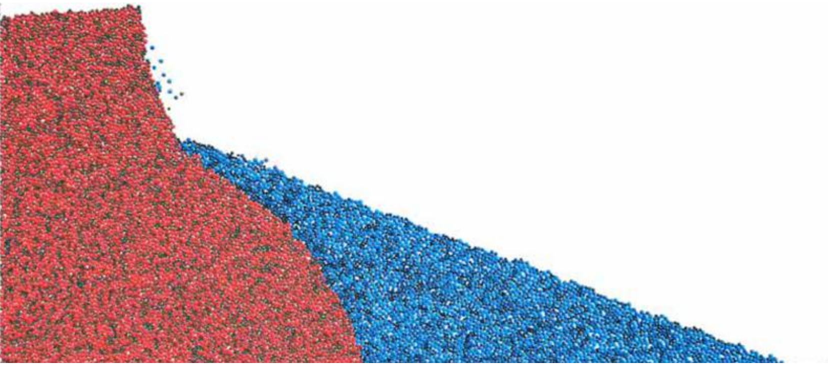
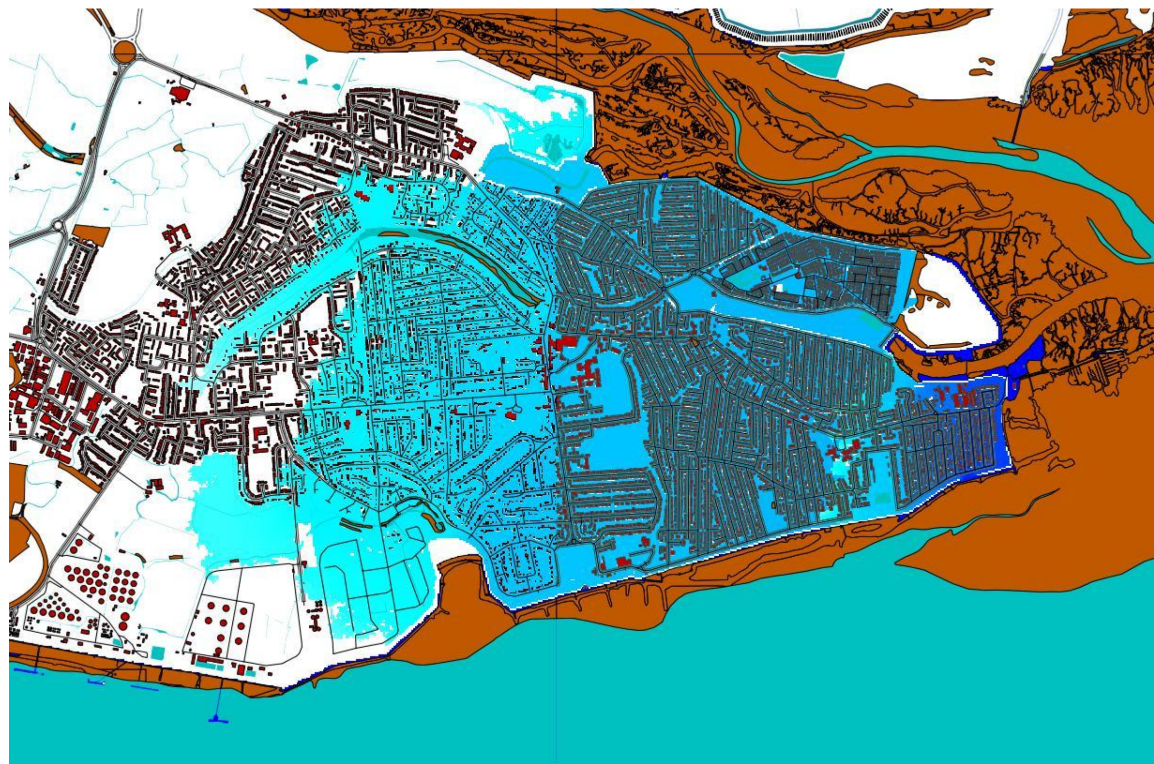
UNIVERSITY OF CAMBRIDGE
Department of Geography

Simulating Environmental Systems: The benefits of being discrete



From flow of rock

To flows of people...



From the galactic scale down to the atomic we are surrounded by discrete objects

Wherever we look on the earth's surface there are discrete things – from rock to trees to animals and people

Discrete systems are generally

- Composed of many *interacting* individuals
- Heterogeneous
- Spatially distributed
- Dynamics are generally complex (not just complicated!)
    - Sensitive to initial/boundary conditions
    - Path-dependent/contingent/adaptive
    - Non-decomposable
    - Tipping points/Phase changes

On the Earth

- Multiple interacting system types at different space and time scales
    - Everything is connected to everything else!

Statistics are typically

- Non gaussian - often with fat-tails
- Non-stationary over time and/or space

Environmental Change Depends on Discrete systems

- Causes and impacts of climate change
- Ecosystems , their services, management and conservation
- Environmental Hazards
- Disease and pandemics
- Urbanization
- Land-use change
- Economics, poverty, wealth distributions...

Explicitly spatial Process-based understanding is needed

- We usually lack equations of motion or conservation laws
  - Approach by simulation of every discrete object in the system
  - Hope that large scale systematic behaviours emerge!

