Ecosystems

Cybernetics and models of population dynamics

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Cybernetics

Cybernetics has many definitions. Loosely speaking it concerns the study of self regulating systems

Key concepts

- Homeostasis
- Feedback loops
- Self regulation

System dynamics

Cybernetic theory is also known as “system dynamics”

Jay W Forrester (MIT) formalised many of the concepts

Feedback loops

Compartment – flow modelling

Dynamic equilibrium

External and internal forcing

Homeostasis

The tendency of a system to return to some particular state

Simple example. A room with a thermostat controlling the central heating

Complex system dynamics models

Club of Rome “World Model”

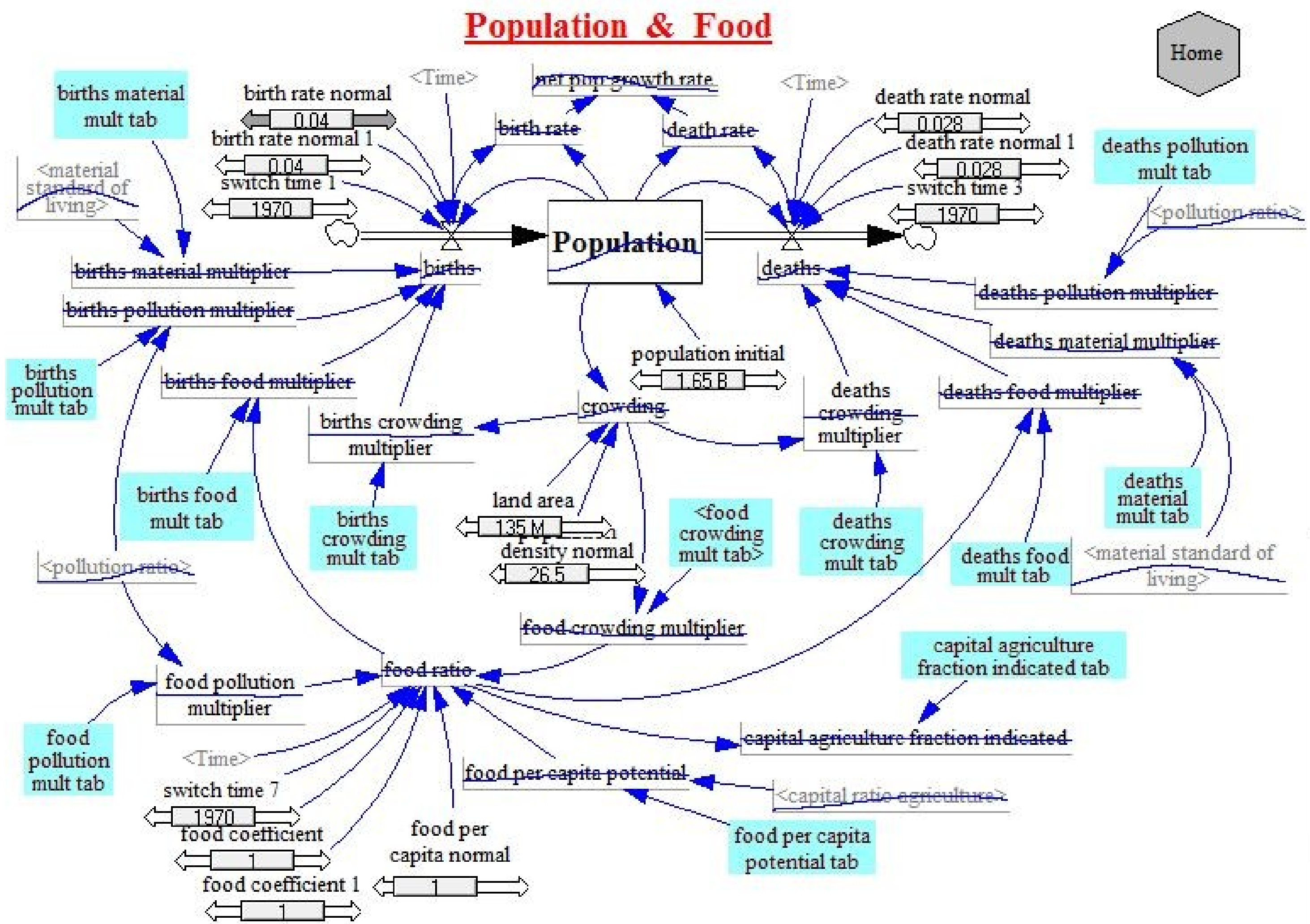
First attempt to use system dynamics to model a virtual world

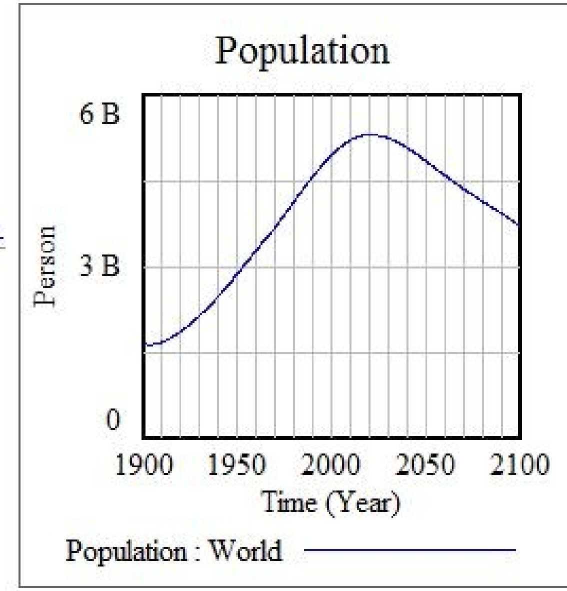
Modelled the human-biological-resource-pollution system as a system of equations

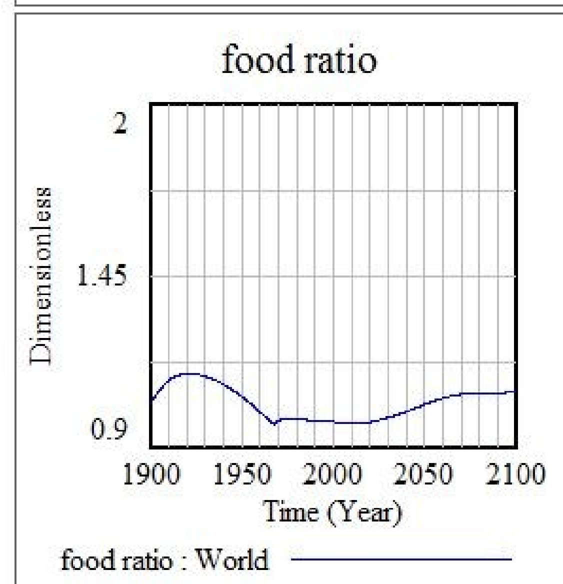
Used in the “Limits to growth” report (1972)

Influenced policy makers to take more of a “whole system” approach to global issues

World model in Vensim







Run the model yourself

The model is included as example with VensimPLE (free Personal Learning Edition)

Multiple positive feedback loops that may lead to undesirable and unsustainable pressure on global system

Widely criticised by economists as unrealistic, but influenced conservation thinking.

An analysis of the model is available as a video on this page

https://vensim.com/model-analysis-world-dynamics/

Simpler starting point

Population modelling

Basis of all ecology

What controls and regulates population growth and size?

How can humans exploit populations of animals and plants sustainably?

What can go wrong?

