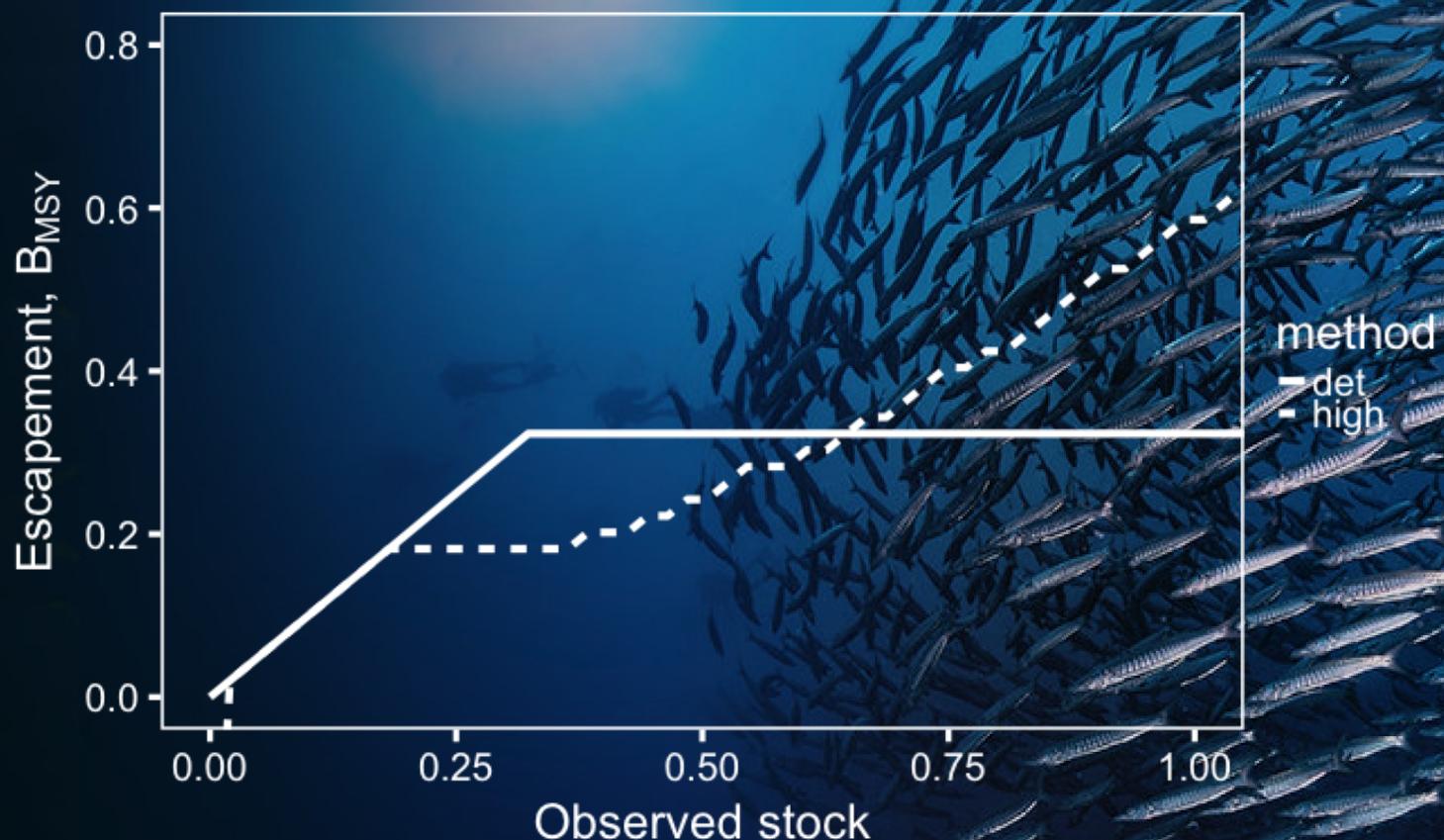
Common sense prevails!