Discrete Element Models

Atomic Scale simulation
Avalanches and debris flows
Cliff-scree systems

Individual-Based Models

Forest simulation
Herds and flocking
Foraging
Predator-prey models

Agent-Based Models

Epidemics
Traffic simulation
Crowds and escape from disaster
Urban populations
Social-Ecological Systems
Land-use Change

Increasing Complexity

Discrete Element Models

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Increasing Numbers

Discrete Element Models

Rock can flow like water

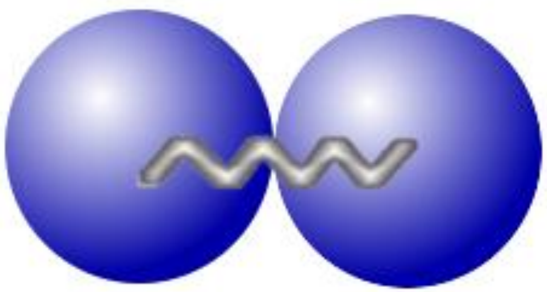
We can model this using Newton's laws, representing every rock in the flowing material

Computationally intensive! We have to use timesteps of order a microsecond

Discrete Element Models

Idealise rocks as spherical particles

Particles in contact are imaging to be connected by linear springs



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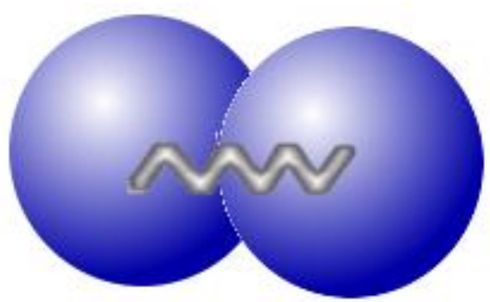

Restoring force is damped according to relative velocity

Discrete Element Models

Idealise rocks as spherical particles

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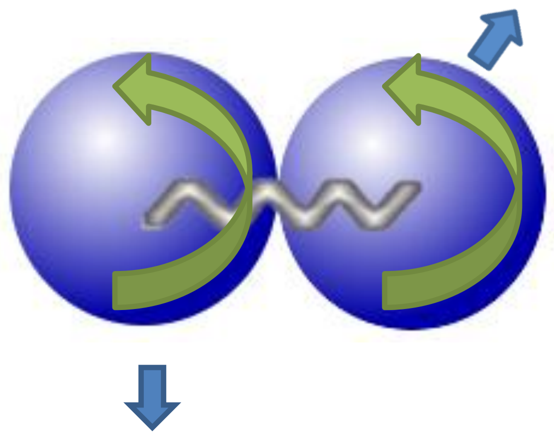
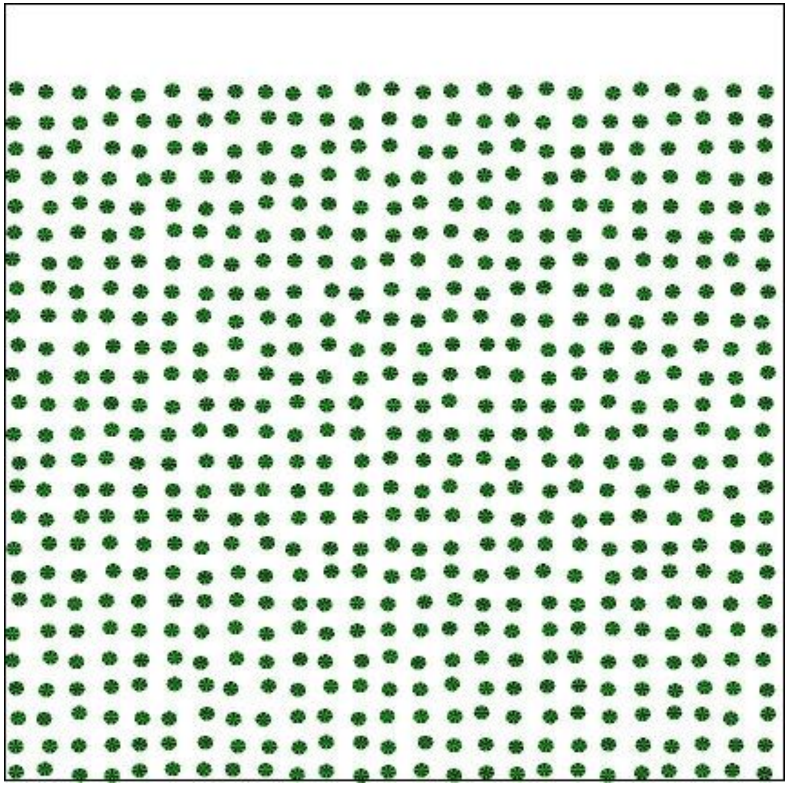


