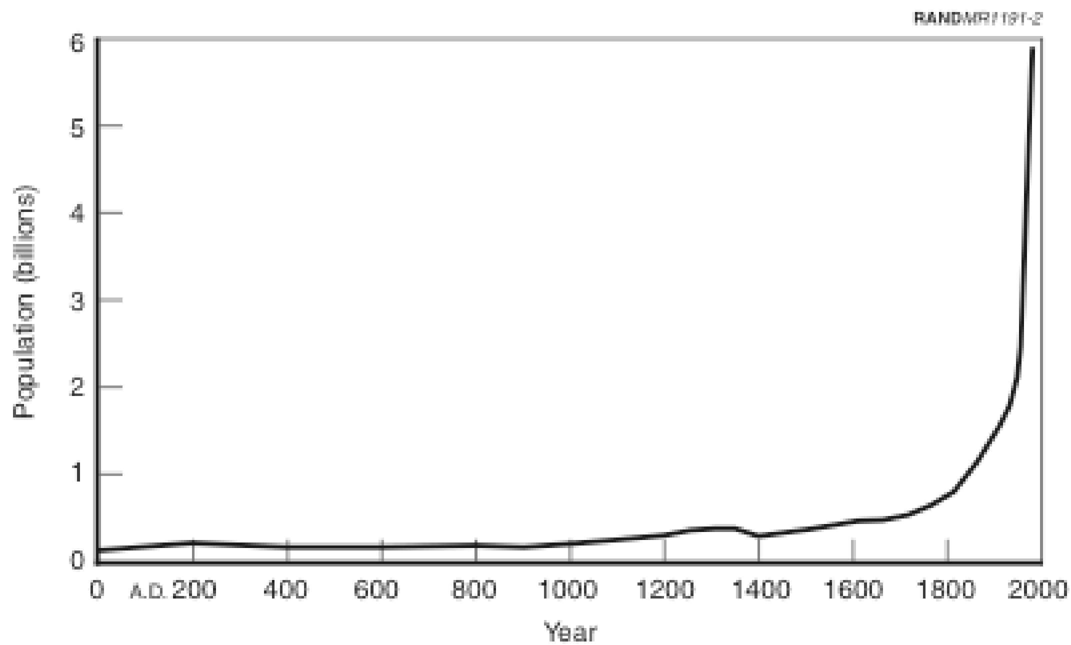
Simple models for evolving populations

Chris Bystroff, Dept of Biology, RPI

18 Nov 2005

Human population.



SOURCE: Adapted from Cohen, 1995, p. 82.

Figure 2.1—Estimated Human Population from 1 A.D. to the Present

What do we do?

Let’s try to predict the future...

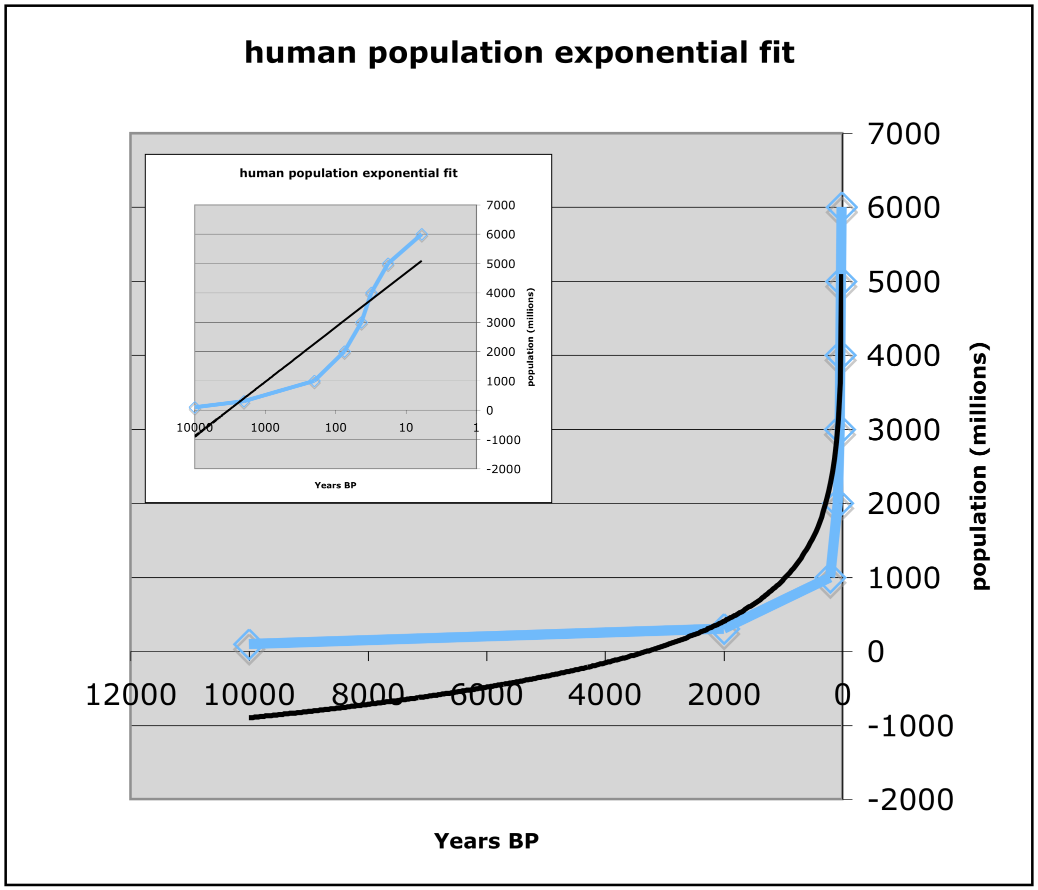
Population data from J. Cohen, going back to the beginning of agriculture.

Years ago	**Human population** (millions)
10000	100
2000	300
200	1000
75	2000
43	3000
31	4000
18	5000
6	6000
year 2050	?

Types of predictive models

- Predictions based only on available data (data mining, informatics, empirical models)
- Predictions based on a theory or theoretical model (equations, simulations)
- Predictions based on a combination of theory and data (*fitting* a theoretical model)