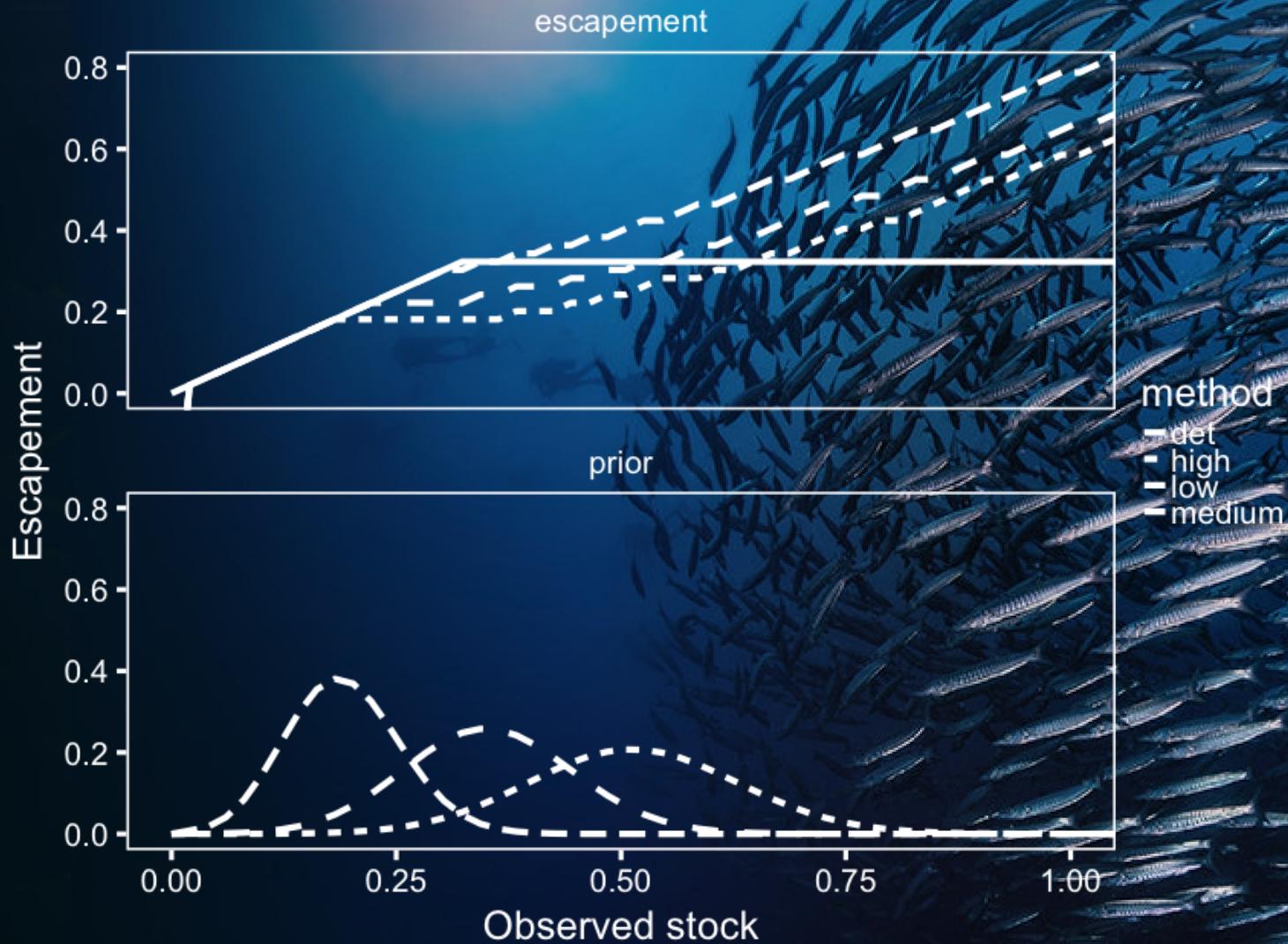
(Prior) beliefs matter