Restoring force is damped according to relative velocity

Relative rotation gives rise to further damped elastic forces

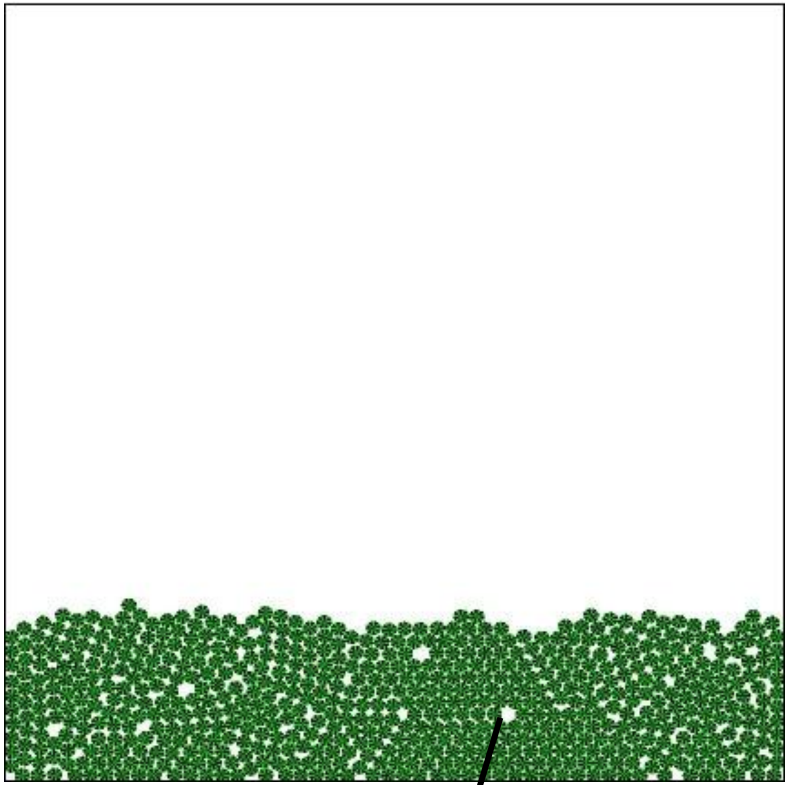
Discrete Element Models

Example – identical particles falling into a 2D box



Discrete Element Models

Example – identical particles falling into a 2D box

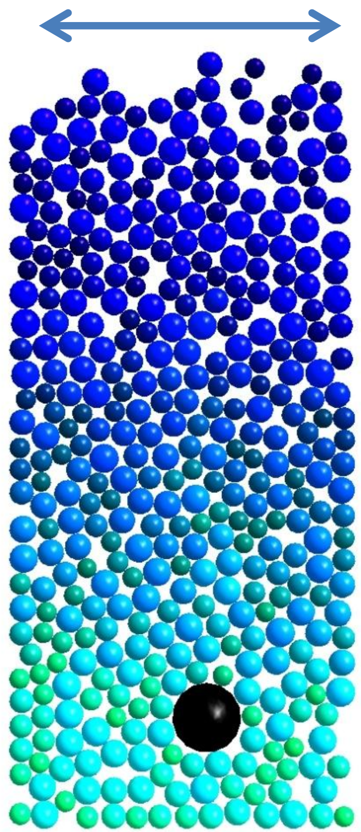


Note "crystalline"appearance – a result of particles all being exactly the same size

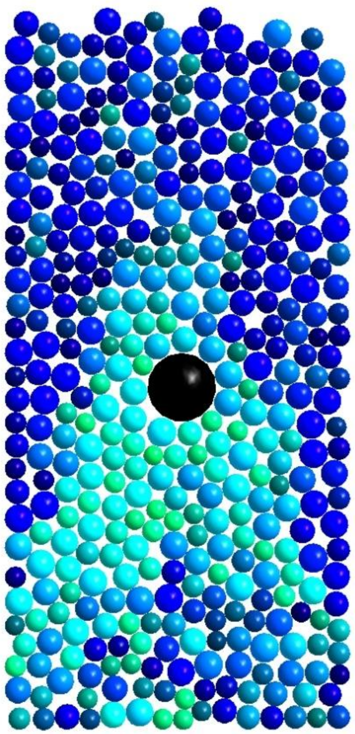
voids and other defetct arise naturally

Discrete Element Models

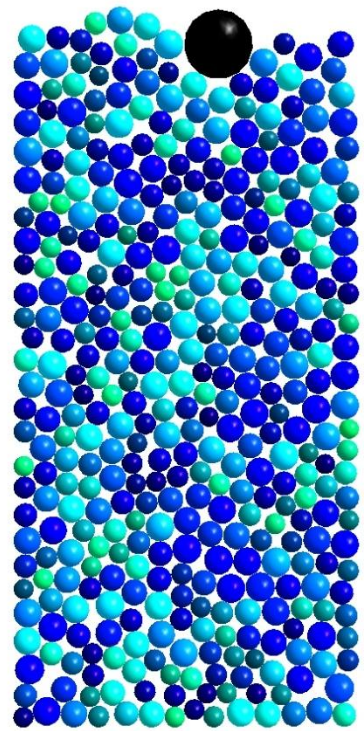
The "Brazil-nut" effect



The large particle



rises to the surface



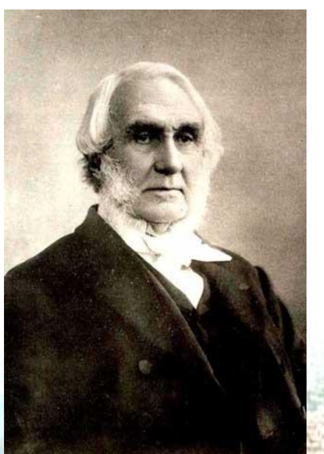
Shake an irregular set of particles in a box