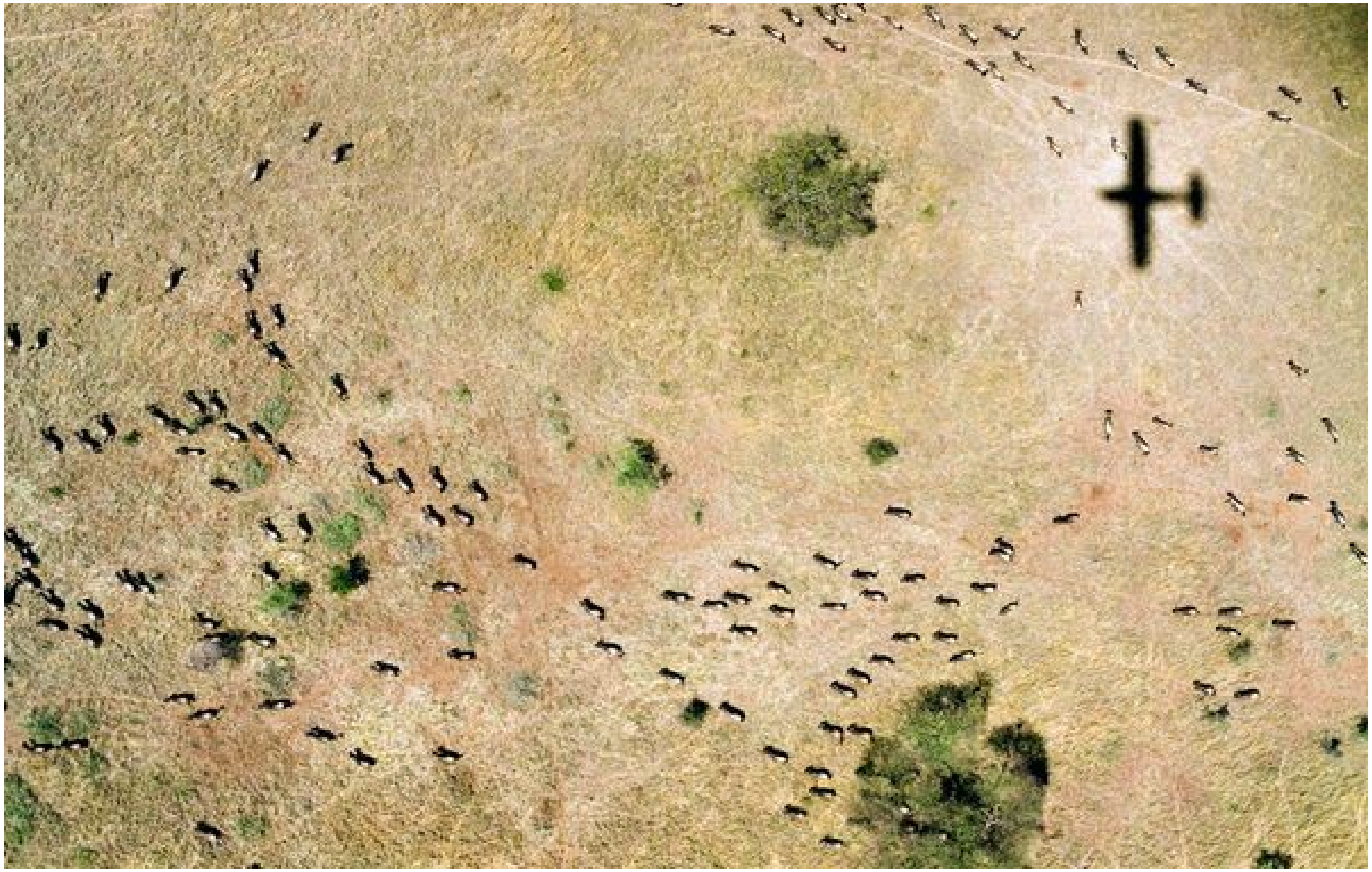
Human activities influence almost all natural populations

When we do not understand population dynamics we may observe unwanted

Extinction
Invasion and over population
Non sustainable use
Population imbalances (boom and bust)

How do we study populations?

Visible populations of conservation concern are continuously monitored.
For example, Wildebeest numbers in the Serengeti



How do we study populations?

Populations change through births, deaths and migration

How do we study populations?

Births deaths and migration are known quantities for some populations

How do we study populations?

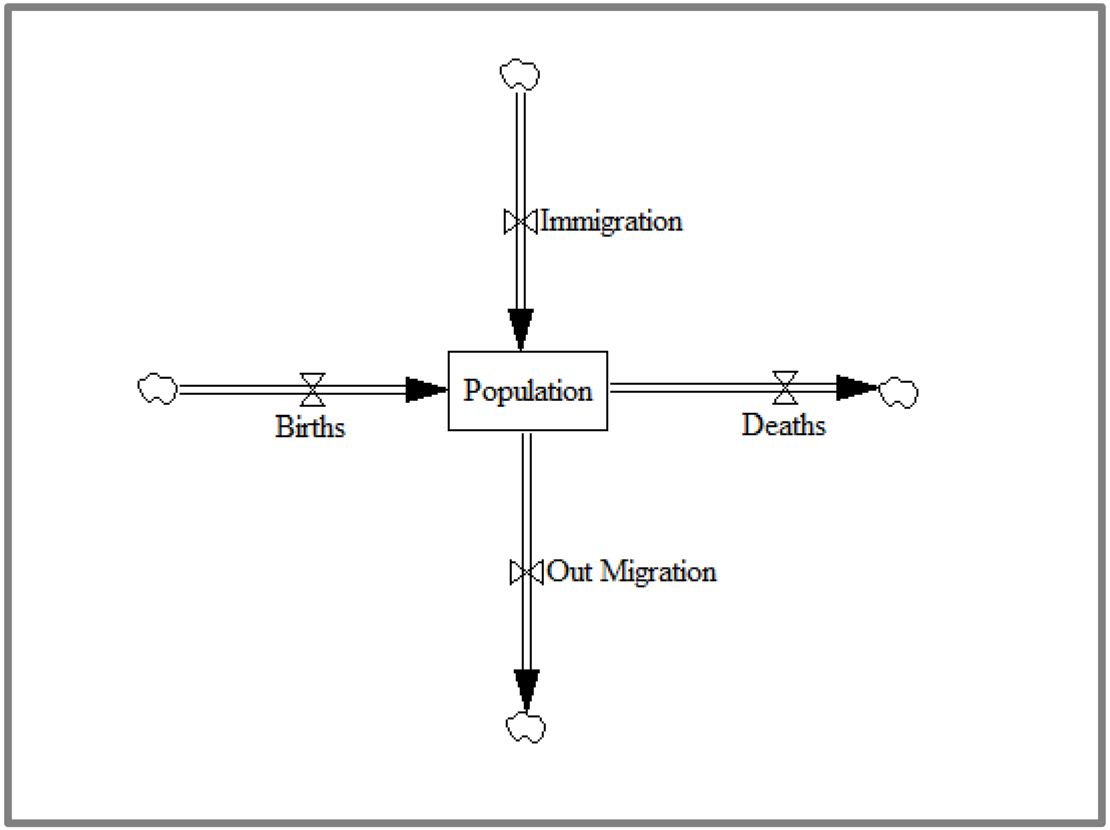
.The populations of most organisms cannot be precisely monitored
We usually have to infer population size and produce indirect estimates.
We also frequently need to make projections regarding population dynamics.

