Oyster population persistence with fluctuating dispersal rates

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Oyster background

- Chesapeake Bay native oyster *Crassostrea virginica*
- Ecosystem services – filtration, habitat
- Economic importance
- Drastic reduction in population due to overharvesting and disease
  - Populations at ~1% of historic abundance
- Restoration efforts are ongoing

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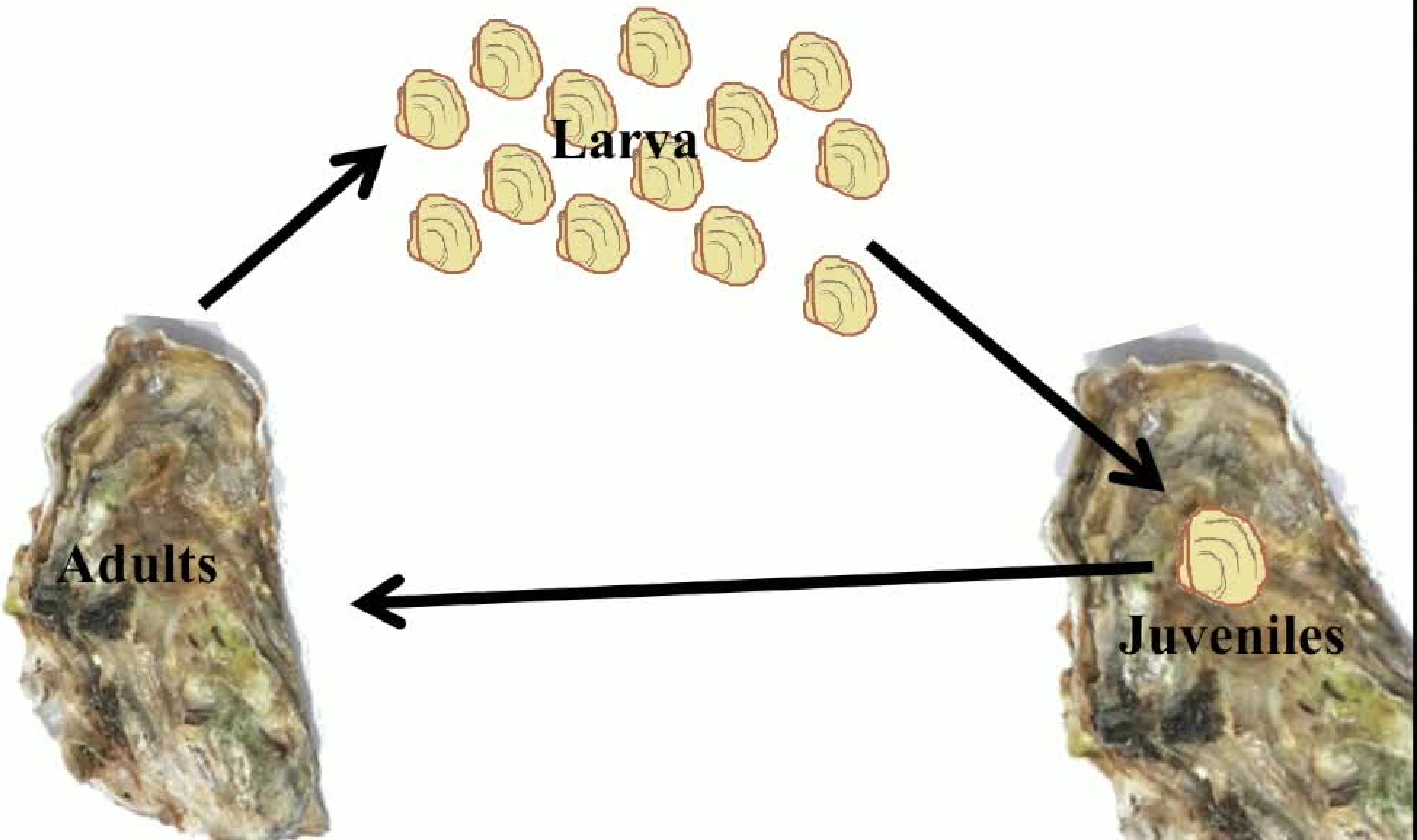
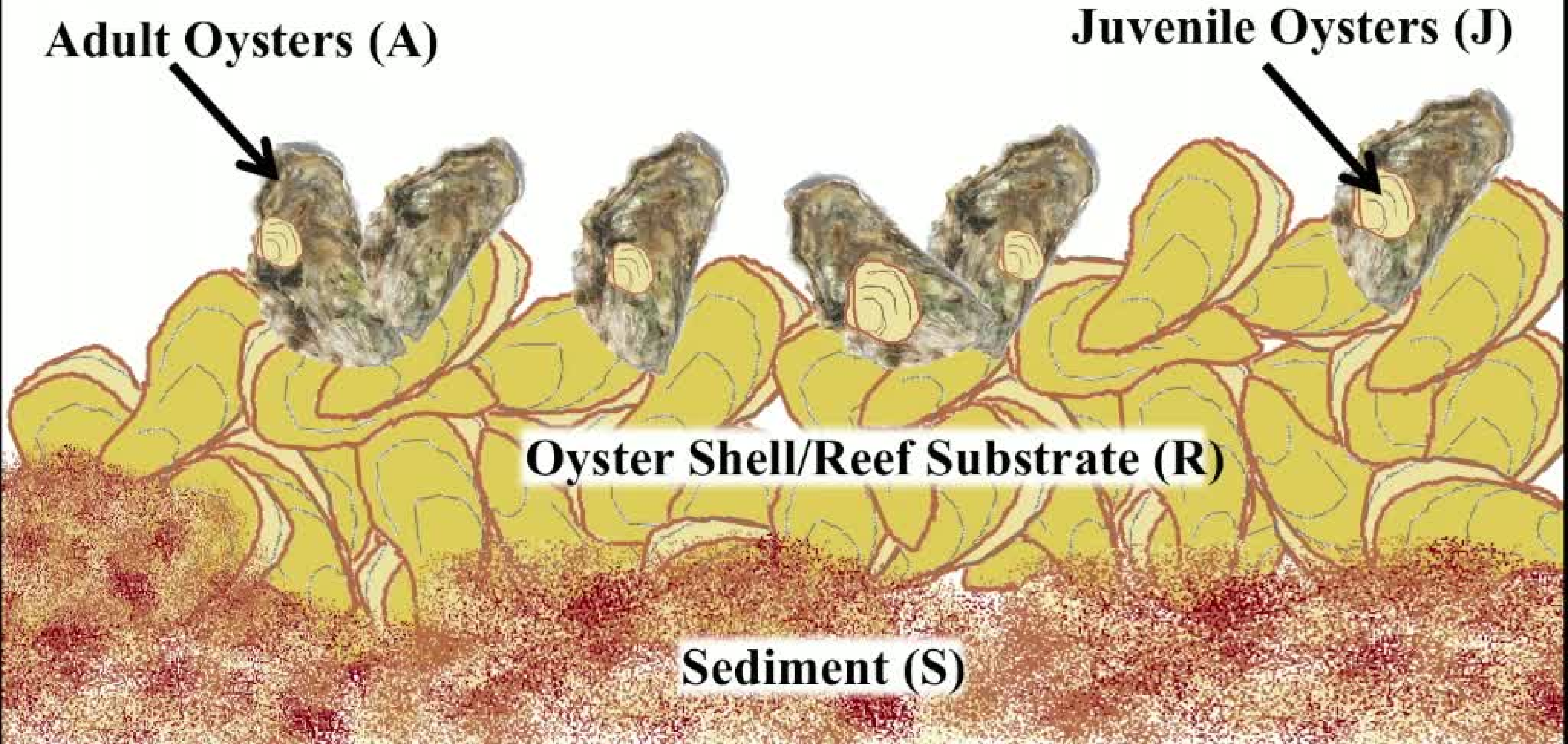
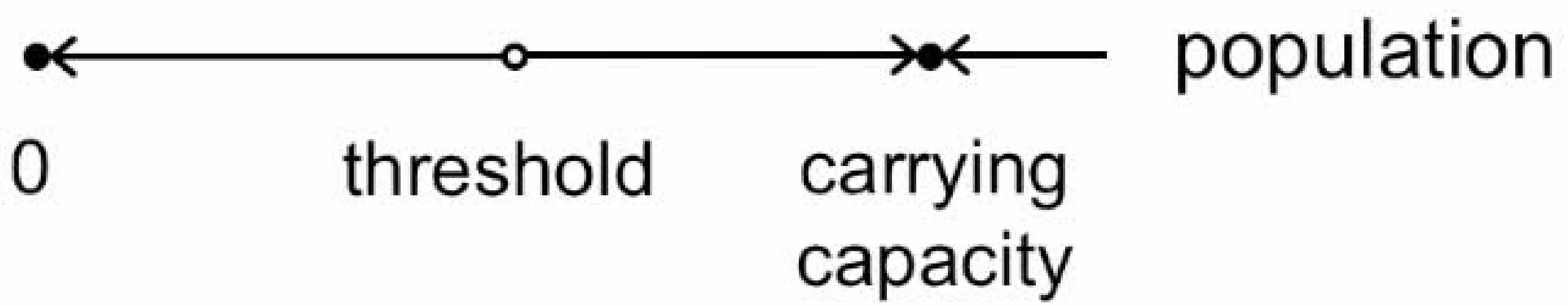
Life cycle