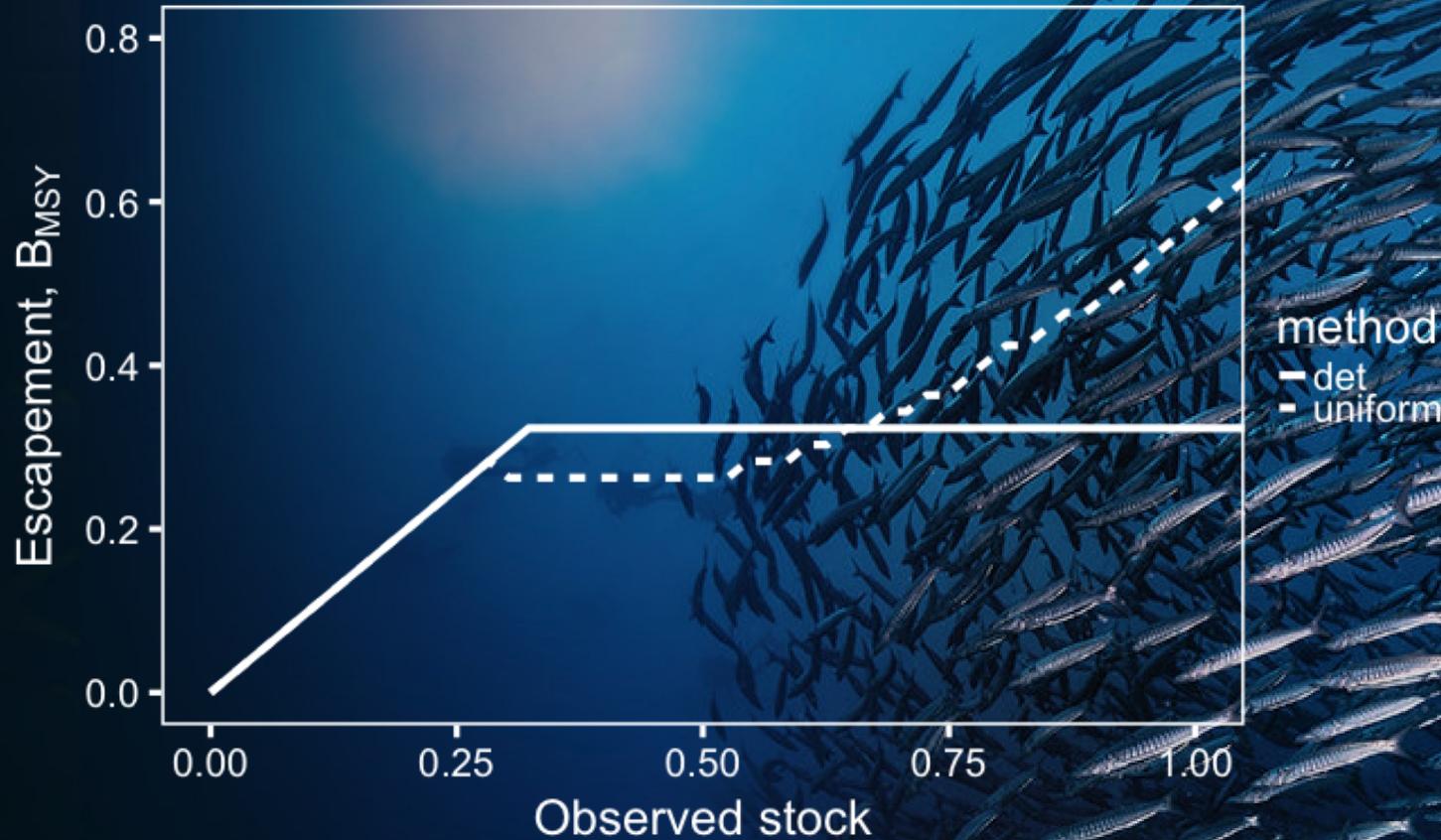


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