Mathematical modelling allows us to …..
1. Estimate unmeasurable population parameters
2. Predict population change over time
3. Understand processes responsible for change

Types of models

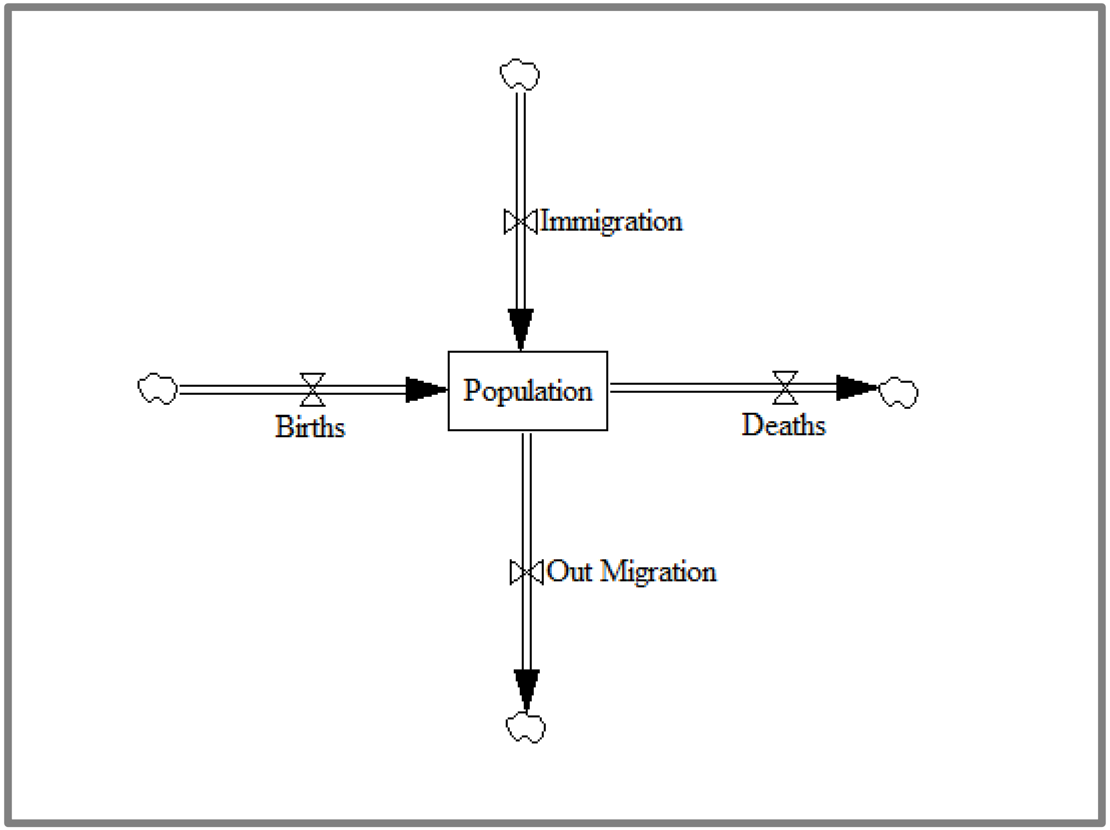
1) Aggregated population models using differential equations – make simple assumptions regarding births and deaths.
2) Disaggregated models (matrix models) - take into account population structure
3) Individual (agent) based models -take into account variability at the level of single organisms
4) Spatially explicit models – take into account effects of habitat patch size and connectivity
5) More complex simulation models - take into account interactions at the community level

Aggregated population model



$$N_{t+1} = N_t + Births_t + In_t - Deaths_t - Out_t$$

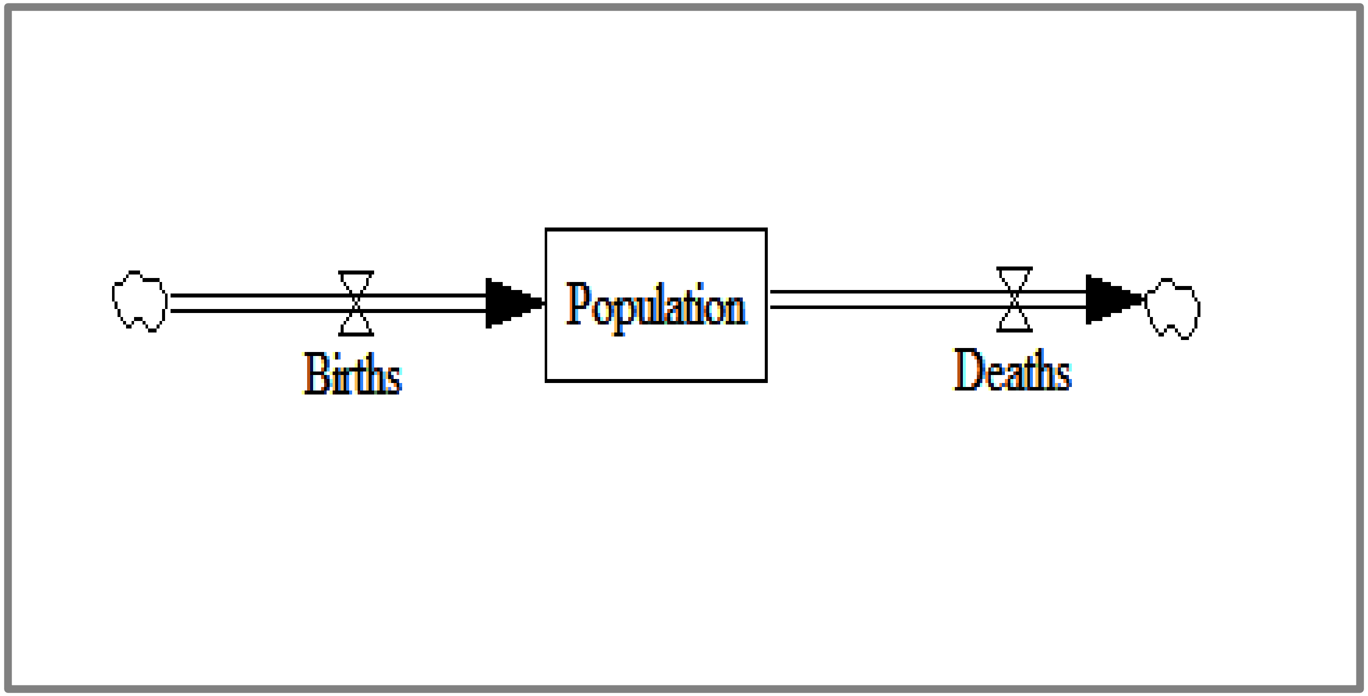
Differential equation



$$\frac{dN}{dt} = Births + In - Deaths - Out$$

"The population size is the integrated result of births, deaths and migration with respect to to time"

Ignoring migration



$$\frac{dN}{dt} = Births - Deaths$$

“The population size is the integrated result of births minus deaths with respect to to time”

Population stability

A population can only be stable if births exactly equal deaths.

This is highly unlikely.