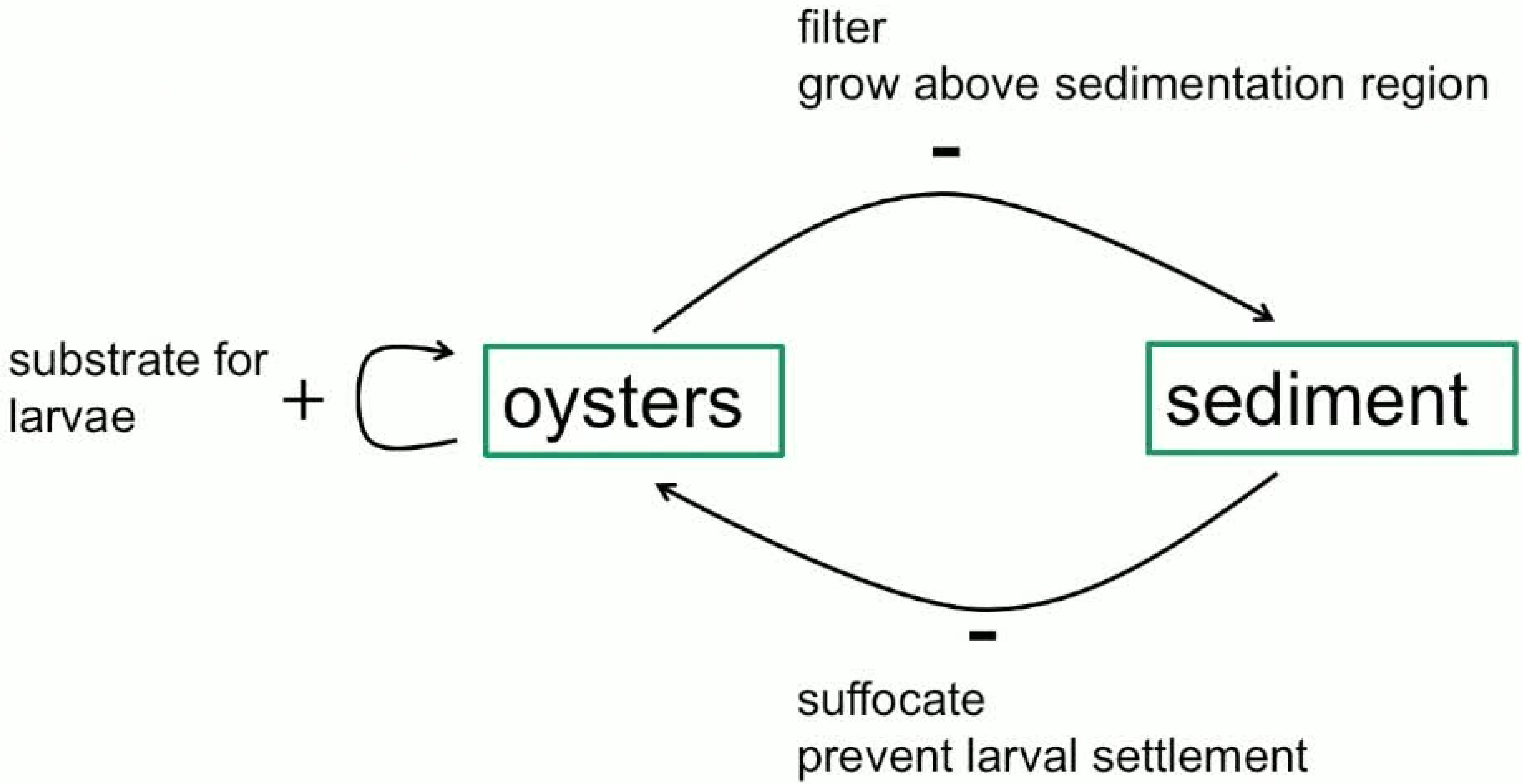
Reef structure



Allee effect



Feedbacks causing Allee effect



Stage-structured oyster-sediment model

$$\frac{dJ}{dt} = \underbrace{PL(A,R)f(d)}_{\text{larval deposition and growth}} - \underbrace{J}_{\text{aging}}$$

$$\frac{dA}{dt} = \underbrace{\alpha J}_{\text{aging}} + \underbrace{\phi A f(d)\left(1 - \frac{A}{K}\right)}_{\text{logistic growth}} - \underbrace{\mu f(d) A}_{\text{natural mortality}} - \underbrace{\epsilon(1 - f(d))A}_{\text{sediment mortality}}$$

J=juvenile oysters
A=adult oysters
R=reef (dead shells)
S=sediment

(Lipcius, Zhang, Zhou, Shaw, and Shi, preprint)

Stage-structured oyster-sediment model

$$\frac{dR}{dt} = \mu f(d)A + \epsilon(1 - f(d))A \underbrace{- \gamma R}_{\text{reef degradation}}$$

$$\frac{dS}{dt} = \underbrace{Cge^{-FA/Cg}}_{\text{deposition}} - \underbrace{\beta S}_{\text{erosion}}$$

(Lipcius, Zhang, Zhou, Shaw, and Shi, preprint)