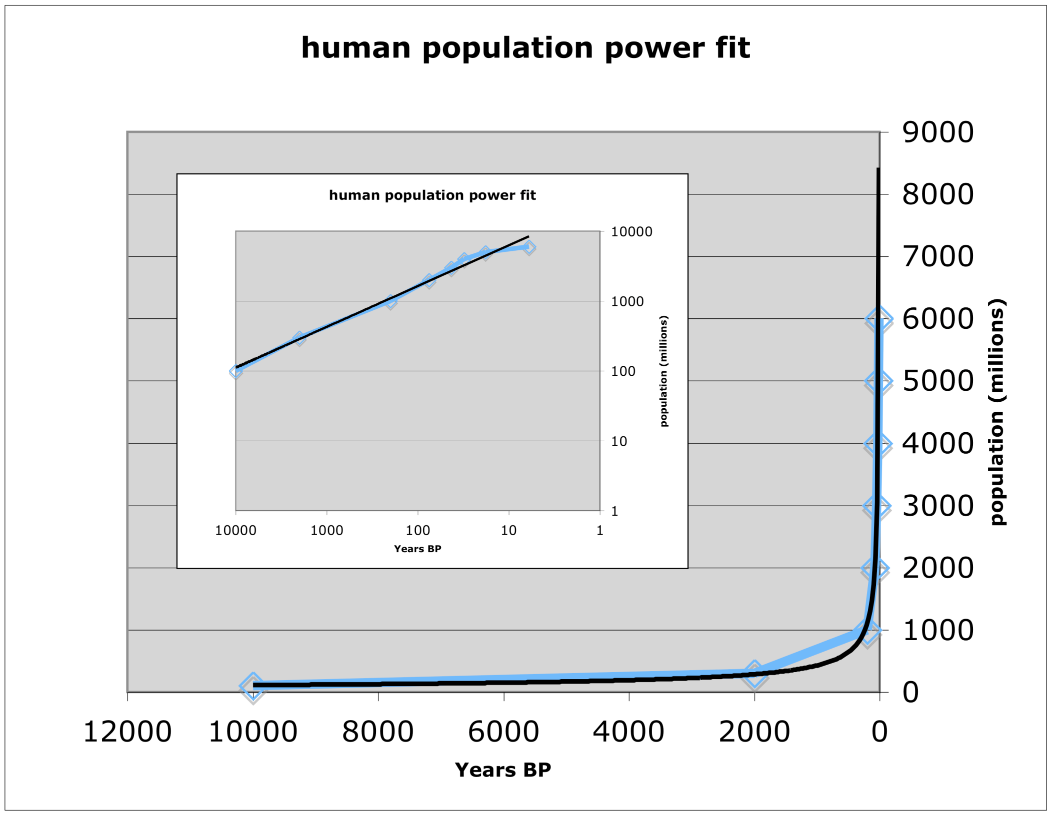
Fitting equations to predict human population



Exponential fit. $y = k \exp(b x) + c$

Data should be linear on a log-linear plot

Fitting equations to predict human population

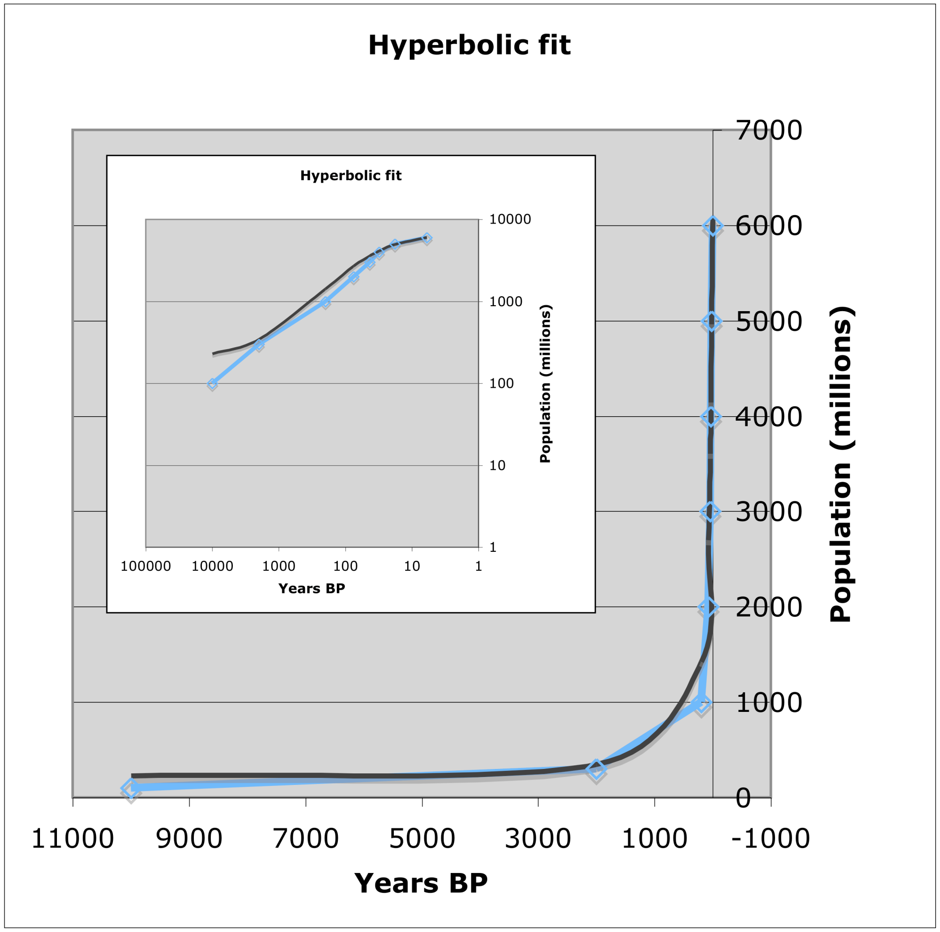


Polynomial fit. $y = k x^b$

Data should be linear on a log-log plot

Note: x (time) must be measured relative to a start time (zero).

Fitting equations to predict human population



Hyperbolic fit. $y = k/x$

y goes to infinity when x=0

Implications of equations on population

- **Exponential**: population growth is proportional to population.
- **Geometric**: population growth is proportional to time since...(??? speciation, agriculture???)
- **Hyperbolic**: population growth increases to infinity as we approach 2050 (!!!)