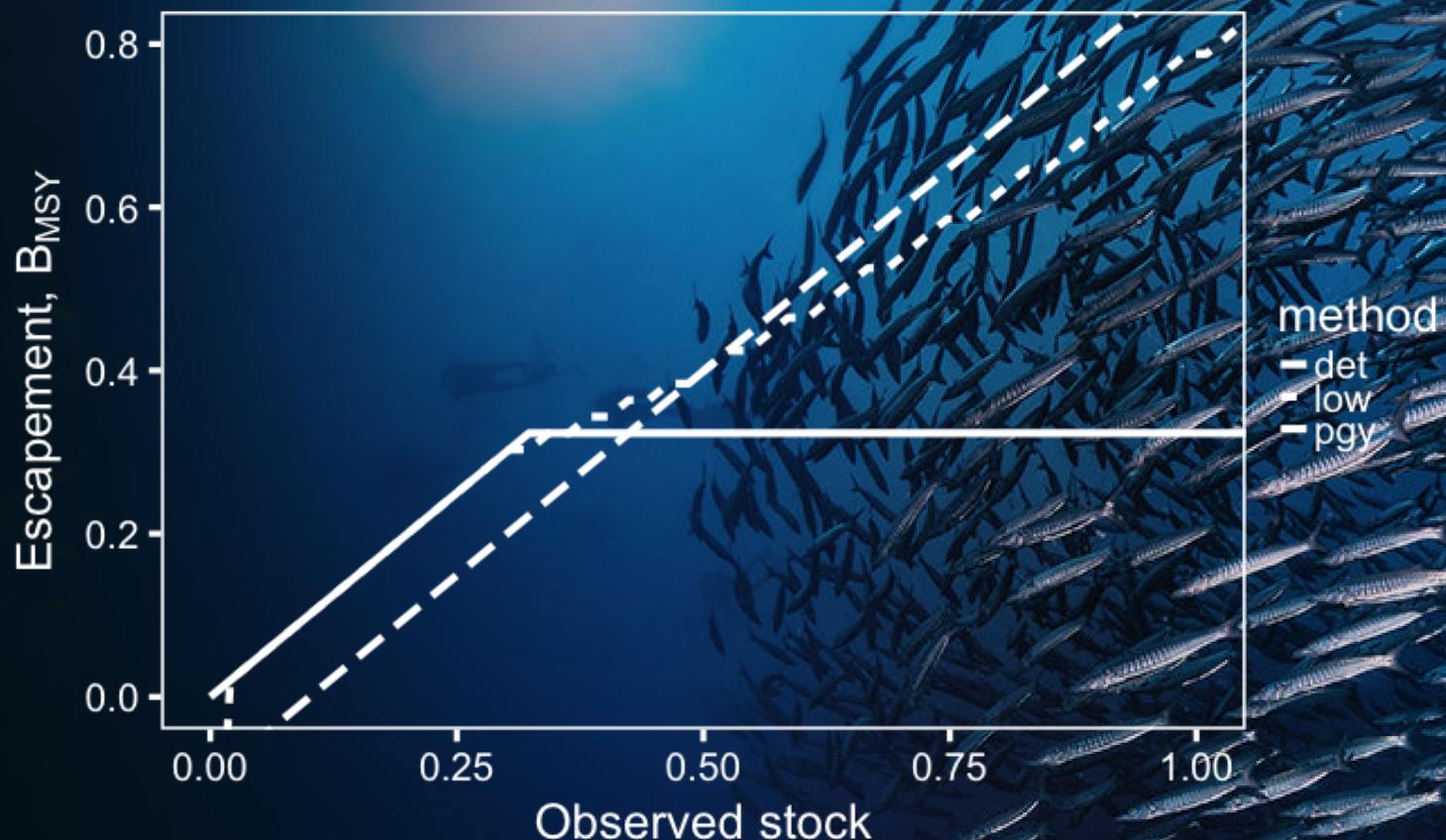