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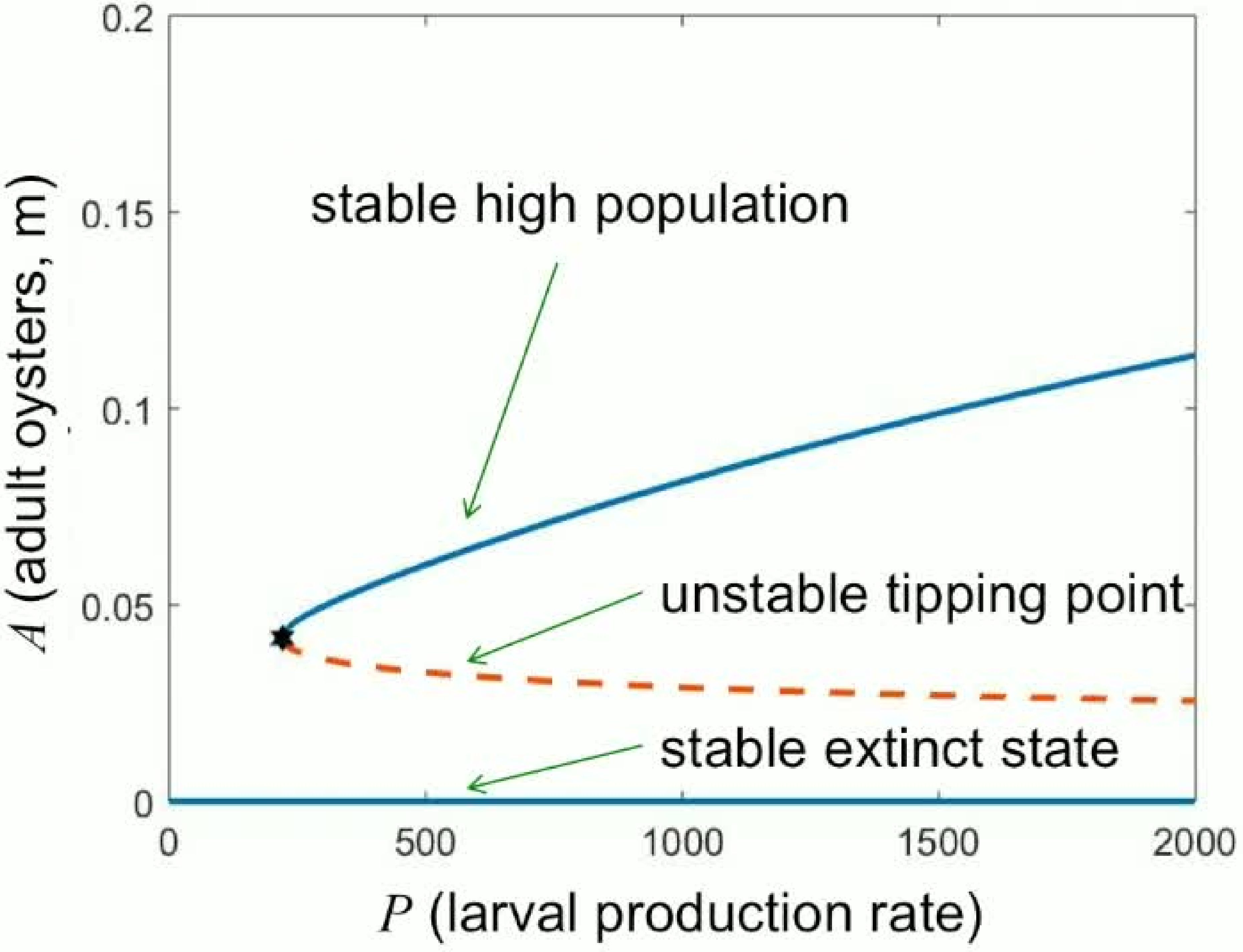
Bistability



Stochasticity

- Larvae are dispersed by currents
- Occurs annually during ~2 week period
- More rainfall means lower larval availability