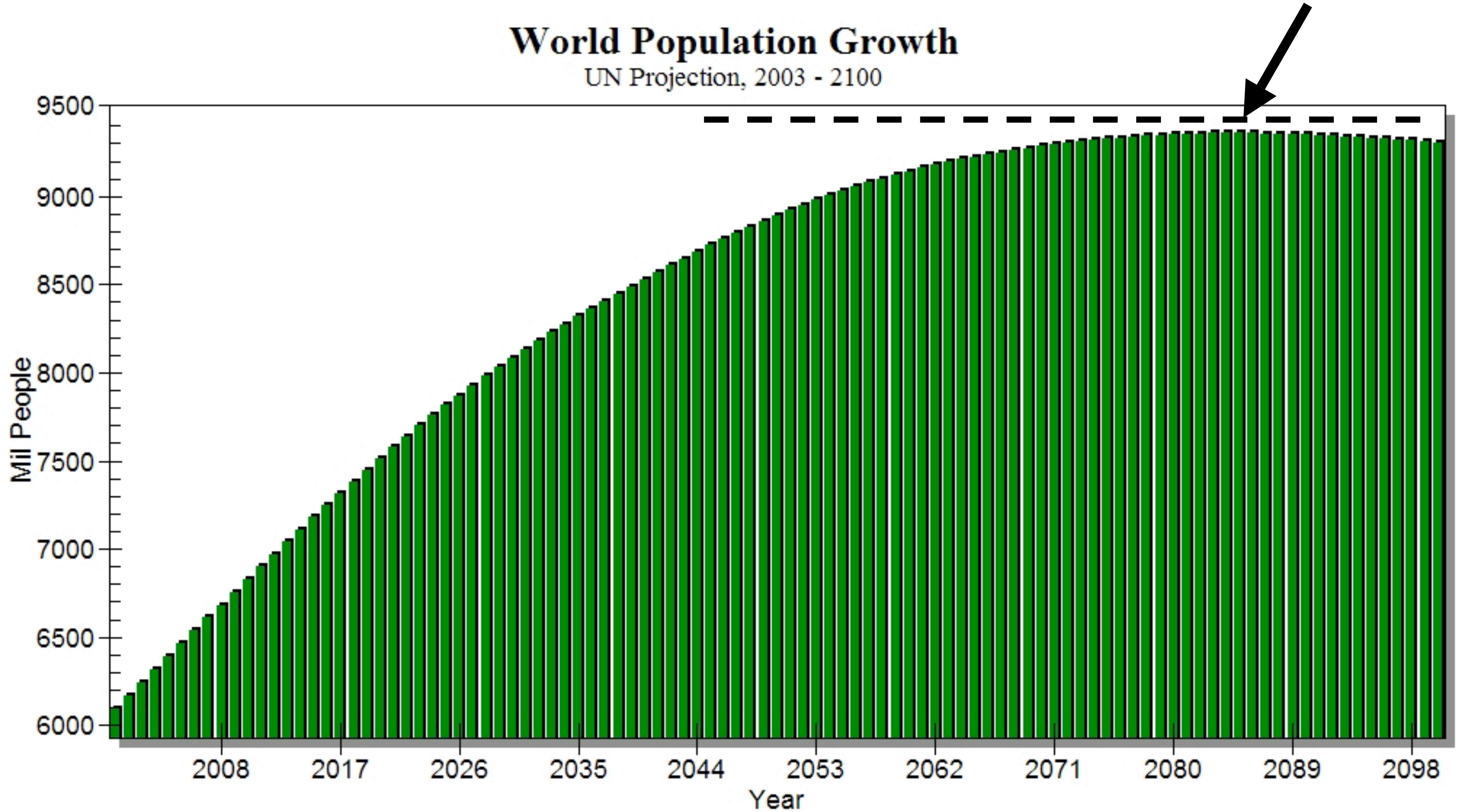
Which one is right?

Models that ignore physical limits are a joke!

<u>Physical Limits to population growth</u>

- Space -- every individual takes up space
- Food -- everyone eats approximately the same amount
  - Theoretical limit to food production: 100% efficient conversion of the energy from the sun to edible food.
  - Practical limit: arable land (crops and livestock) plus oceans (fisheries).

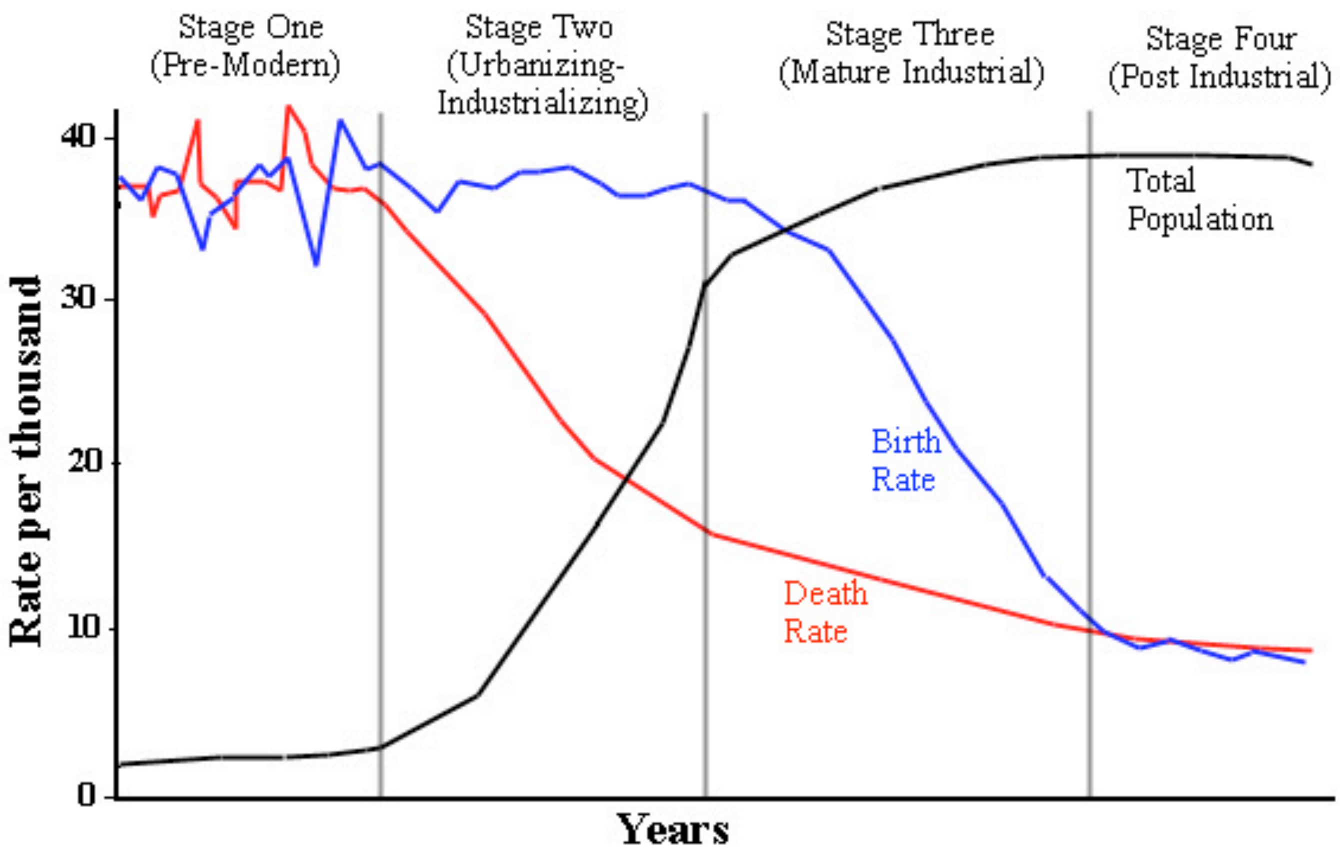
UN Estimated carrying capacity for humans



Most predictions set a carrying capacity, which is the maximum number of a species that can be supported by the food supply.

Growth phases for humans?

http://www.faculty.fairfield.edu/faculty/hodgson/Courses/so11/population/population.htm



Does this remind you of the growth curve for *E. coli*?