(Prior) beliefs matter





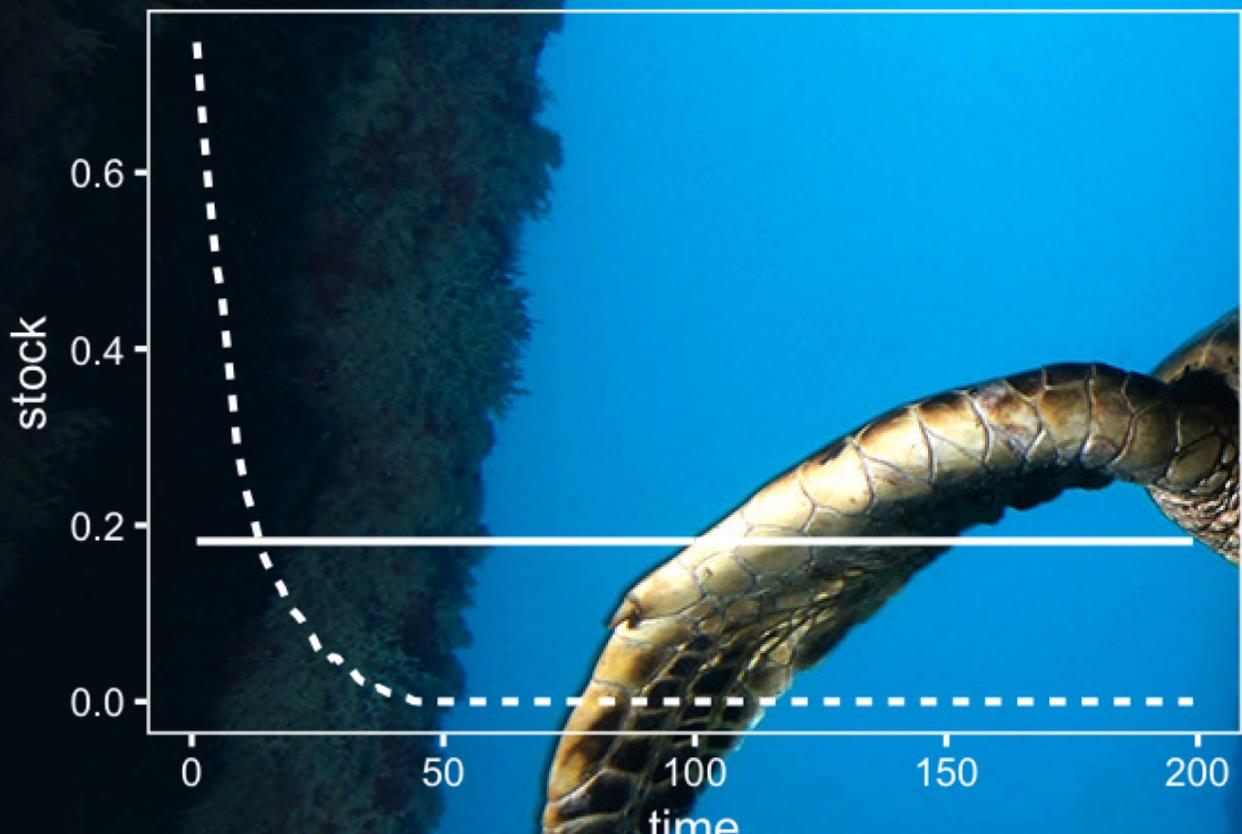
Paradoxical earlier results effectively ignored prior information



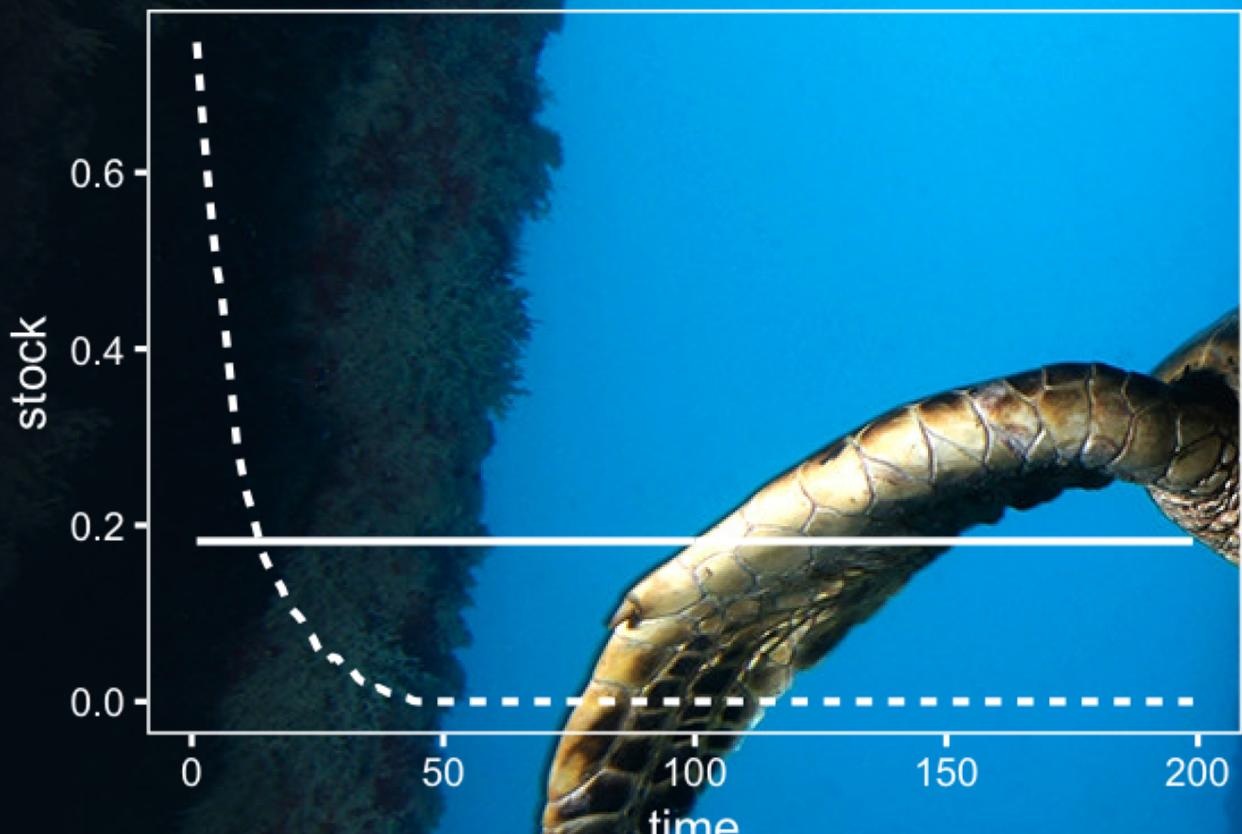
"Pretty Good Yield" isn't always more conservative