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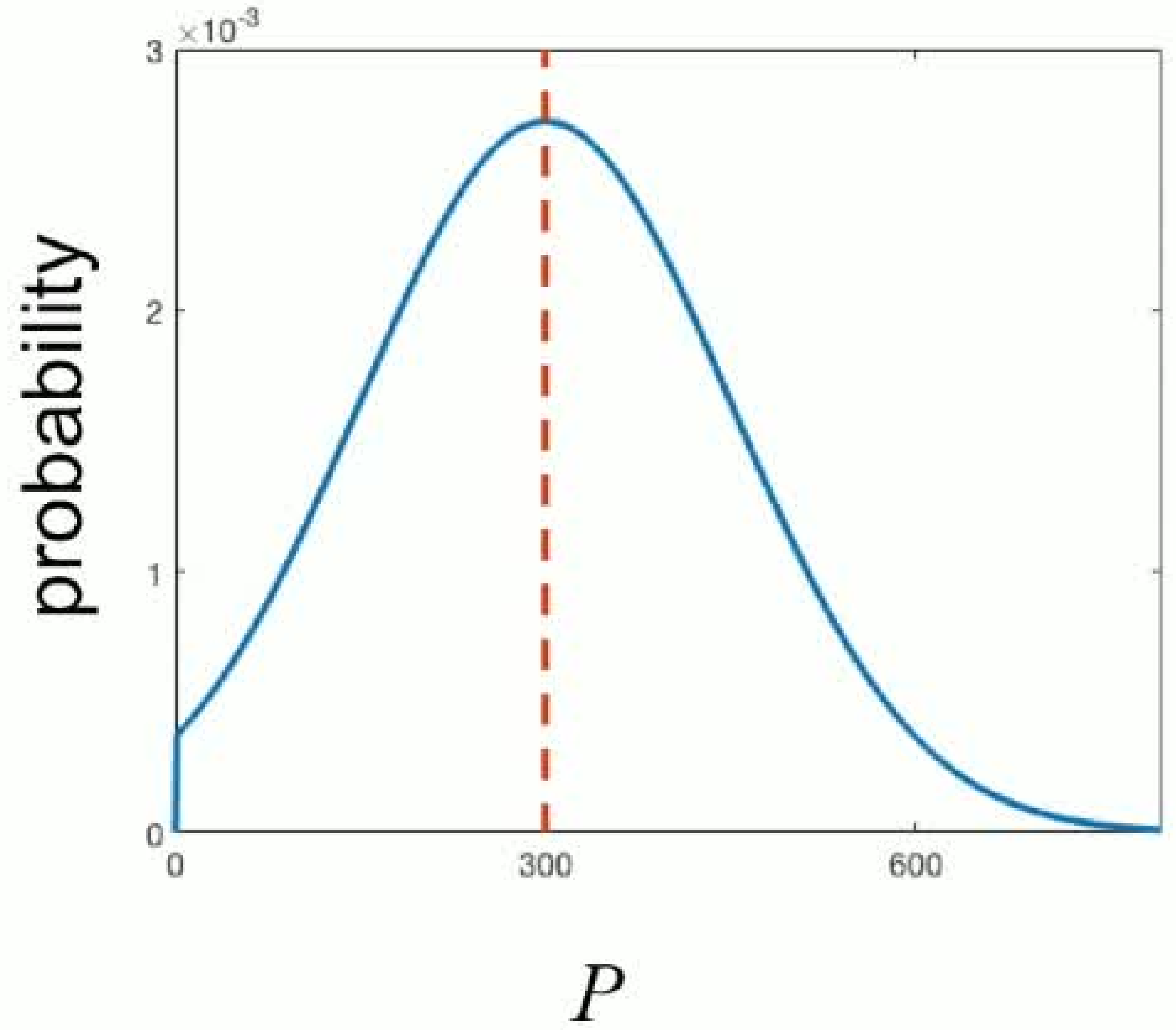
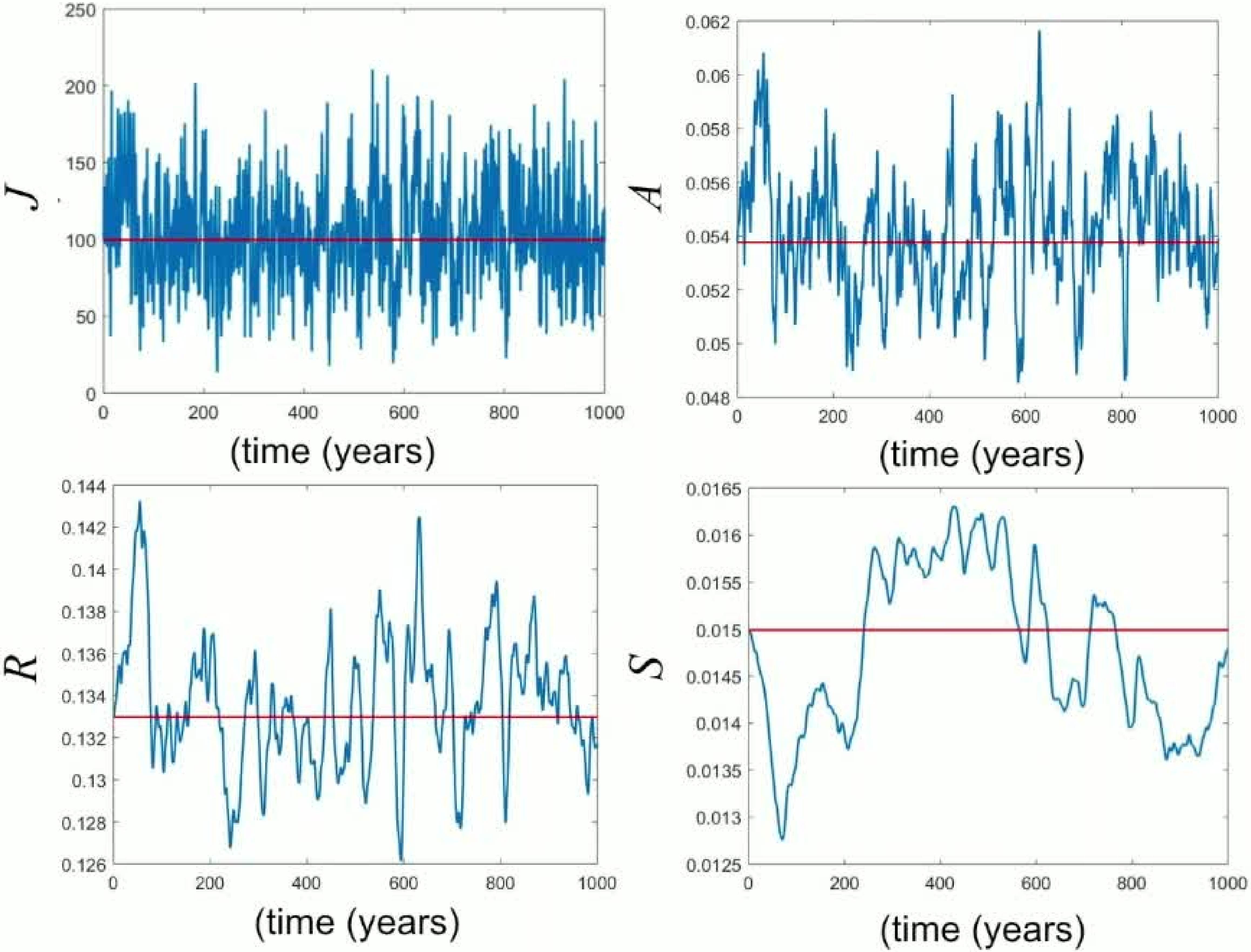
- Larvae are dispersed by currents
- Occurs annually during ~2 week period
- More rainfall means lower larval availability
- Standard deviation in larval availability can be 30% to 115% of mean
  - Based on 2 years of data in 3 locations (Lipcius, Zhang, Zhou, Shaw, and Shi, preprint)

Stochasticity

- Draw larval production rate P annually from a truncated normal distribution
- Integrate ODEs piecewise