"logistic" equation for population

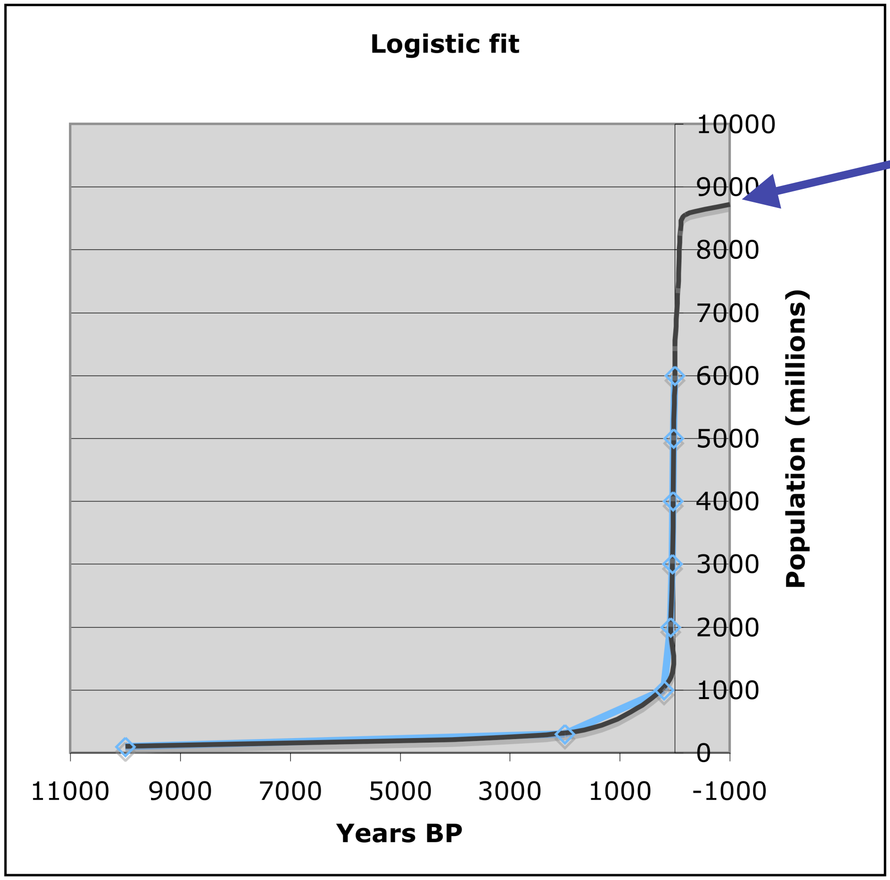
$$\frac{dP(t)}{dt} = rP(t)\left(1 - \frac{P(t)}{K(t)}\right)$$

K(t) is the carrying capacity.

$$P\left(t + \Delta t\right) = \frac{K(t)}{1 + \left(\frac{K(t)}{P(t)} - 1\right)e^{-r\Delta t}}$$

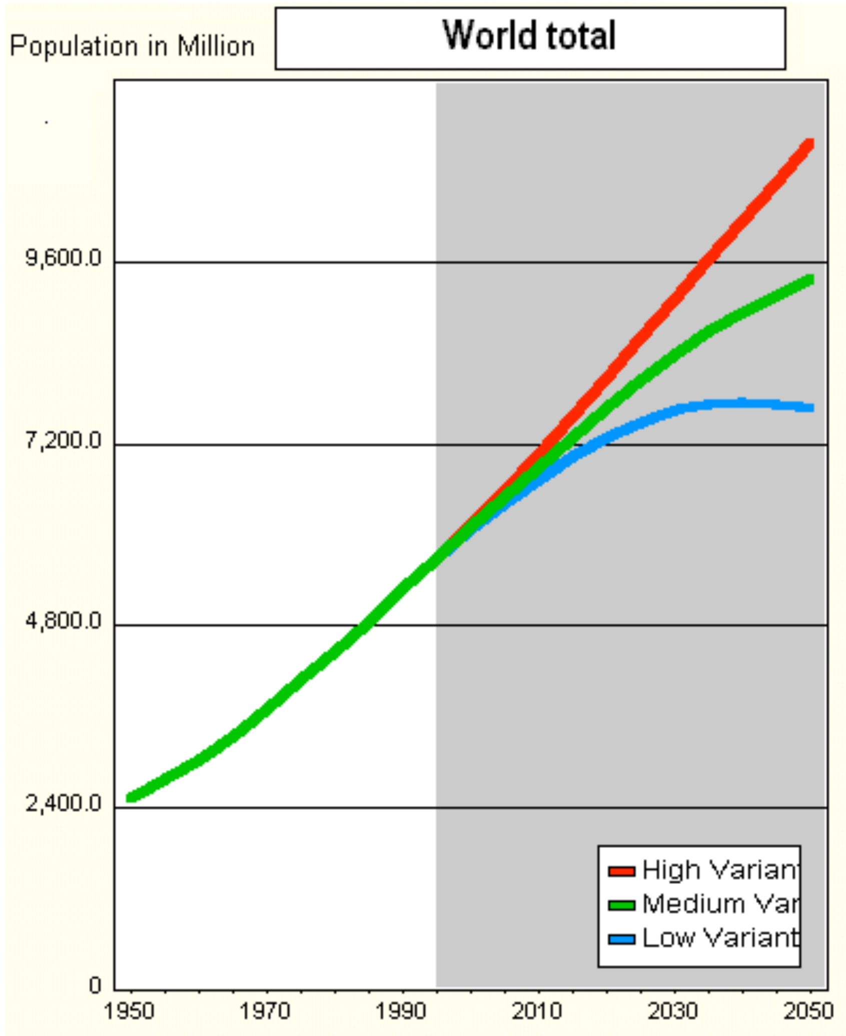
Growth is exponential as long as P(t) << K(t), then goes to zero as P(t) approaches K(t). *r* is the rate of exponential growth.

“logistic” equation for population



Population levels out as it approaches the carrying capacity. Population is “asymptotic” to the carrying capacity.

NOTE: Carrying capacity can change with time!



Given that the carrying capacity and the change in carrying capacity are unknown, we can fit the data to many equations. Which is right?

Is population really asymptotic?

- What happens to population growth faces fixed limits? moving limits?
- What if carrying capacity decreases with increased population?
- Thomas Malthus (1798) described a model in which geometric growth is followed by periodic catas-trophic population loss. (“boom-bust”)

http://evolution.berkeley.edu/evosite/history/humanecol.shtml

Carrying capacity decreases with population

Carrying capacity is a moving target because...

- Agricultural use of land slowly decreases crop yields.
- Overfishing reduces rate of recovery of fisheries.

http://www.infoforhealth.org/pr/m13edsum.shtml#top

In class exercise: Malthusian oscillations

- Start two columns of numbers. The first is the population, and the second is arable land. Population starts at 1. Arable land starts at 100 acres. Each unit of population consumes 1 acre of land per unit time. Each acre of land takes 2 time units to recover. The population grows by a factor *b* each unit of time.