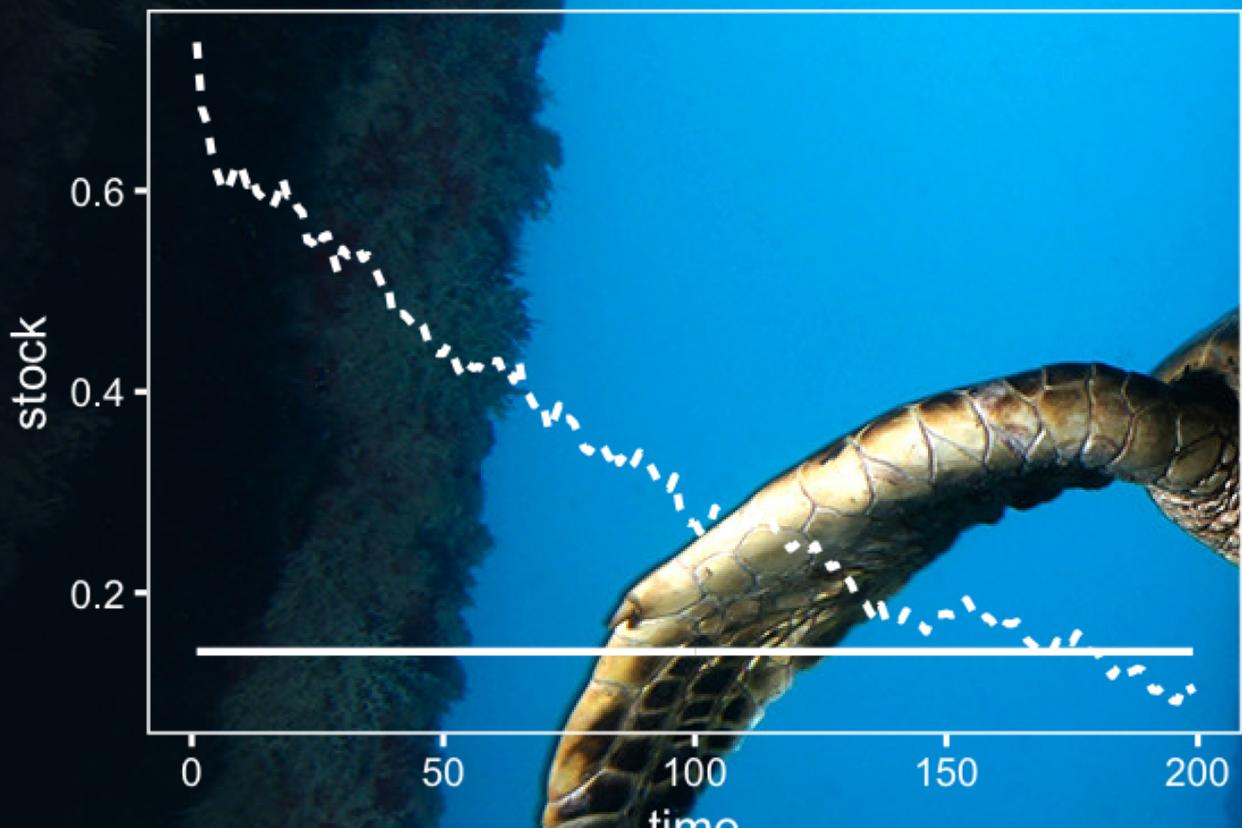
So how do these policies actually play out?