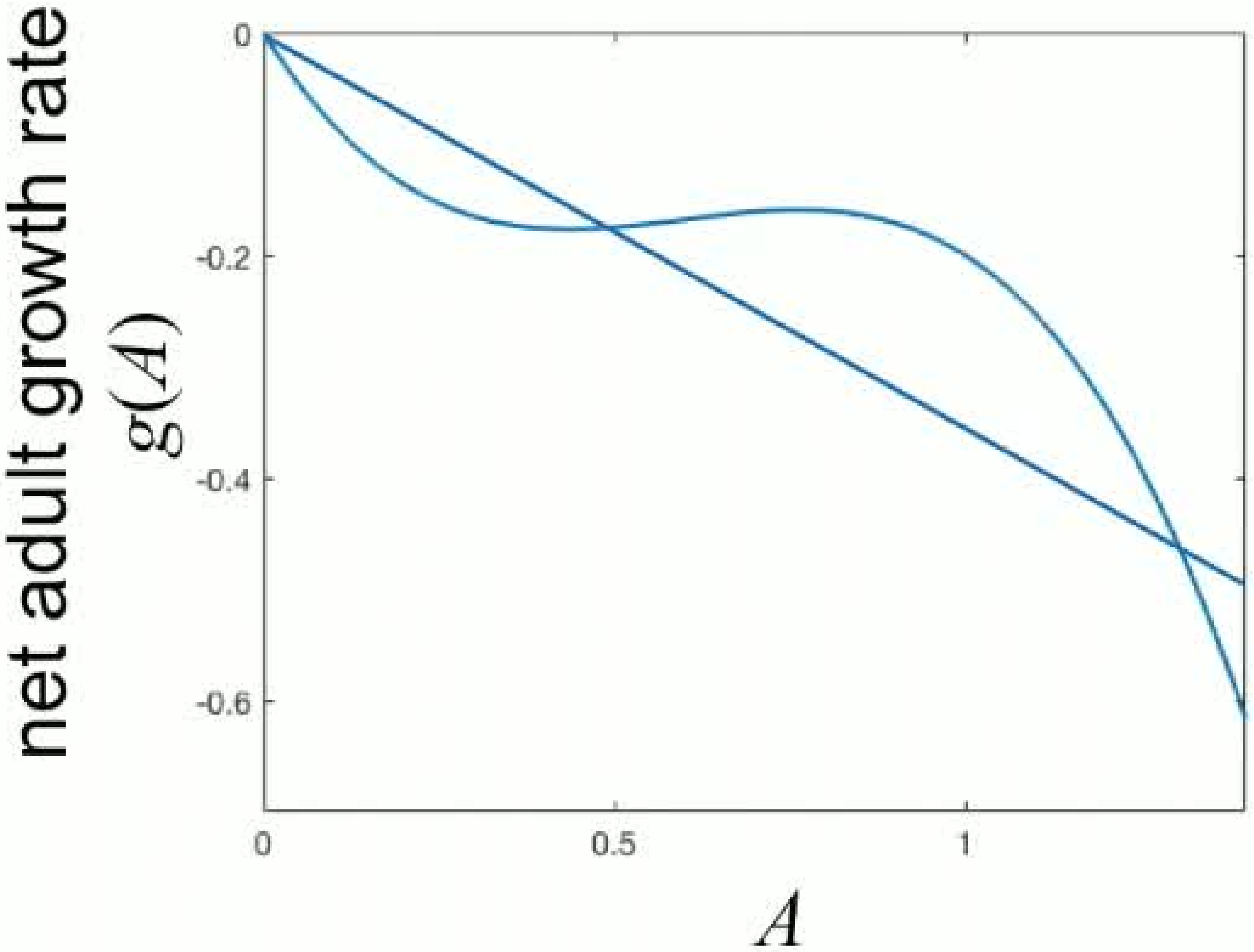



J
(time (years))
A
(time (years))
R
(time (years))
S
(time (years))

Simpler model

$$\frac{dJ}{dt} = PA - mJ$$
$$\frac{dA}{dt} = \alpha mJ + g(A)$$

Larval production rate:
$P = P_0 + \eta(t)$
(continuous noise, SDE)



(Extinction in non-stage structured models with Allee effect has been studied before, e.g., Assaf and Meerson 2010, Nieddu et al 2014)