$P(t) = \min(b*P(t-1), L(t-1))$

$L(t) = \max(0, L(t-1)-P(t)) + P(t-r)$

r = recovery time = 2

In class exercise: Malthusian oscillations

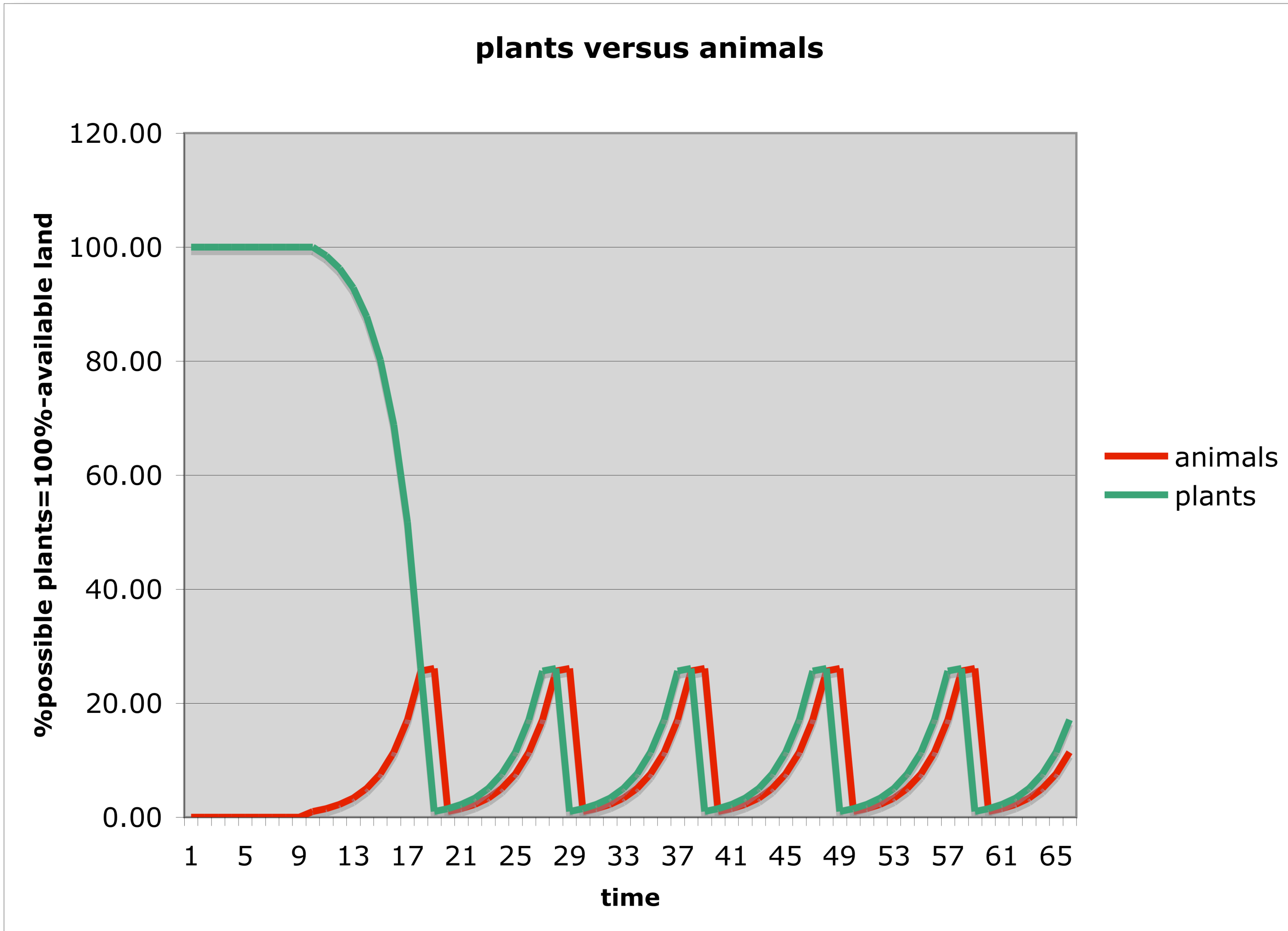
t

population	arable land
0.00	100.00
1.00	99.00
2.00	97.00
4.00	94.00
8.00	88.00
16.00	76.00
32.00	52.00
52.00	16.00
16.00	32.00
32.00	52.00
52.00	16.00
16.00	32.00
32.00	52.00
52.00	16.00
16.00	32.00

32.00	52.00
52.00	16.00
16.00	32.00
32.00	52.00
52.00	16.00
16.00	32.00
32.00	52.00
52.00	16.00
16.00	32.00
32.00	52.00
52.00	16.00
16.00	32.00
32.00	52.00
52.00	16.00
16.00	32.00
32.00	52.00
52.00	16.00

Try Excel spreadsheet at :
http://www.bioinfo.rpi.edu/~bystrc/pub/population.html

Malthusian oscillations



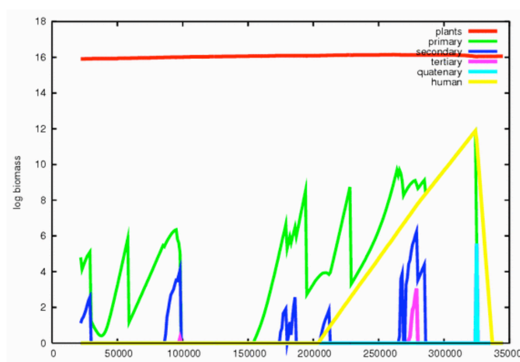
Results of Excel simulation using

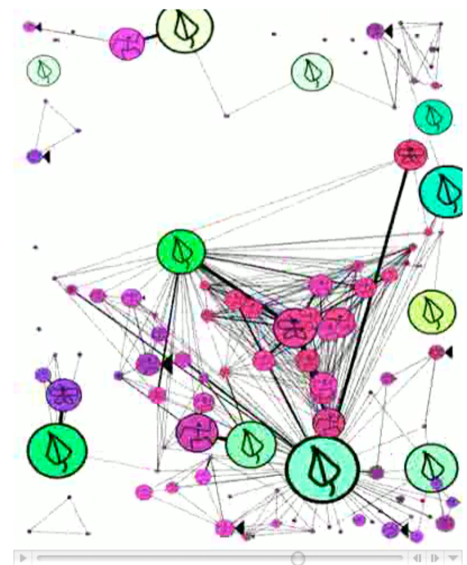
Is Malthus' model realistic?

- Malthus assumes that technology remains constant.
- In fact, our ability to produce and find new sources of food has continually advanced, keeping one step ahead of the collapse.
- Can it advance indefinitely? (No, because of physical limits.)

ECOME

- A computational simulation for an evolving global ecosystem.
- May be used to test principles of population dynamics.



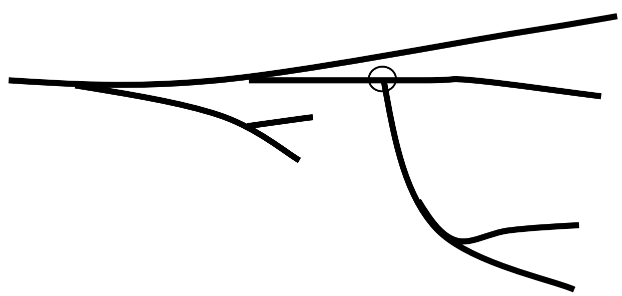


Why are humans so successful versus other animals?

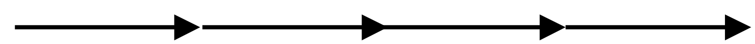
- Big brain
- Voice box
- Language
- Culture
- Cultural evolution

What is culture?

- The ability of a species to pass on advantageous behavioral traits non-genetically.



Genetic evolution consists of speciation events,
in which a small portion of a population gains a new trait.



Cultural evolution enables new traits to be passed to the **entire** population.