In reality all populations undergo natural fluctuations in size

We therefore attempt to model and understand **population dynamics**

Building a simple model

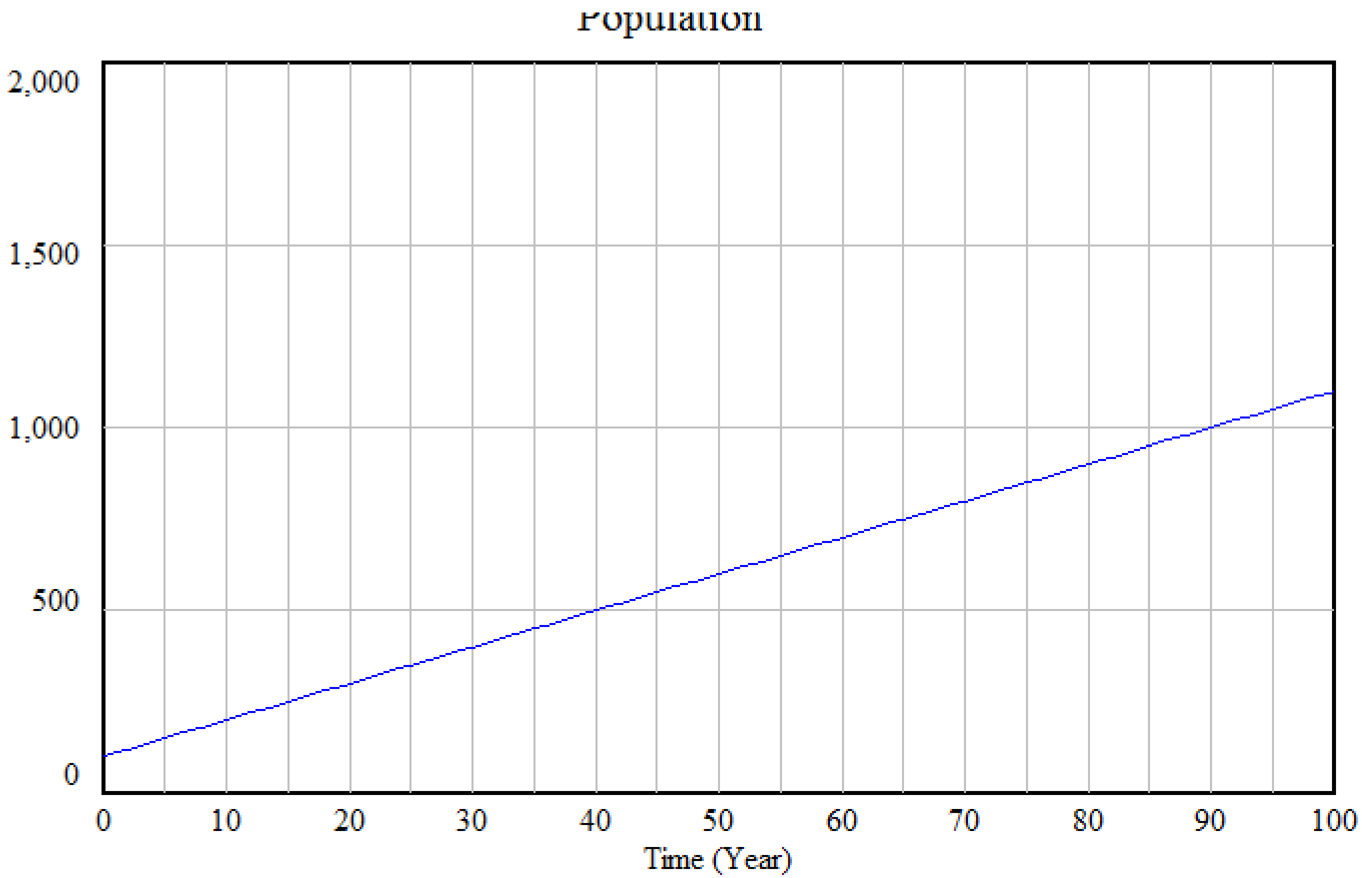
Let's first assume that a population (call them rabbits) consisting of 100 individuals has a fixed number of births each year (let's say 100).

Let's set a fixed number of deaths (say 90)

So after one year N_{t+1} = 100 + 100 -90 = 110

Building a simple model

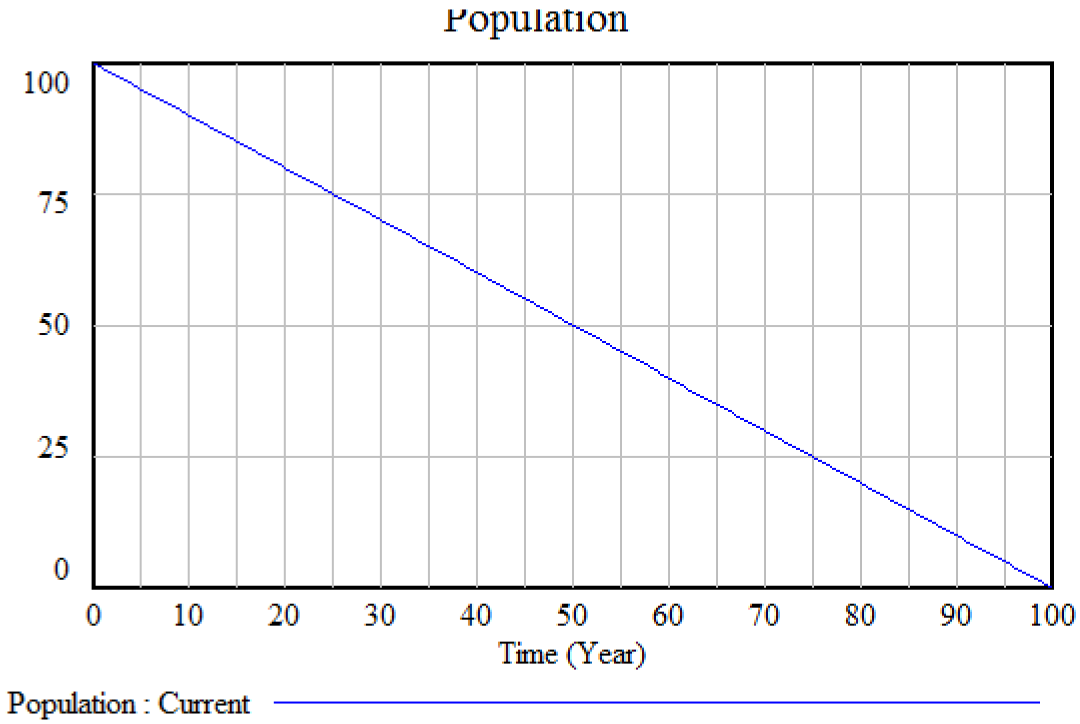
What happens if this continues year after year?



Building a simple model

What happens if number of deaths always are greater than births?

N_{t+1} = 89 -90



Building a simple model

This is NOT a suitable model!

Births and deaths **cannot** be a constant number!

We need (at least) to think about birth and death rates

$$r = BirthRate - DeathRate$$

$$\frac{dN}{dt} = rN$$

What does this imply?

Stability only occurs when r = 0

If is positive we get exponential growth.

$$\frac{dN}{dt} = rN$$

Exponential growth

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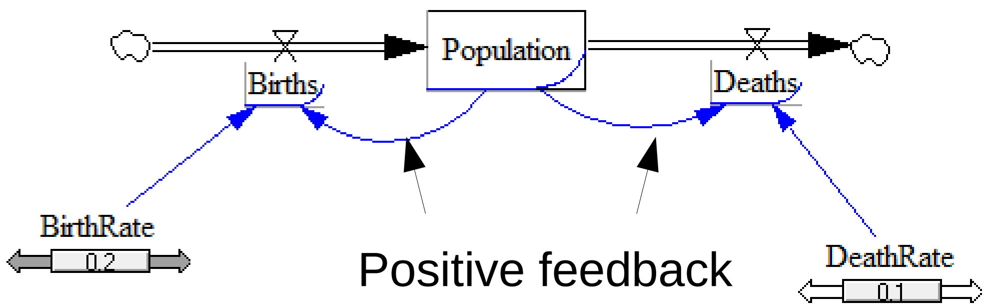