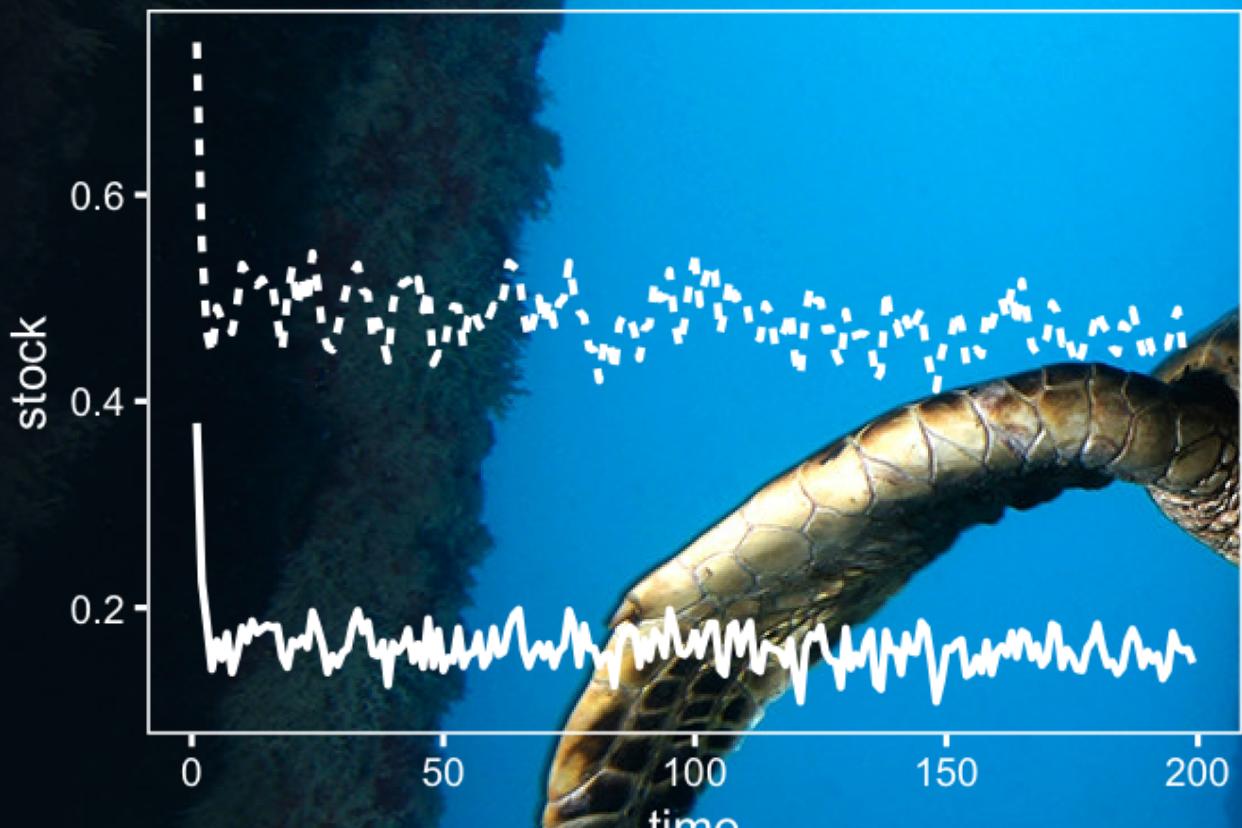
Maximum Sustainable Yield



Reed's MDP



Pretty Good Yield



POMDP

Conclusions

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- Predictions are not enough: Decisions need their own theory
- Precaution cannot be tacked on
- Beliefs / prior experience matters
- Much to learn from other fields

Acknowledgements



Milad Memarzadeh



ESPM Dept (startup)



Image credits



Cloud Computing

Appendix: Age structure

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- Larval only density dependence -> MSY solution, harvest only on most valuable age class (Reed 1980, Getz 1980)
- Age+stage structured may not be an MSY (cyclical escapement, still an average B_{MSY})
- Stochastic age-structured models: also support either larger or smaller harvest than the deterministic equivalent, but still at a constant escapement policy