Humans “evolve” faster

- If culture is a means to pass on advantageous traits, then we humans are evolving without waiting for our genes to change.
- Since no speciation takes place, a new trait can be adopted by the entire culture, not just a sub-population.
- Humans can “evolve” much faster than animals of comparable size.

How to we model this?

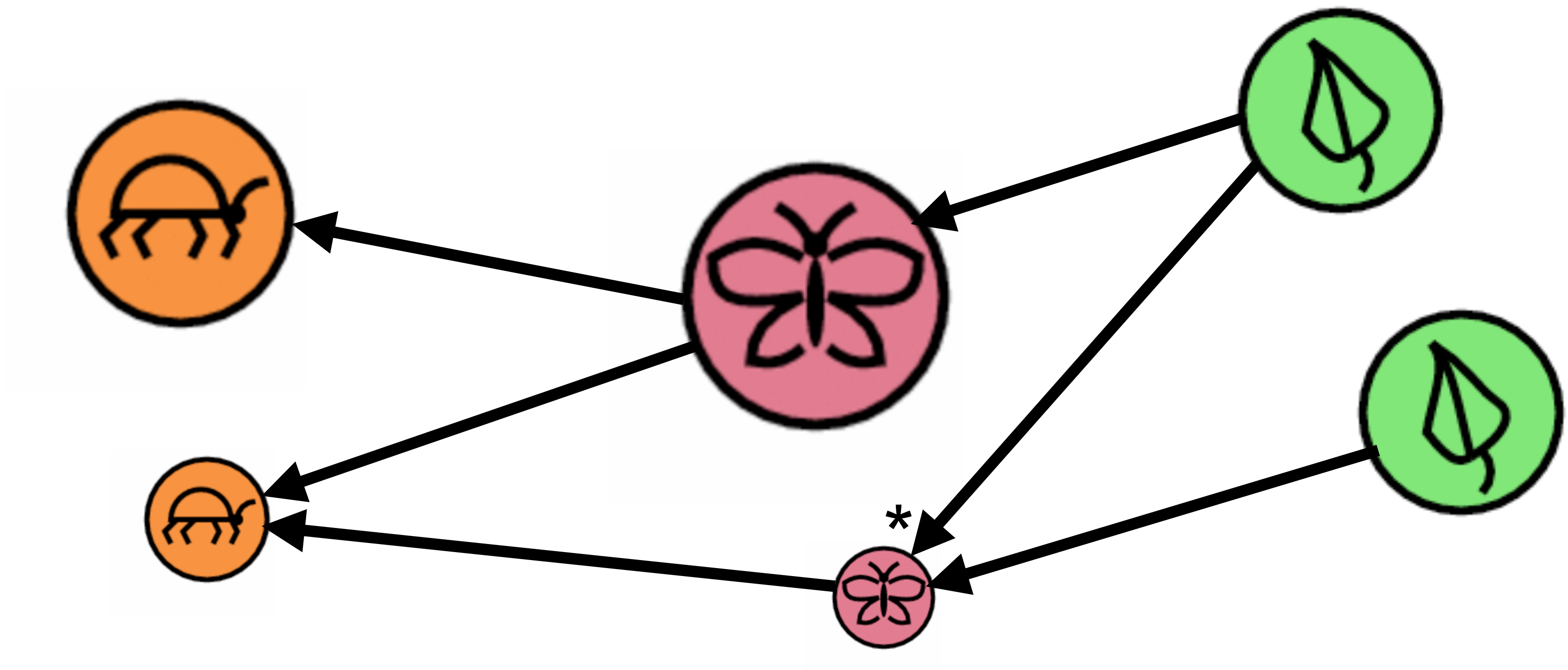
ECOME: basic assumptions

- Populations are represented in common “**biomass**” units.
- Predator-prey relationships define the **transfer of mass** between populations.
- **Decay/decomposition/respiration** all represent means of losing energy to the atmosphere without predation. These are lumped together and modeled as the “decay rate.” Every species has a decay rate.
- The Earth receives a constant amount of energy from the Sun. The maximum plant growth rate is limited by this **Sun-limit**.
- Animal populations grow in proportion to their biomass, but limited by **food availability**.
- Animals and plants can **speciate** to...
  evade a predator
  gain new prey
- **Speciation** is an uneven division of the biomass.
- Humans can **evolve without speciation**.
- **Extinction** is when biomass goes to zero.

ECOME: variables

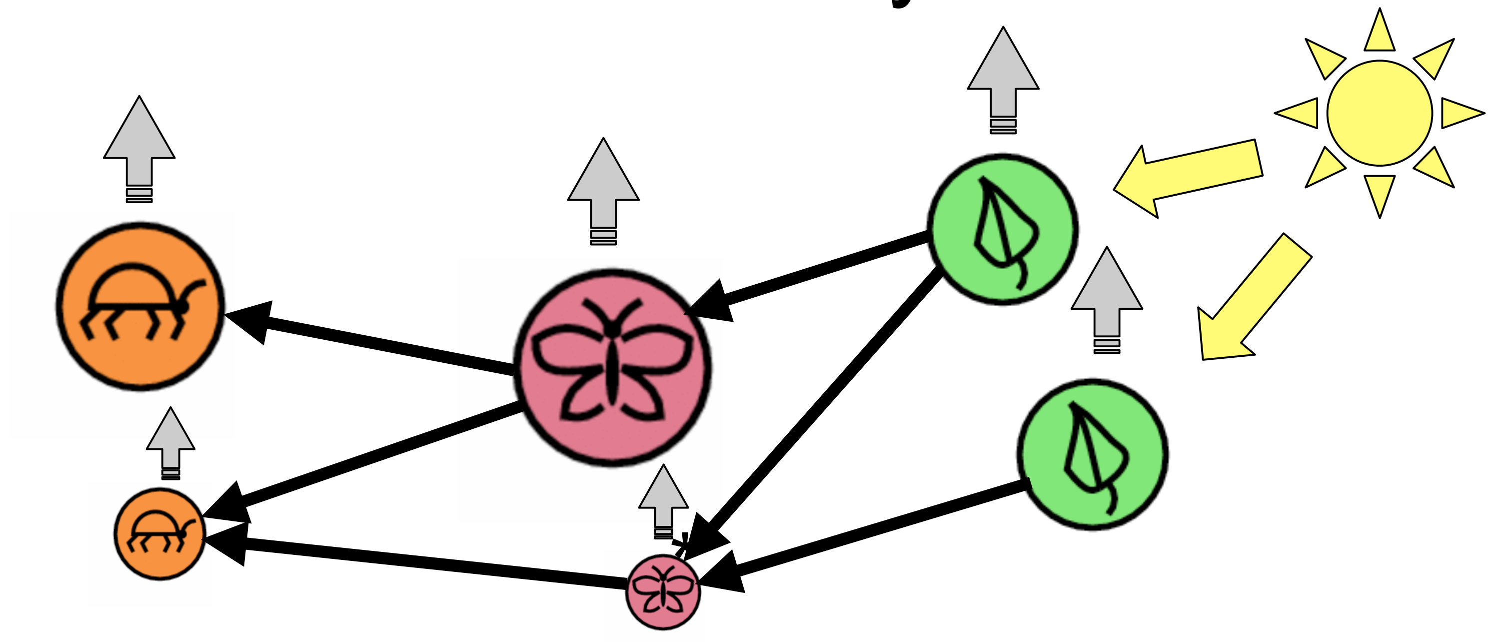
- Populations can move in their rectangular screen-world.
- Growth rates, growth rate distribution.
- Number of prey per predator.
- Evolution rates (cycles per speciation event).
- Local versus nonlocal prey.
- Canabolism.
- Animal response functions for calculating likelihood of successful “hunt”.
- Human culture levels:
  - 1. Humans choose new prey when starving
  - 2. Humans choose new prey even when not starving.
  - 3. Humans prey on predator species.
  - 4. Humans reproduce as a function of food supply.