Discrete Element Models

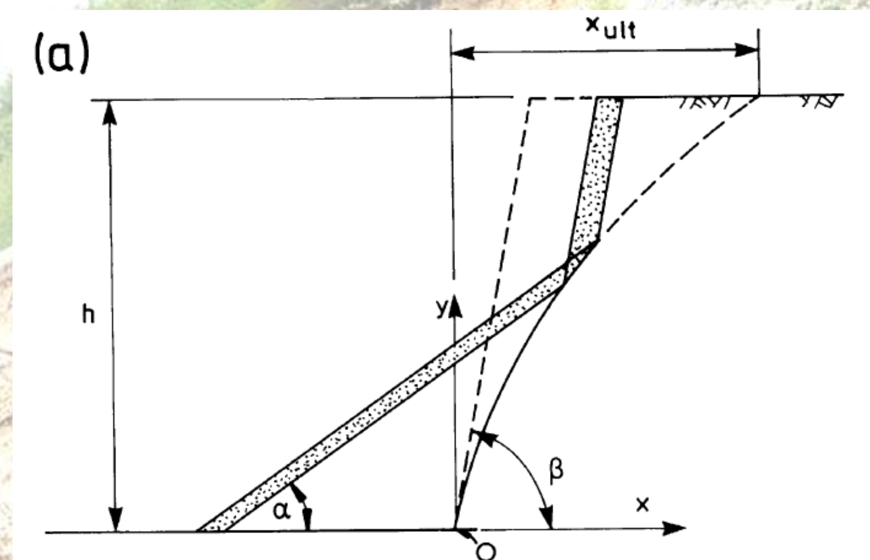
A more Geological example –

Cliff –scree systems

Rev. Osmond Fisher



Writer of the first geophysics textbook



Fisher, 1866

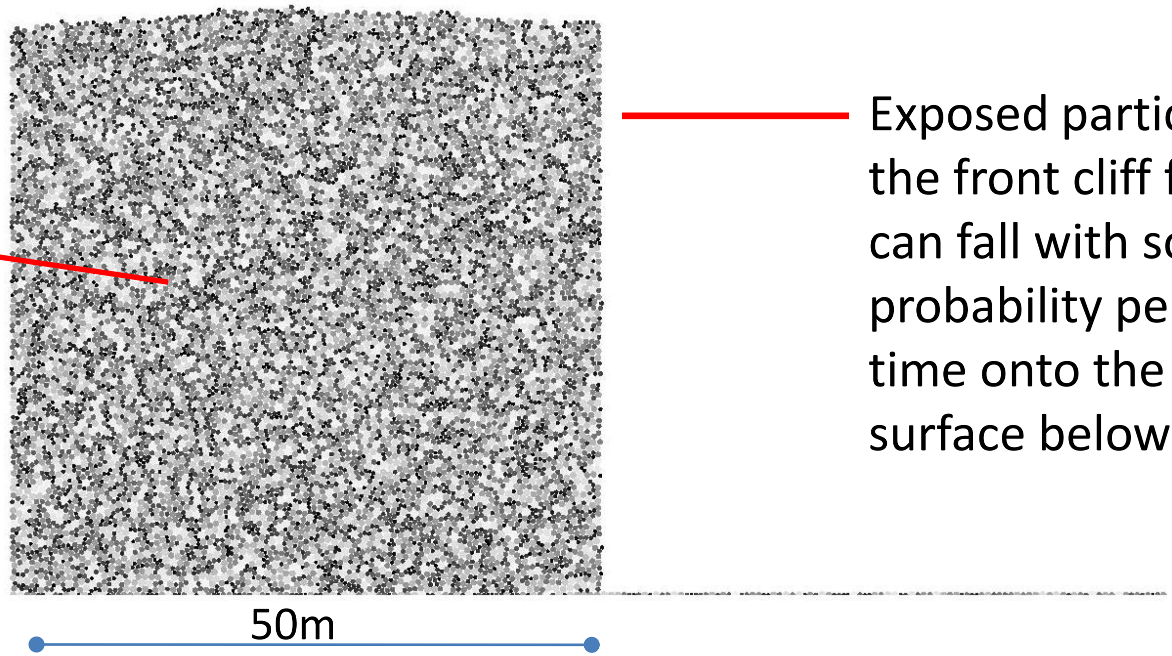
Photo by Keith Richards

Discrete Element Models

Cliff –scree systems

What happens as particles erode from the cliff face and fall to make a scree?

10,000 particles start off in a 2-D block



Particle sizes are distributed between 0.3 and 0.6 m diameter

Exposed particles on the front cliff face can fall with some probability per unit time onto the fixed surface below

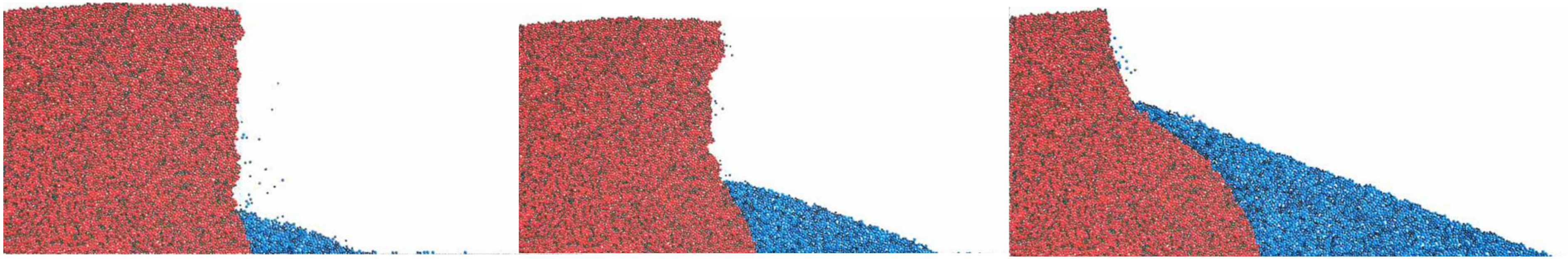
Discrete Element Models

Cliff –scree systems

What happens as particles erode from the cliff face and fall to make a scree?