Stochastic extinction

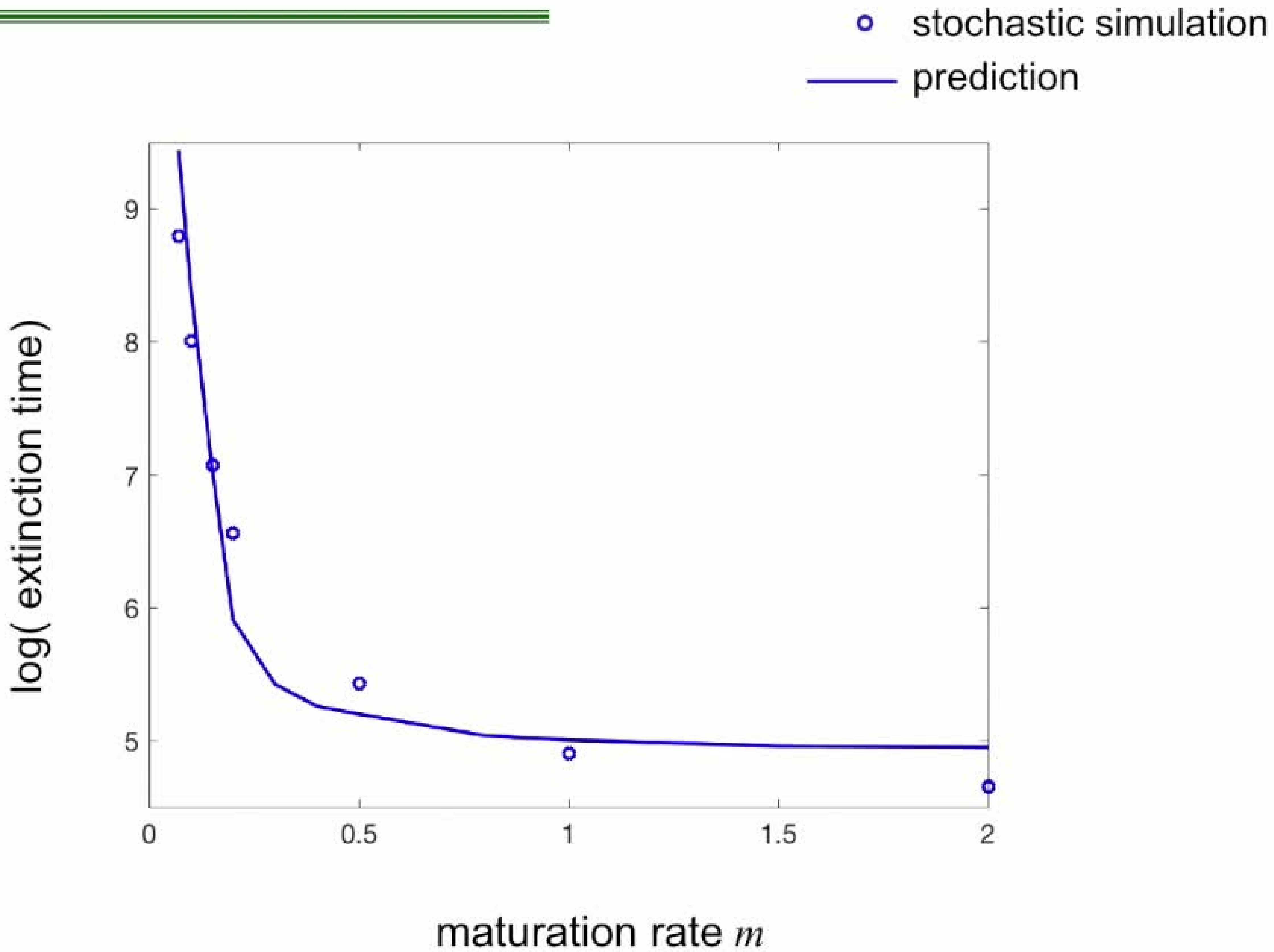
- Due to noise on juveniles, extinction is inevitable in long time limit
- Probability of a given trajectory $x(t)$ depends on probability of associated noise:

$$p[x(t)] \propto e^{-\frac{1}{2D}\int \eta^2 dt} \propto e^{-S[x(t)]/D}$$

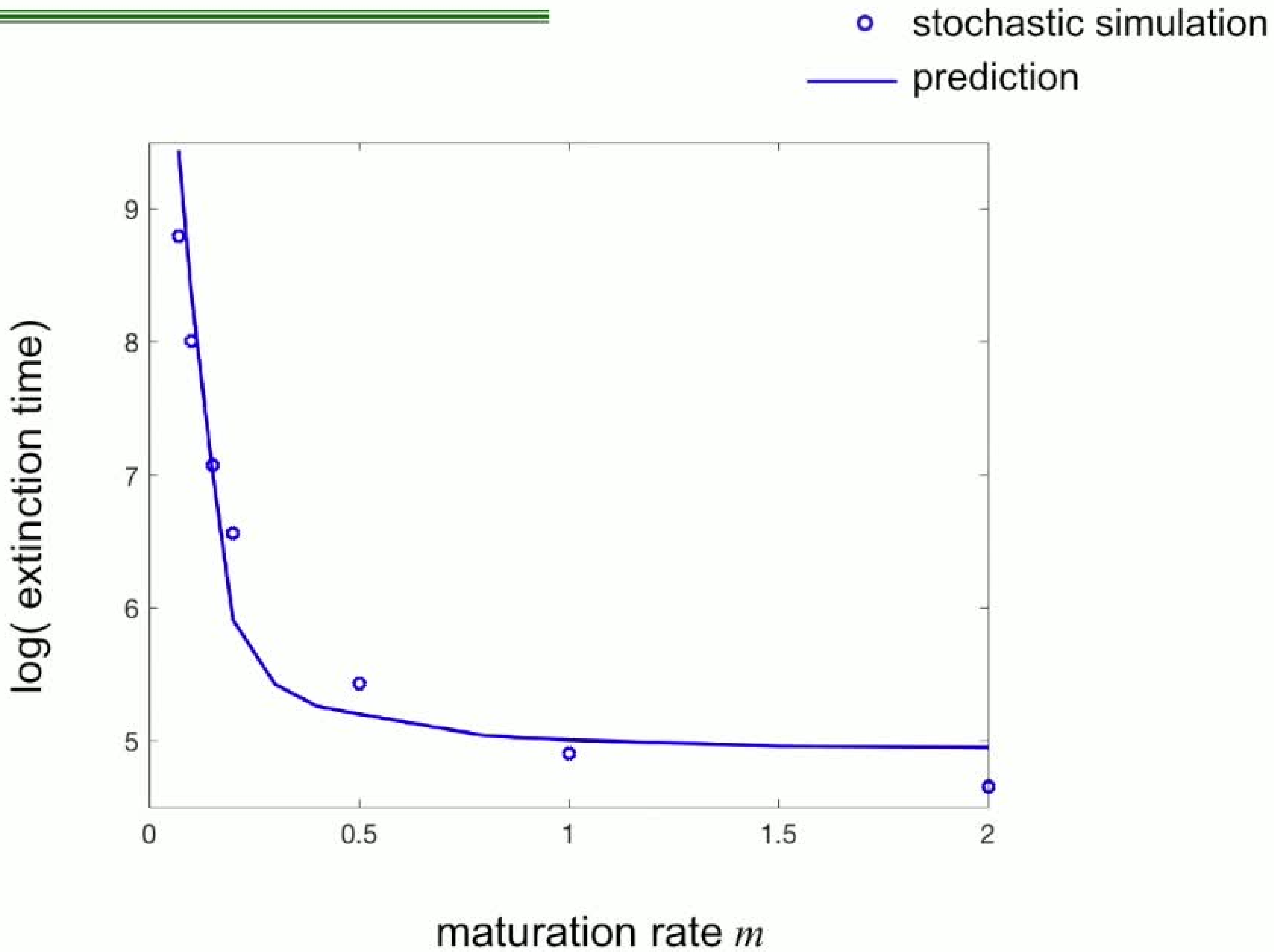
where D is variance of noise and $S(x)$ is the action
(see Forgoston and Moore SIAM Rev 2018 for a recent review)