Example of animal speciation



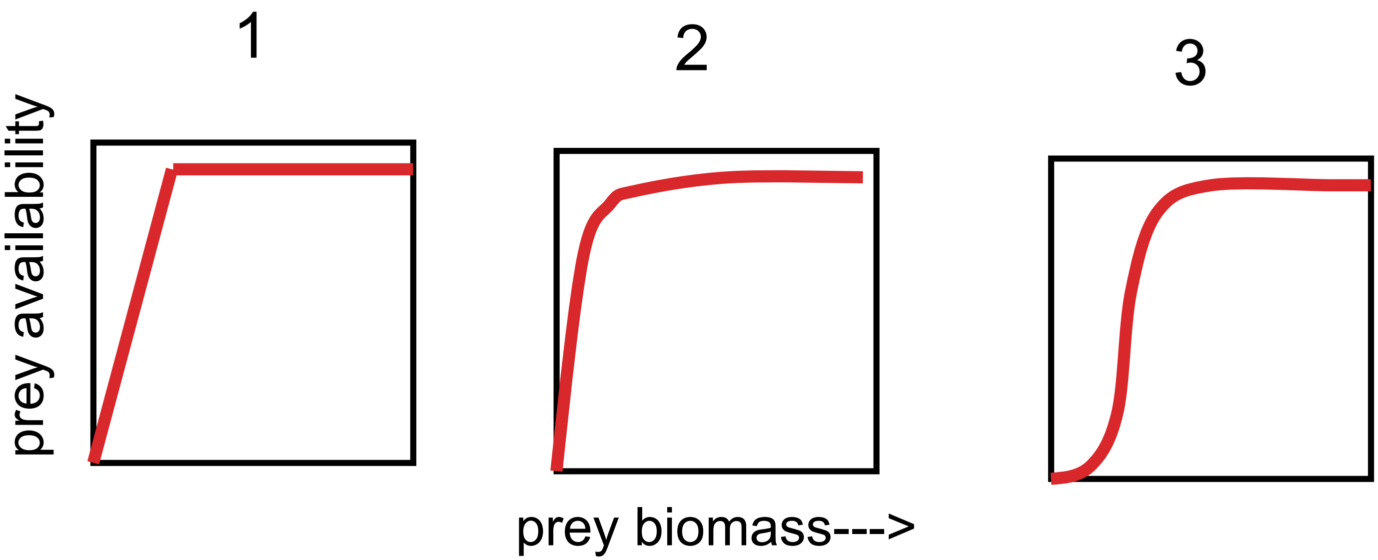
The butterfly splits into two nodes, the larger "parent" species and the smaller "child" species(*). The child species retains some of the predators, and gains some new prey.

One simulation cycle



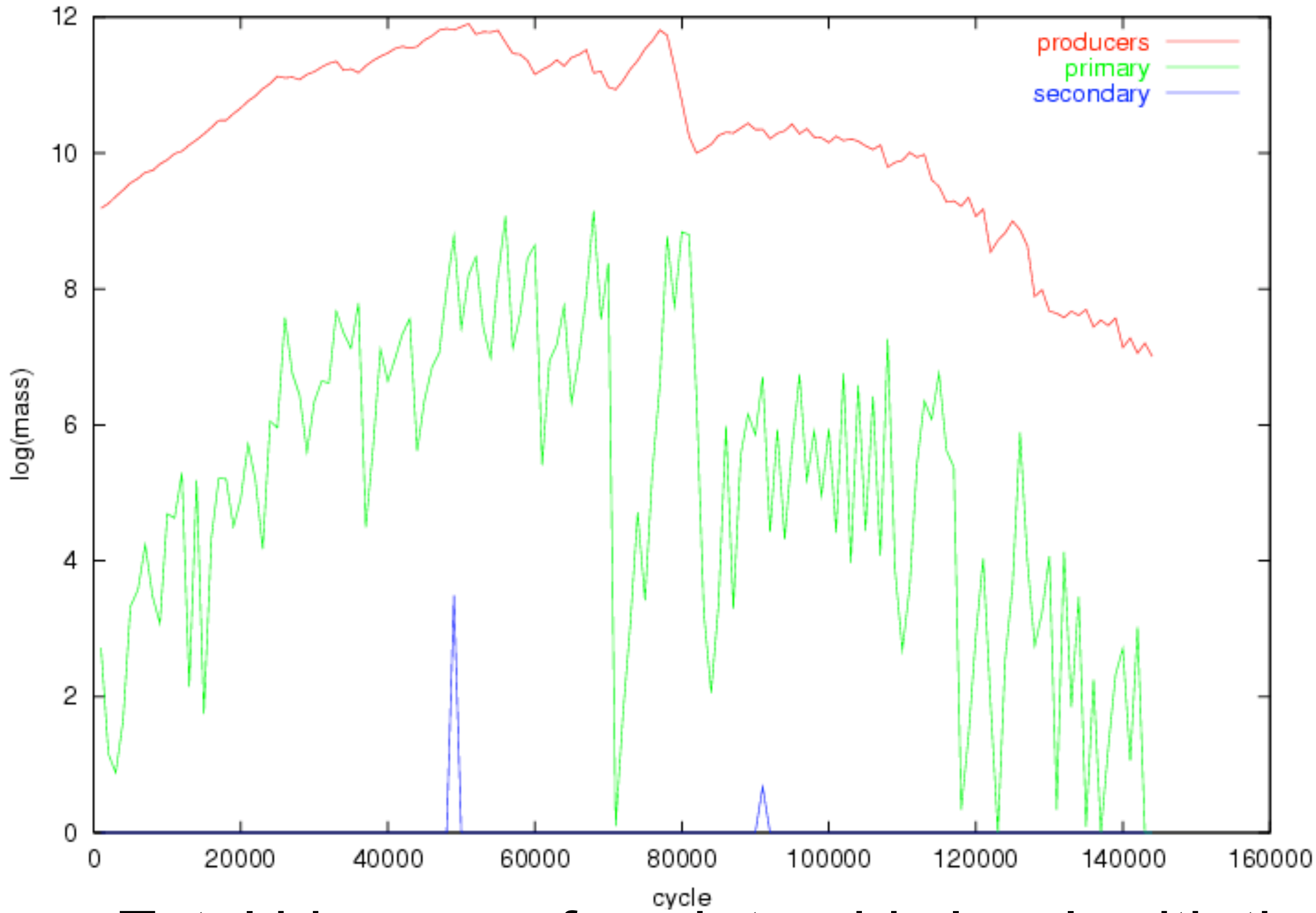
- Plants grow proportional to biomass.
- Mass is transferred along arrows, using equations that depend on (a) predator growth rate, (2) prey biomass, (c) predator response function.
- All species decay at a species-specific rate.