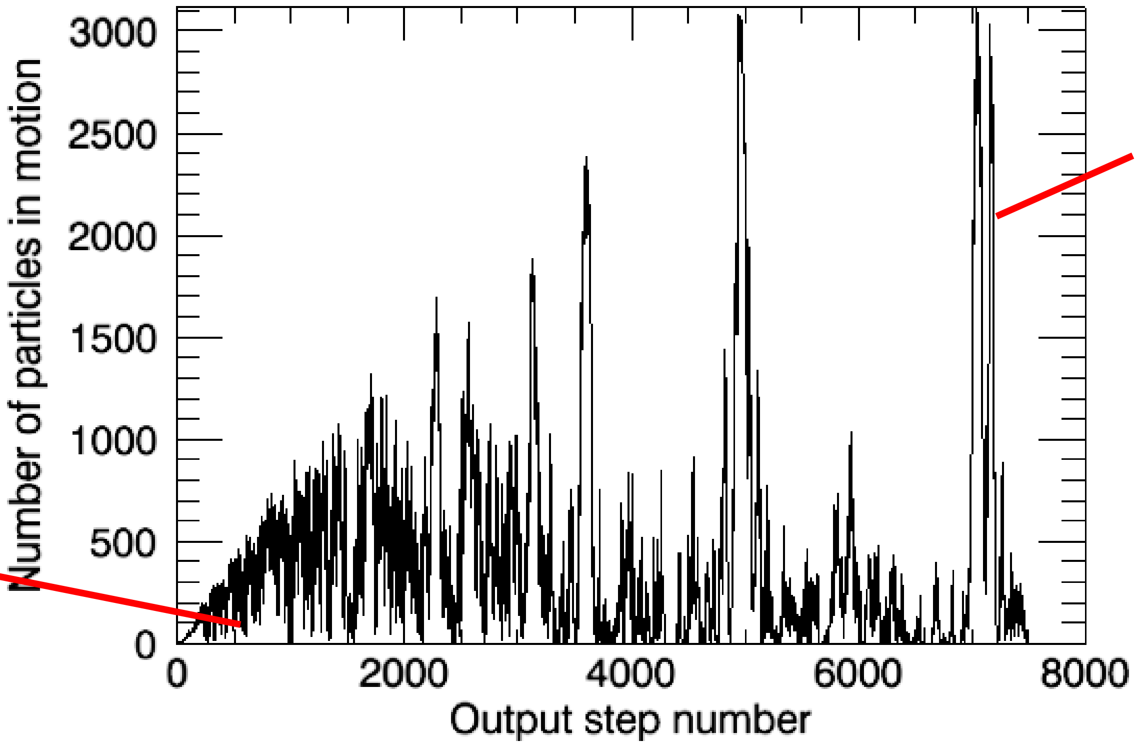
The scree builds but undergoes a series of progressively larger avalanches

Behind it the rock surface evolves into a quadratic shape



Cliff-scree systems – time series of avalanches

Early events are frequent with a typical minimum size. Largely driven by rock fall from the cliff.



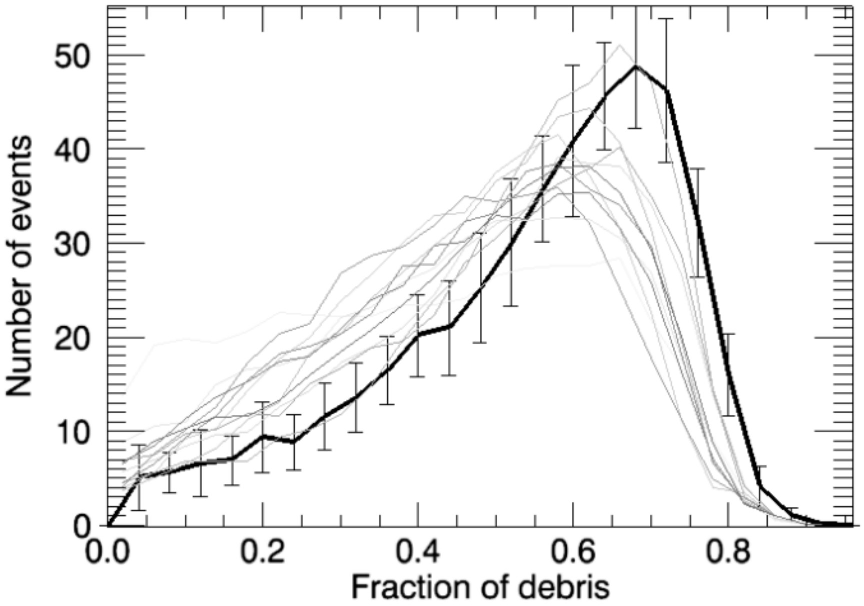
Late events have a long tail of very large slope failures. Largest events can occur very near the "end" of the evolution

Cliff-scree systems – distribution of avalanches

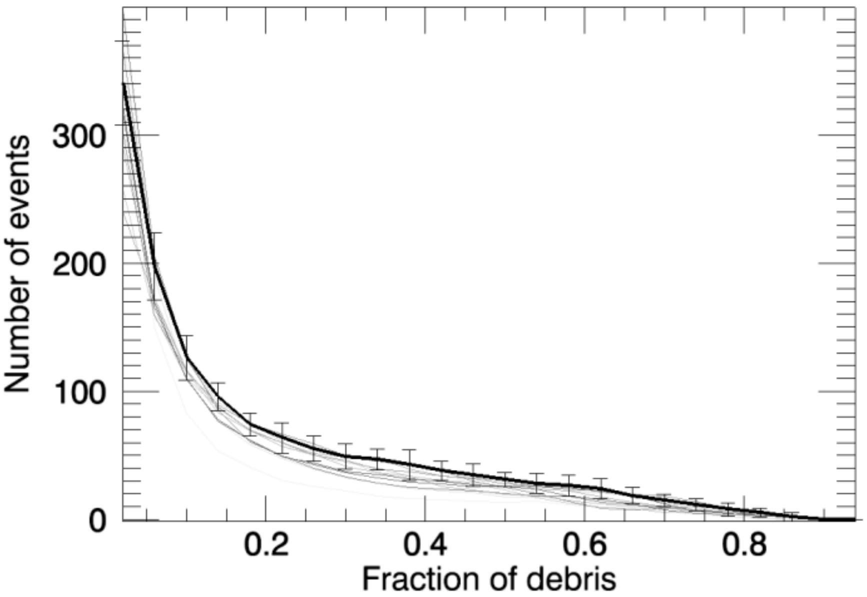
Early evolution – left-skewed, short tail, characteristic size

Later evolution – long tail, power law – self-organized criticality

Early period statistics –
a short tail and a modal value



Late period distributions - long tail, no typical size, distribution is close to a power law