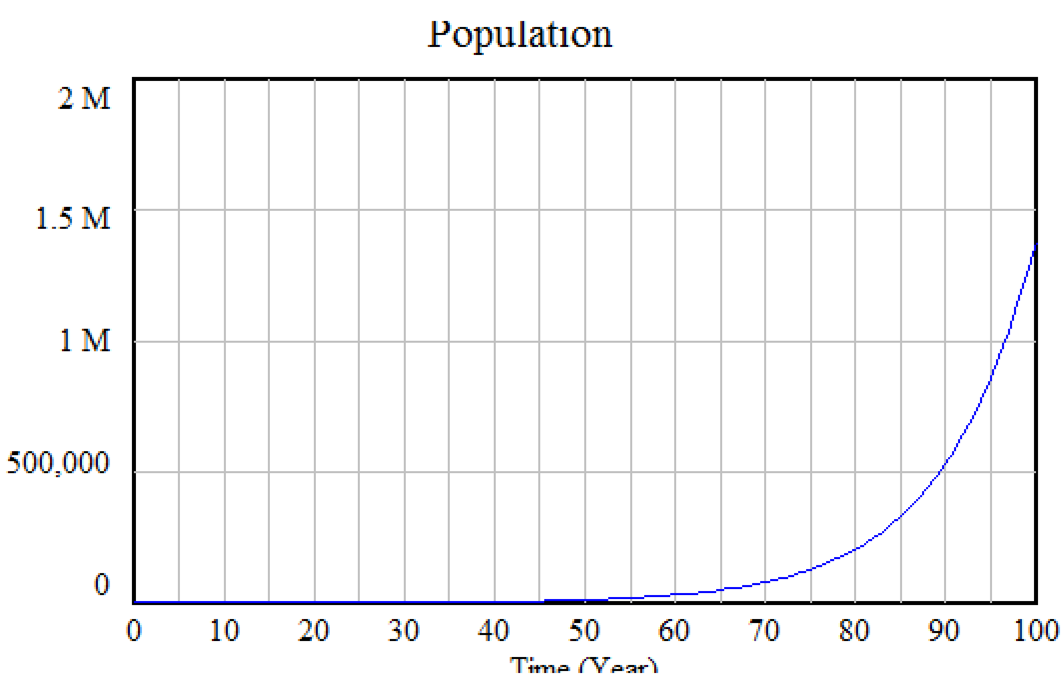

Exponential growth

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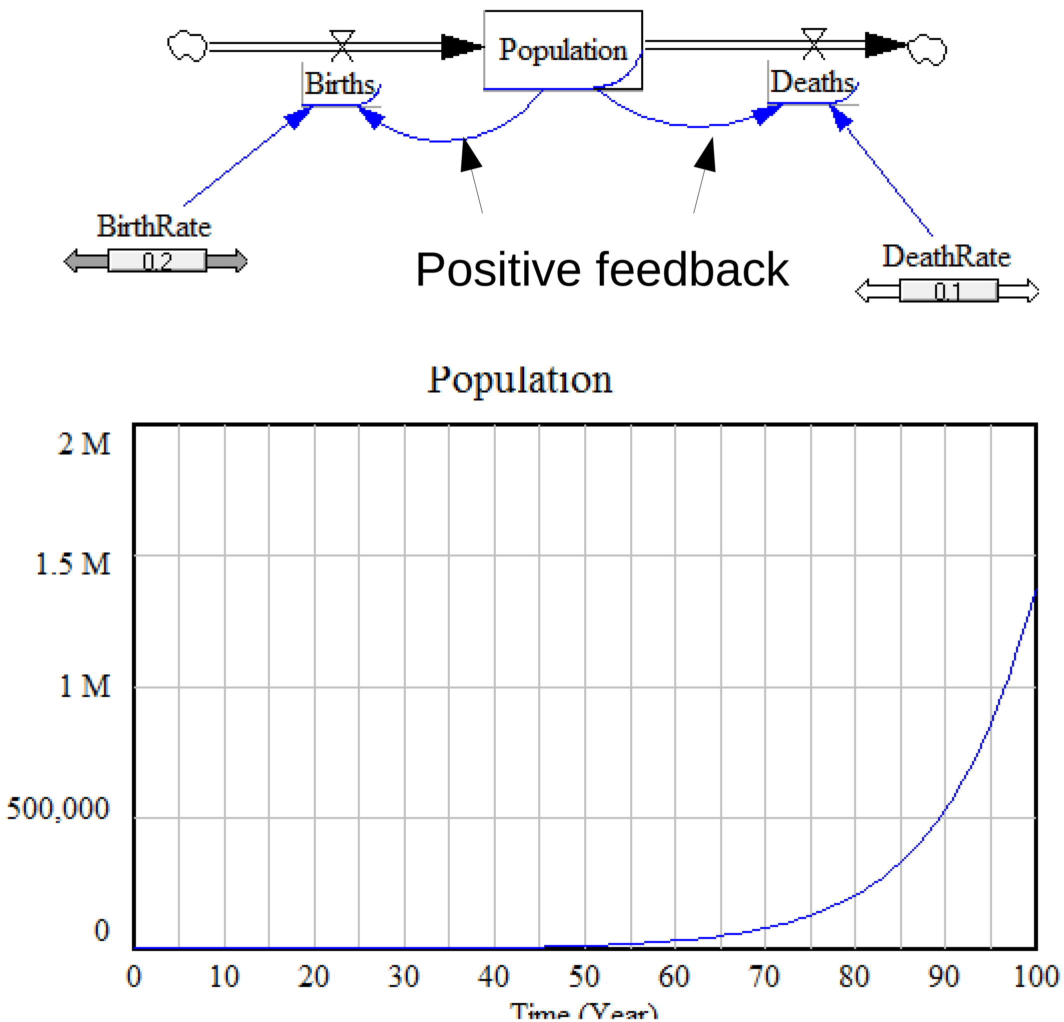

How do we avoid exponential growth?

We need to include some measure of the carrying capacity in our mathematical model.

As the population approaches the carrying capacity growth should slow to zero.

If the population exceeds the carrying capacity (overshoots) it will decline (negative growth rate)