Holling’s response functions



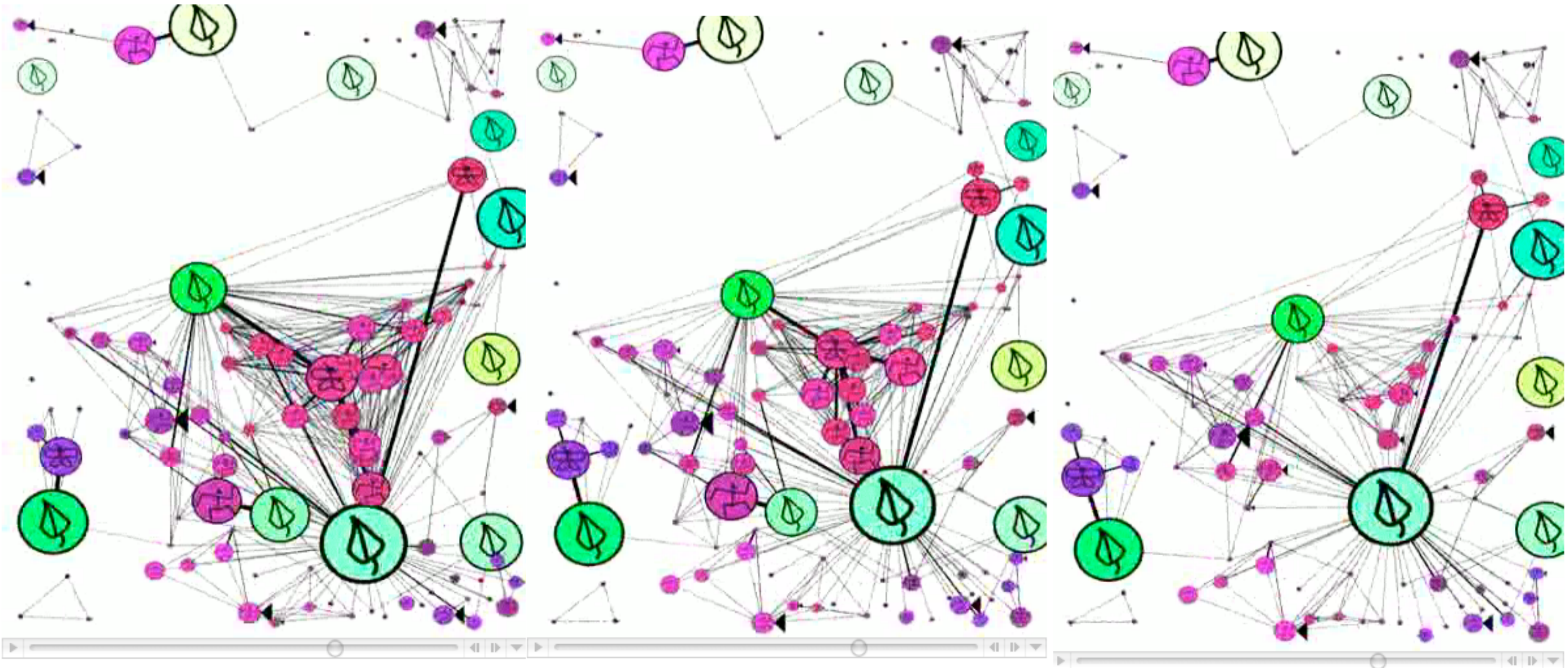
Predators consume prey as a function of availability. If the prey biomass is low, they are “hard to find.” Therefore predators consume less of that prey.

ECOME: output



Total biomass of each trophic level, with time

ECOME: output



Food web view.

ECOME: results

- When all speciation rates are set to zero, all animals go extinct.
  - Evolution is essential for a sustainable ecosystem!
- If the (evolving) ecosystem does not collapse early, it will continue indefinitely.
- Introducing humans leads to human extinction for culture types 1 and 2 (fig. 1), ecosystem collapse for culture type 3 (fig. 2), and stability for culture type 4.
  - 1. Humans choose new prey when starving
  - 2. Humans choose new prey even when not starving.
  - 3. Humans prey on predator species.
  - 4. Humans reproduce as a function of food supply.

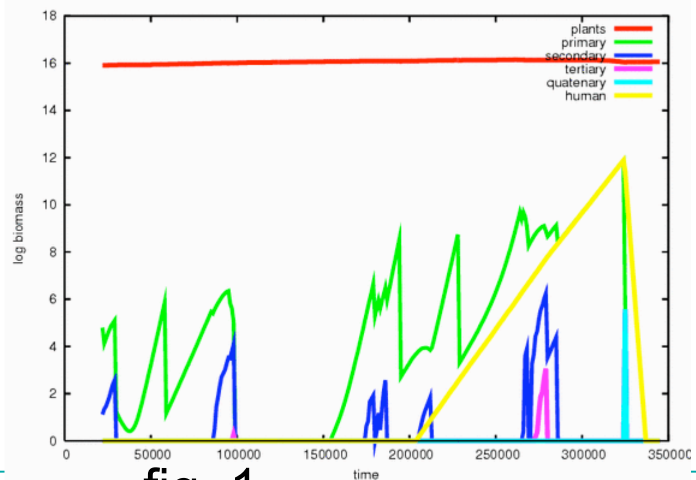


fig. 1

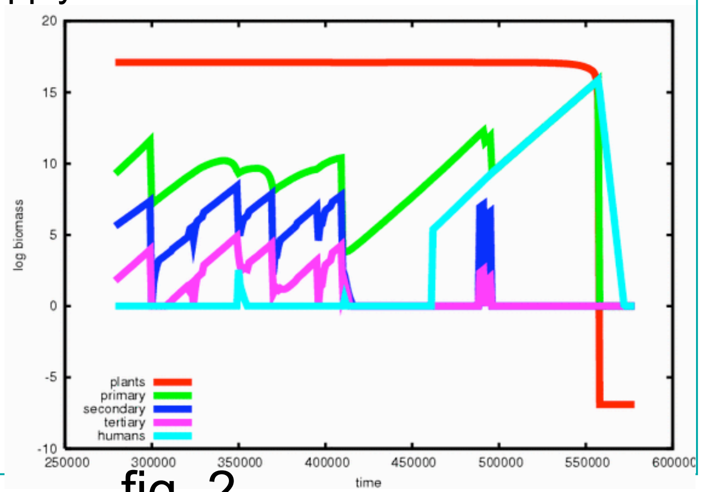


fig. 2

Can we treat Humans as animals, behaviorally?

NO

Humans have free will, therefore

(a) we can control our reproduction rate.

(b) we can control our consumption rate.

We have infinite energetic resources (Julian Simon, 1991)

YES

Humans reproduce proportional to food supply, like other animals. (Hopfenberg, 2001)

We cannot control our reproduction rate!