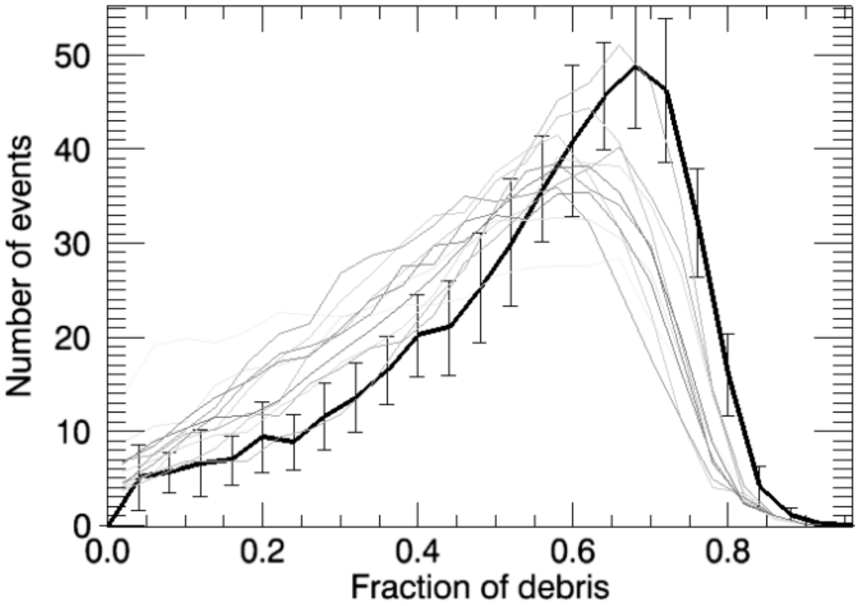
Cliff-scree systems – distribution of avalanches

Early evolution – left-skewed, short tail, characteristic size

Later evolution – long tail, power law – self-organized criticality

Results largely independent of model parameters

Early period statistics –
a short tail and a modal value



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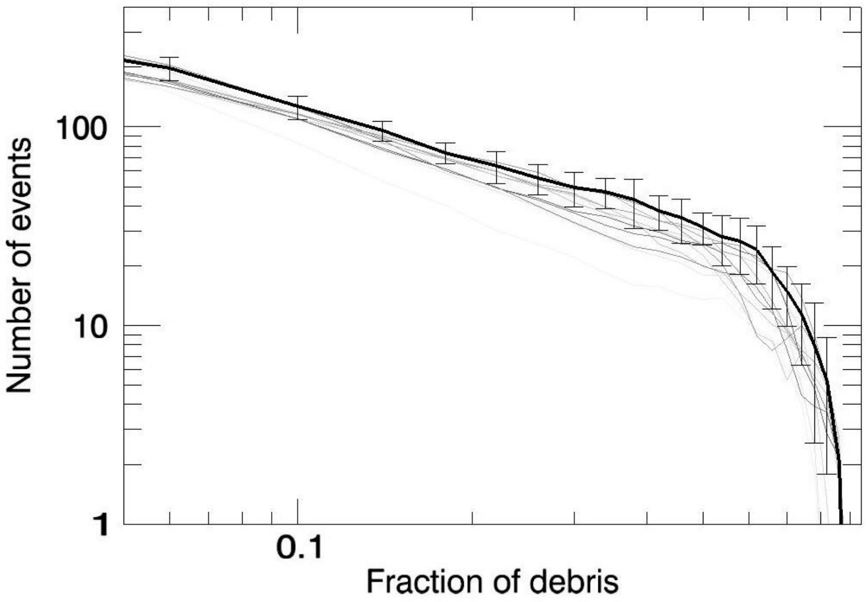

Increasing Complexity

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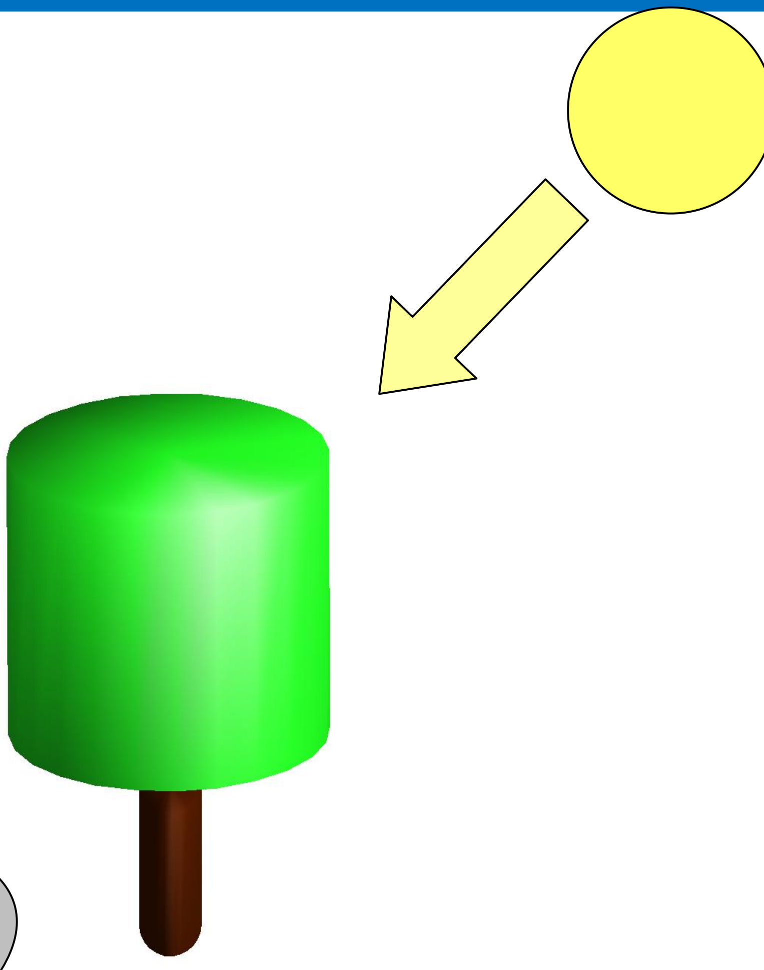
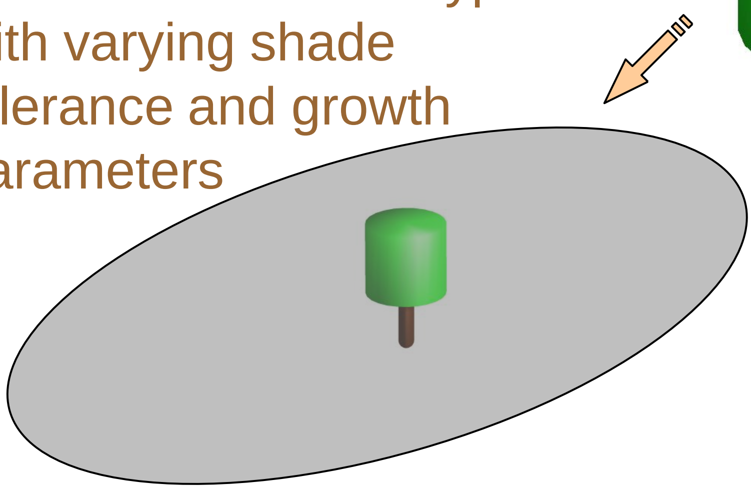
Increasing Numbers