Adding carrying capacity

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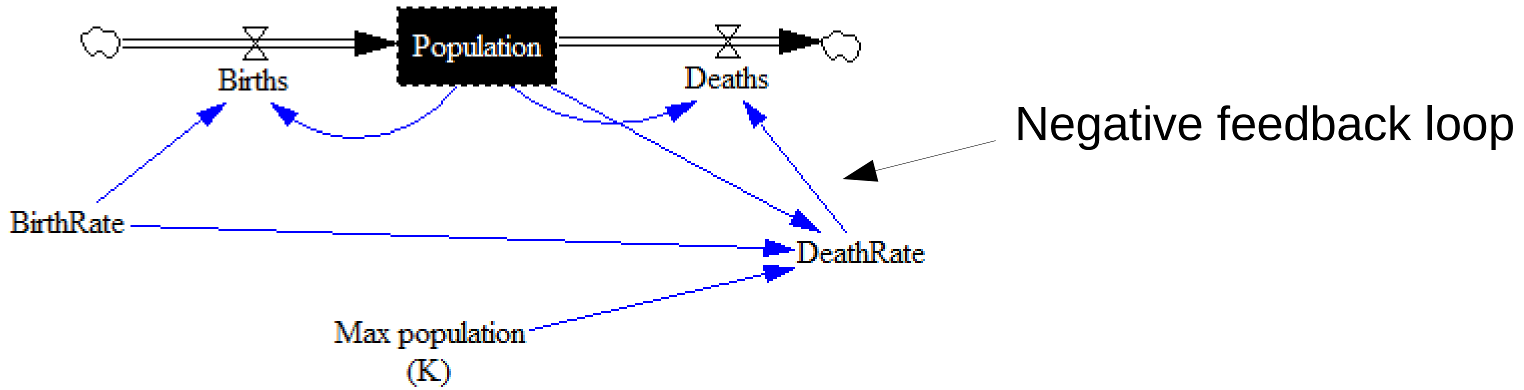
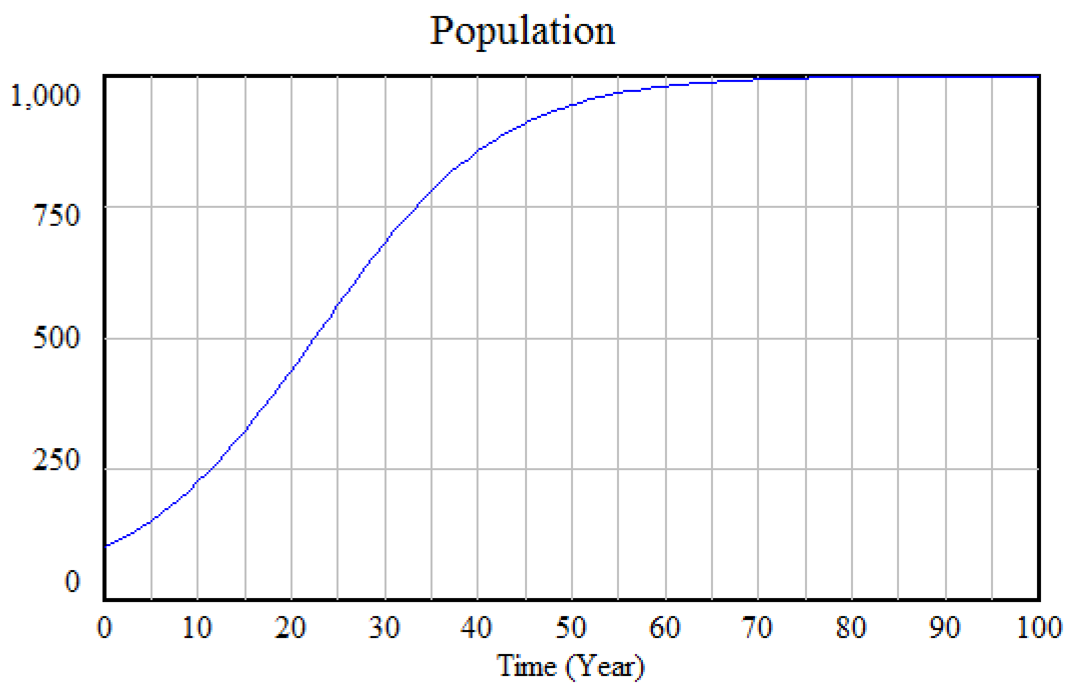
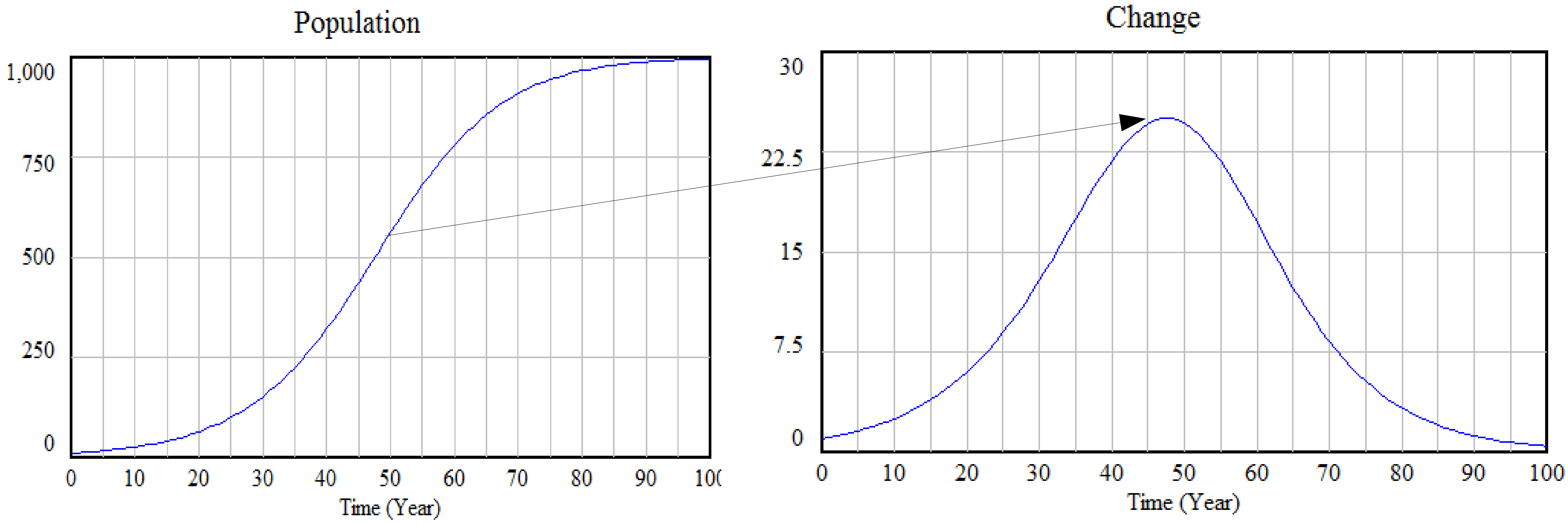




The logistic equation

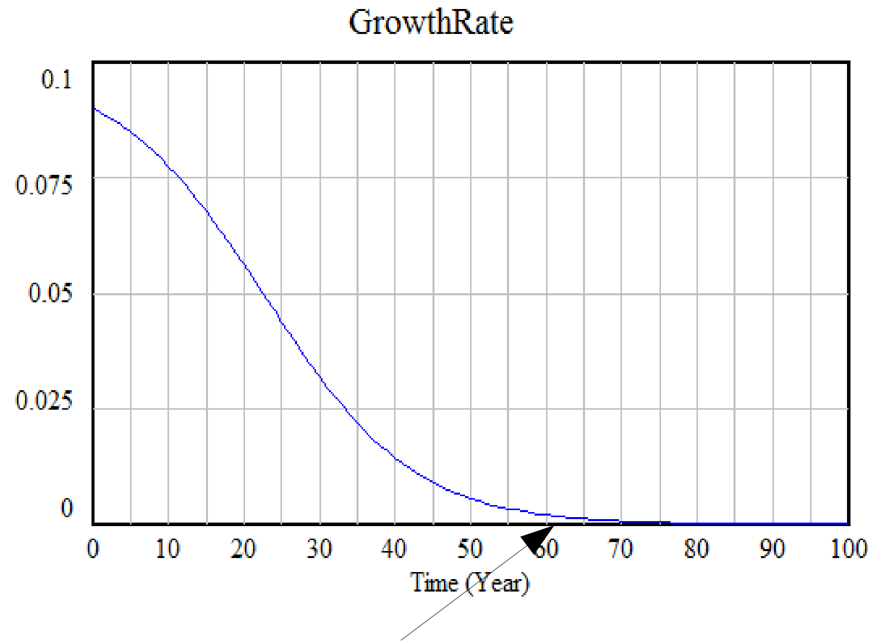
$$\frac{dN}{dt} = rN * \left(1 - \frac{N}{K}\right)$$



How does this work?

