Understanding Model Trade-offs in Ecology and Evolution (Based on Levins (1966))

A MulQuaBio Lecture

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Overview

- Models help simplify ecological and evolutionary complexity
- Levins (1966) identified a key trade-off:
- **Generality vs. Realism vs. Precision**
- You can’t maximize all three at once
- Let’s break these down with examples from ecology and evolution

GENERALITY

- **What is it?** — How broadly the model applies across systems
- **Simple definition:** "Works for many species/situations"
- **Ecological example:** Logistic growth model
  - $\frac{dN}{dt} = rN(1 - \frac{N}{K})$
  - Applies to many populations, regardless of species
  - Ignores age, environment, interactions
- **Evolutionary example:** Hardy–Weinberg model (null expectation)
  - Genotype frequencies: p^2, $2pq$, q^2 (with $p + q = 1$)
  - Applies broadly as a baseline across many diploid populations
  - Ignores selection, drift, structure, mutation, migration

Realism

- **What is it?** — How accurately the model reflects biological detail
- **Simple definition:** "Captures the messy real world"
- **Ecological example:** Spatially explicit individual-based predator–prey model
  - Includes movement, behavior, stochasticity
  - Can match a particular system well
  - But highly specific and hard to generalize
- **Evolutionary example:** Forward-time simulation with explicit genotypes and selection
  - Tracks individuals, inheritance, recombination, and selection on traits
  - Realistic mechanisms, but parameter-hungry
  - Often used for "what if" scenarios rather than universal laws

PRECISION

- **What is it?** — How exact or quantitative the model predictions are
- **Simple definition:** “Makes sharp forecasts”
- **Ecological example:** Short-term population forecast (state-space model)
  - With good data, can produce tight prediction intervals for N_{t+1}
  - Useful for management, but often system- and time-window-specific
- **Evolutionary example:** Trait evolution under directional selection (quantitative genetics)
  - Predicts a response like $R = h^2 S$ given heritability h^2 and selection differential S
  - Can be very precise when assumptions hold and parameters are well estimated
  - Precision does not guarantee accuracy if assumptions break (e.g., changing environments, non-additive genetics)

Realism vs. precision (and accuracy)

- **Realism** asks: *Are the ecological and evolutionary mechanisms/assumptions biologically faithful?*
  - High realism can still be wrong if key processes are missing or mis-specified.
- **Precision** asks: *Are the predictions tightly constrained (low uncertainty)?*
  - High precision can still be misleading if it is consistently “off”.
- **Accuracy** asks: *How close are predictions to the truth (on average)?*
  - Intuition: **accuracy** depends on both **bias** (systematic error) and **variance** (scatter).
  - A model can be **precise but inaccurate** (low variance, high bias) or **realistic but imprecise** (low bias, high variance).

WHY TRADE-OFFS MATTER

- You must sacrifice one:
  - Want realism + precision? Lose generality
  - Want general + precise? Lose realism
  - Want general + realistic? Lose precision
- **There's no free lunch in modelling!**

Summary table

Goal	Simple definition	Example	Main trade-off
Generality	Applies to many systems	Ecology: logistic growth; evolution: Hardy–Weinberg	Ignores detail
Realism	Includes real-world complexity	Ecology: spatial IBM; evolution: forward simulation	Hard to generalize
Precision	Sharp numerical predictions	Ecology: short-term forecast; evolution: $R = h^2 S$	Often assumption-sensitive

STUDENT DISCUSSION POINTS

- Can you think of an example from your field where a model prioritizes one goal over the others?
- Are modern models (e.g., simulations, machine learning) changing this trade-off?
- When is it *better* to be less realistic or less precise?
- Is generality always desirable in ecology and evolution?
- How might a model cluster approach help manage these trade-offs?