Forest Model

- Individual-based model representing each tree
- Allometric rules for tree growth
- Competition primarily through shading
- Different functional types with varying shade tolerance and growth parameters

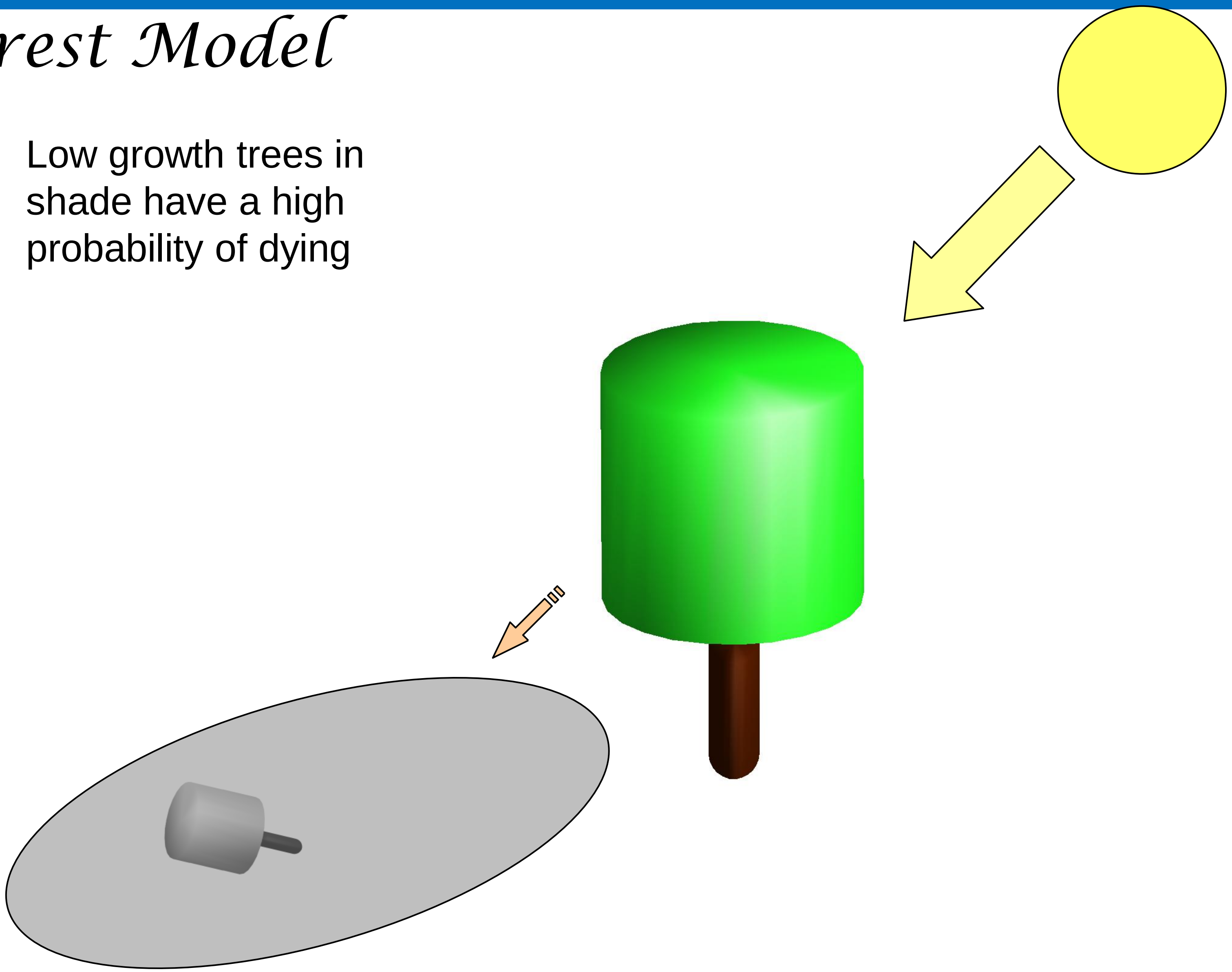




- Examples
  - SORTIE (Pacala et al 1996)
  - TROLL(Chave 1999)