Look at the second term in the equation

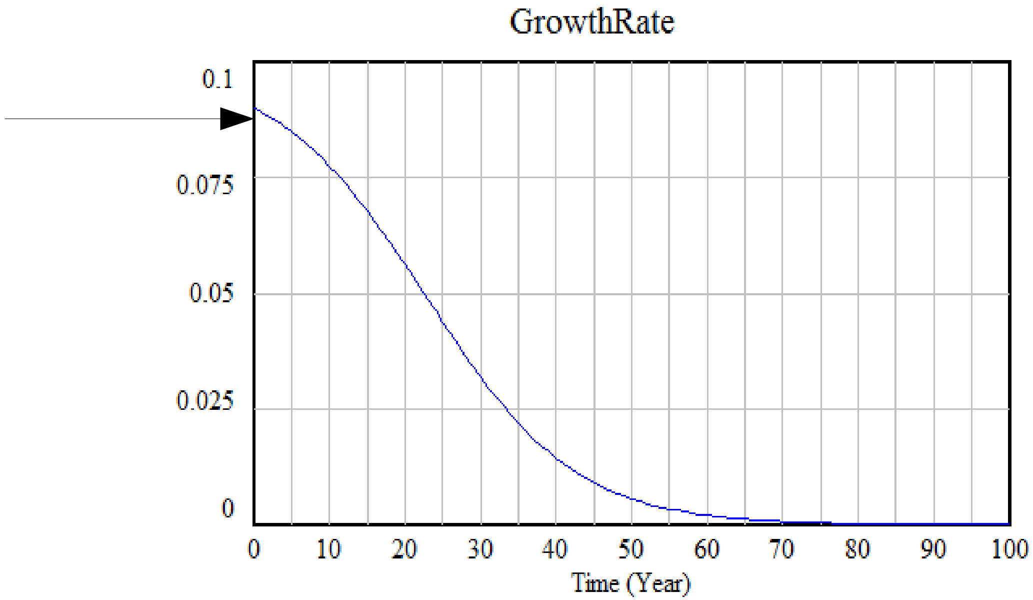
$$\left(1 - \frac{N}{K}\right)$$



If N= K it becomes N/N
This is equal to one
So 1-1= zero
NO GROWTH at the carrying capacity

What if N is small?

$$\left(1 - \frac{N}{K}\right)$$



If N is very small N/K tends to zero

So 1-0= 1

So the initial growth rate is not affected by the carrying capacity

What does this imply?

If we ignore genetic effects (which we shouldn't) populations increase more quickly when they are small.

This is because each individual has greater access to resources

When populations reach the carrying capacity they stop growing

If a population overshoots the carrying capacity it declines

If populations did not tend to “rebound” after declines extinctions would take place more frequently

What does this imply?

If we manage populations we may wish to hold their size below carrying capacity

"Maximum sustainable yield" may theoretically be obtained by keeping the population around half the carrying capacity.

R vs K selected species

Populations of large, long lived species may frequently reach and exceed carrying capacity

Natural selection may act on traits that allow survival when competition takes place for resources (K selection)

Small, short lived animals are subject to fluctuations in population size.

Natural selection may act on traits that allow rapid population growth (r selection)

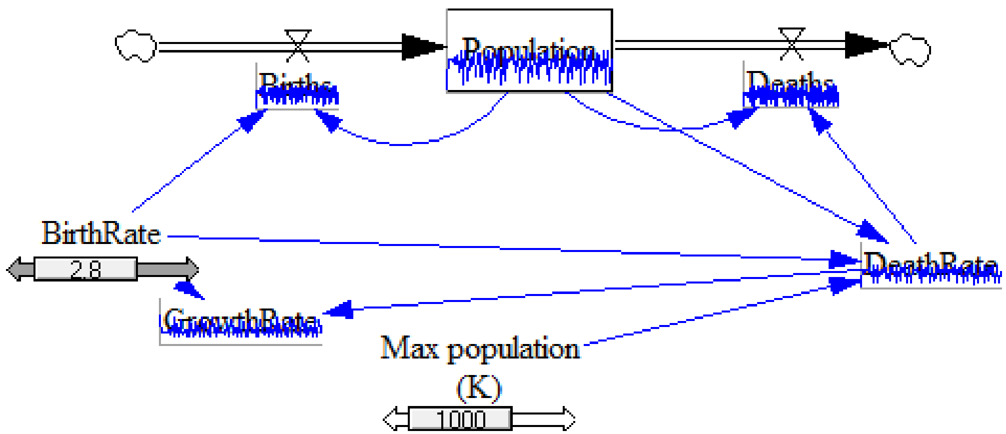
Cycles and chaos

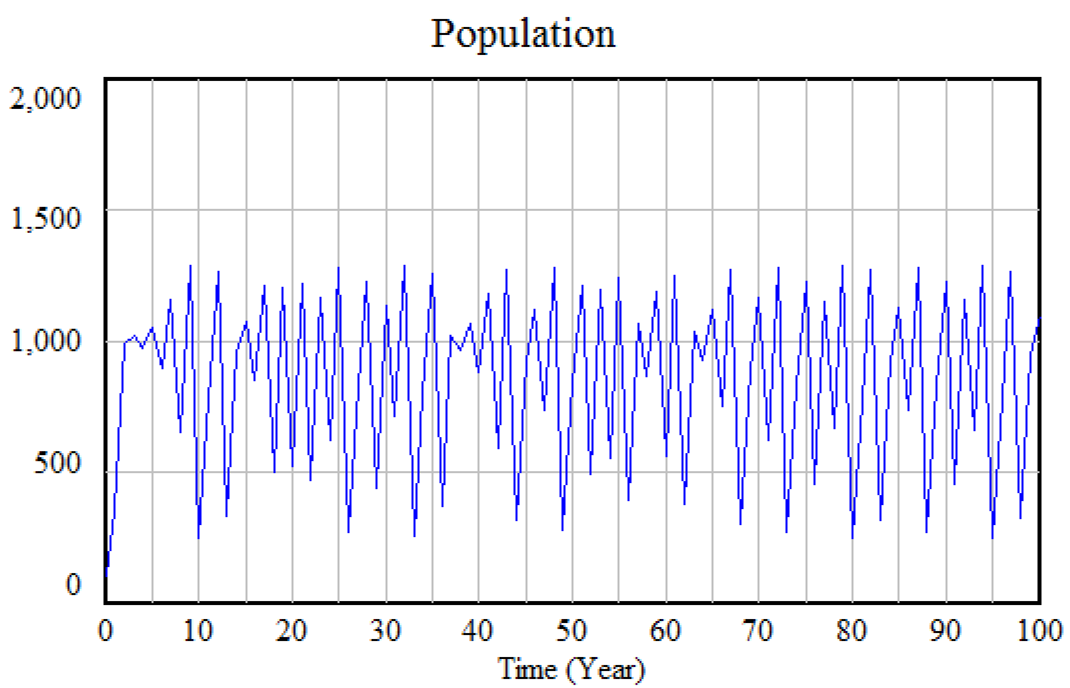
If populations “overshoot” the carrying capacity they will fall

In some circumstances this may produce “boom and bust” cycles

Organisms that are very short lived with high reproductive rates may show chaotic behaviour