- Maximizing extinction probability requires minimizing action over all possible paths to extinction—calculus of variations problem
- When extinction occurs, it does so along a most likely path (optimal path)
- Solve for path numerically using geometric minimum action method (gMAM) (Heymann and Venden-Eijnden 2008)

Extinction time

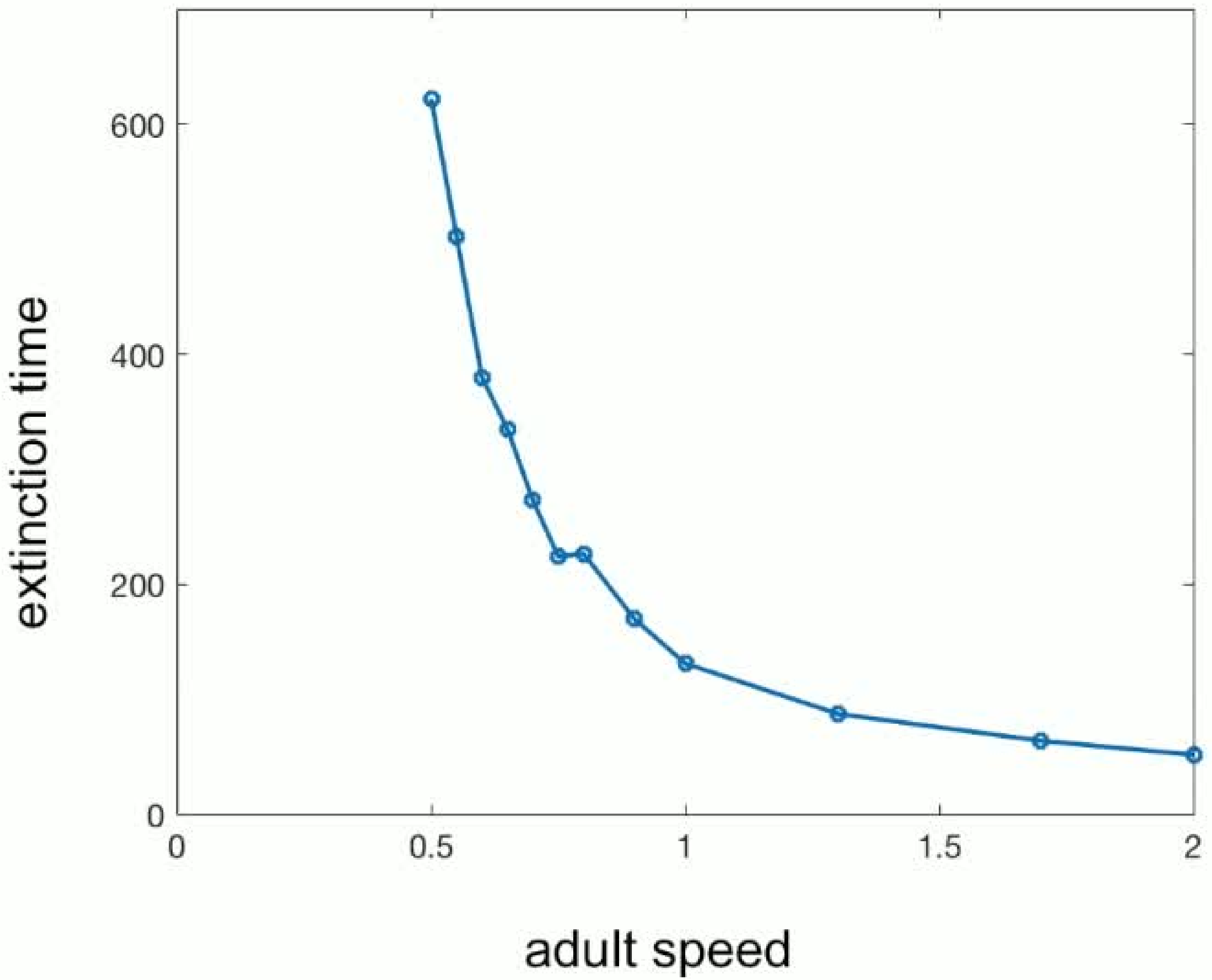


Extinction time



Decreasing adult lifetime

Varying adult rates and efficiency α together to keep adult population fixed



Conclusions

- Allee effect in oysters
- Fluctuating availability of oyster larvae due to rainfall variation
- Noisy juvenile recruitment is buffered in downstream compartments
- Stochastic extinction occurs along an optimal path
- Extinction occurs more rapidly when fewer juveniles, shorter-lived adults