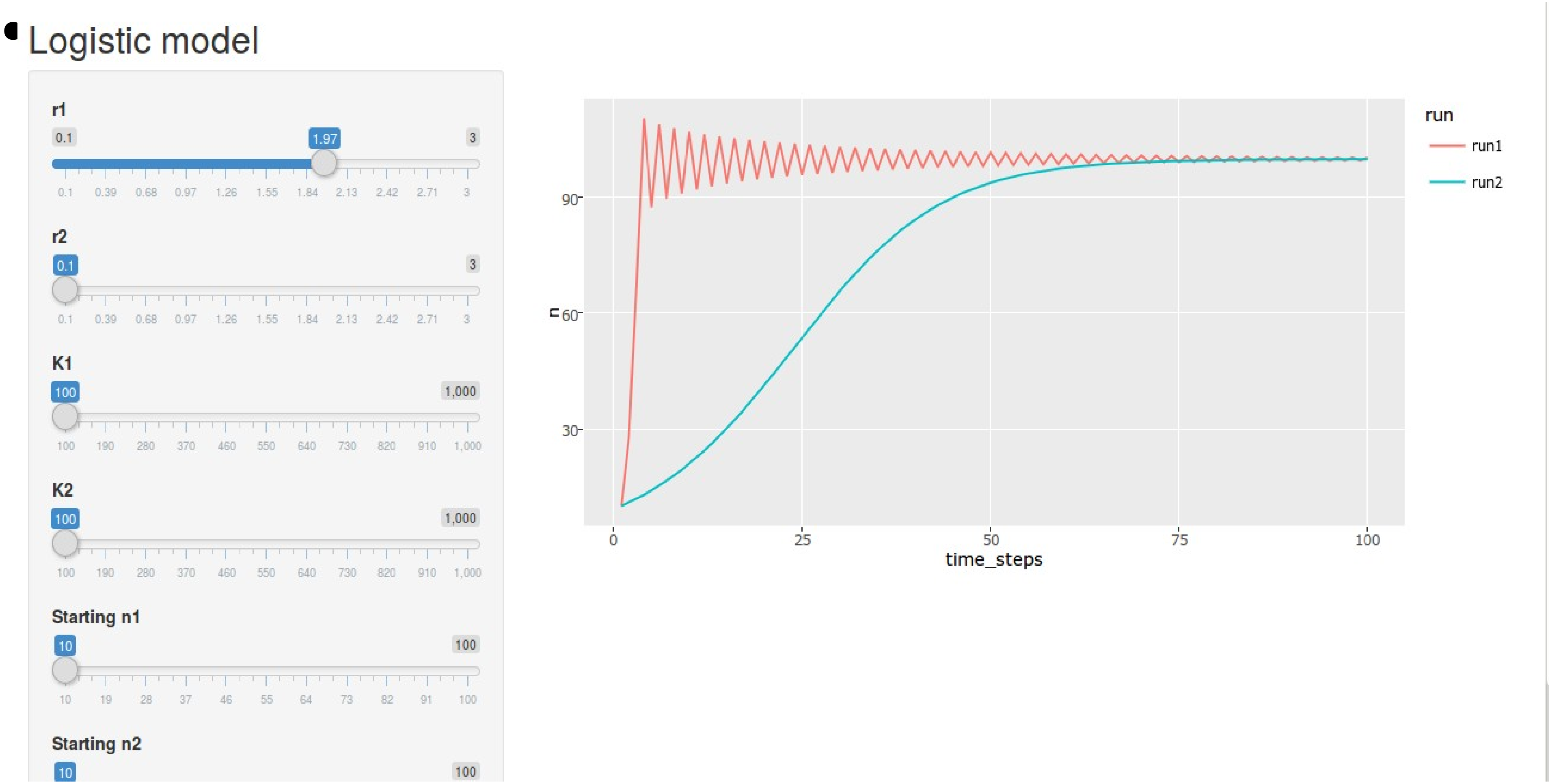
Chaotic dynamics





Test it yourself

https://dgolicher.shinyapps.io/Logistic_model



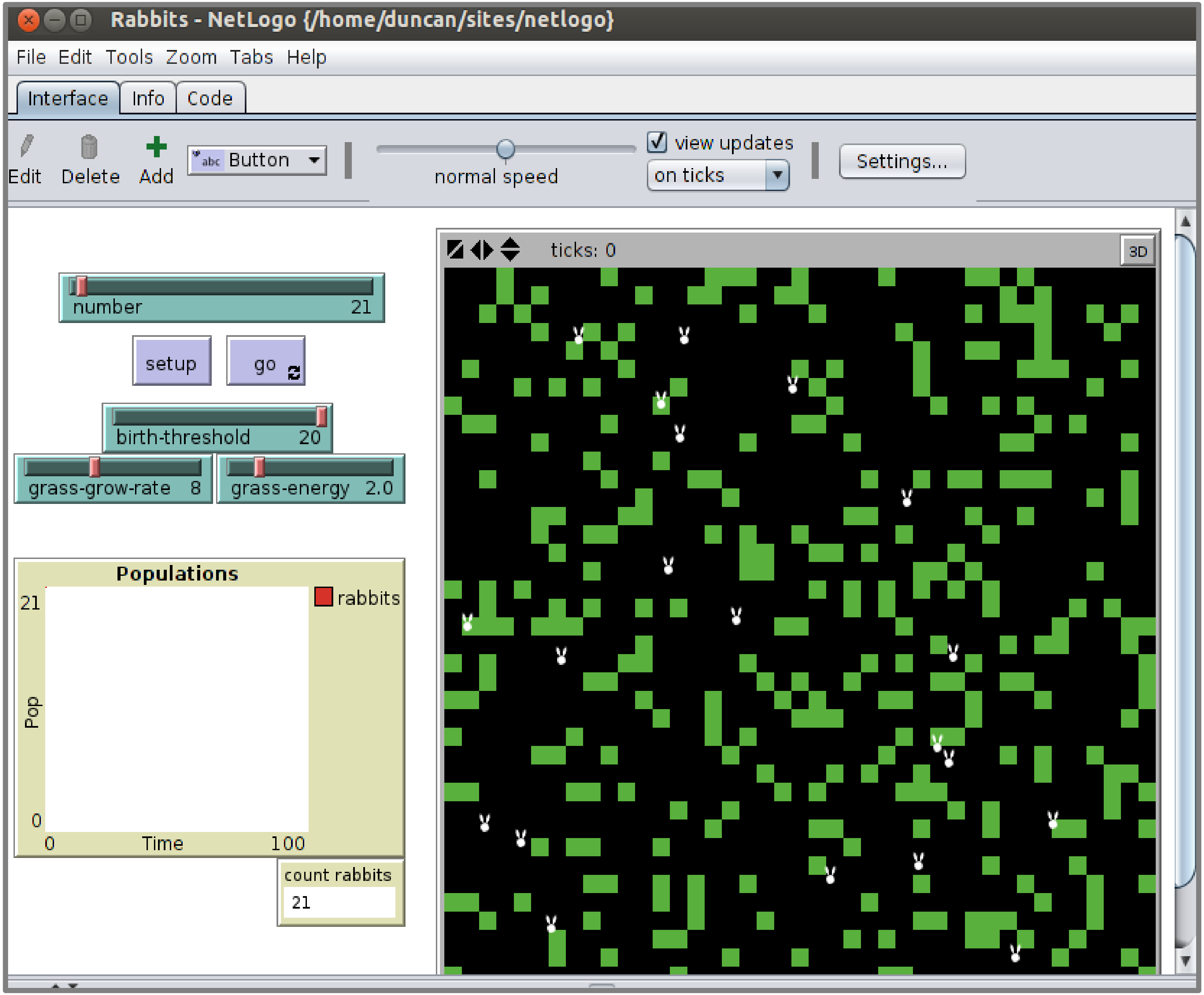
Individual based model simulation

Use simple rules to investigate system behaviour

Rabbits eat grass to gain energy.

When they obtain enough energy they may reproduce.

The total amount of energy depends on the nutritive value of the grass and the rate of growth after being eaten.


Rabbits - NetLogo {/home/duncan/sites/netlogo}
File Edit Tools Zoom Tabs Help
Interface Info Code
Edit Delete Add
Button
normal speed
view updates
on ticks
Settings...
number 21
setup
go
birth-threshold 20
grass-grow-rate 8
grass-energy 2.0
Populations
rabbits
21
Pop
0
0 Time 100
count rabbits
21
ticks: 0
3D

Play with the model yourself

http://ccl.northwestern.edu/netlogo/models/RabbitsGrassWeeds

Conclusions

Key words and concepts to take from the lecture

- Cybernetics: The study of complex self regulating systems
- System dynamics modelling: Interlinked sets of differential equations that represent complex systems with states that change over time.
- Homeostasis: The tendency of systems to return to a given state
- Positive feedback loops: Processes and linkages that reinforce and accelerate a given trajectory of change
- Negative feedback loops: Processes and linkages that slow down a given trajectory and tend to return a system to an equilibrium state

Conclusions

Key words and concepts

Deterministic chaos. Systems that are determined by definable rules but which produce dynamics that are highly sensitive to the initial state and are thus intrinsically unpredictable (butterflies' wing effect)