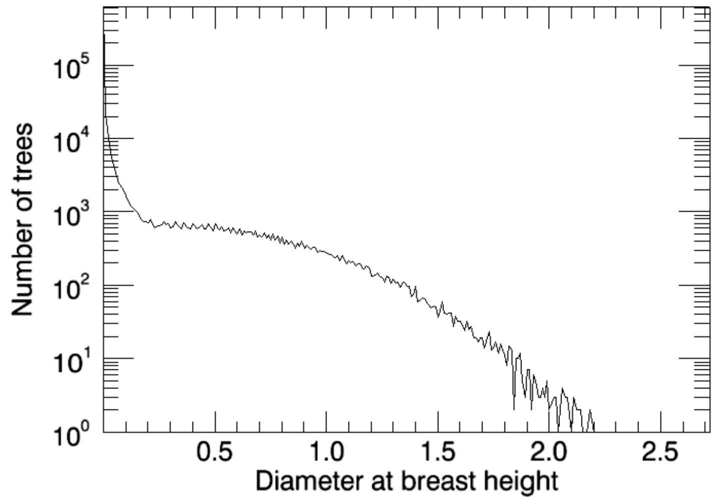
Forest Model

Low growth trees in shade have a high probability of dying

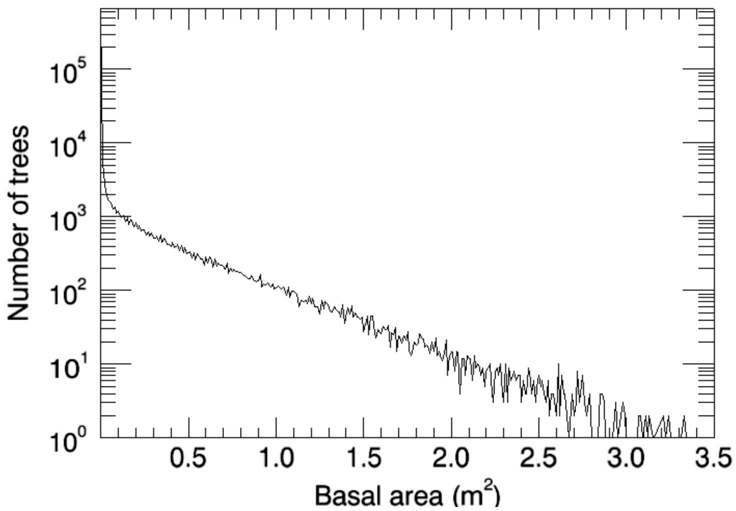


Forest Model

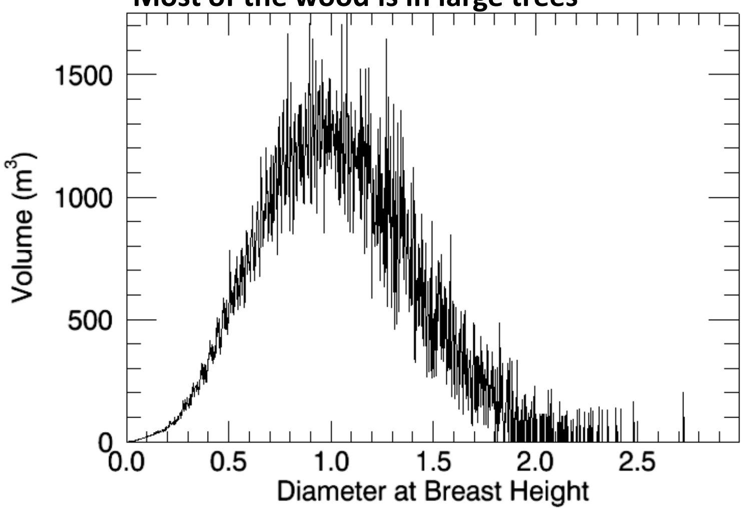
Huge number of seedlings – but they don't make it to maturity



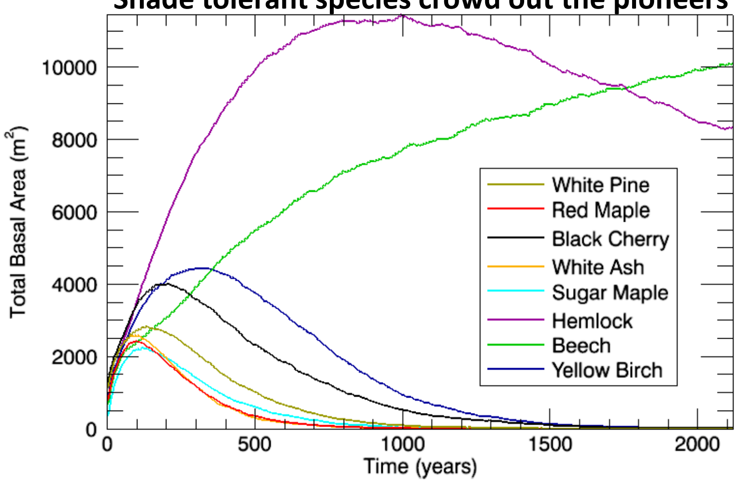
Number by area distribution is exponential



Most of the wood is in large trees

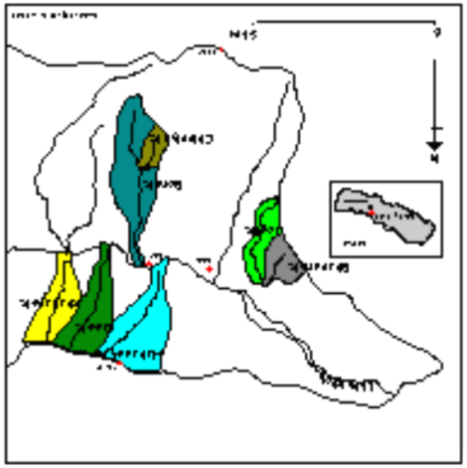


Shade tolerant species crowd out the pioneers



Forest Model – a specific example

- Bore Khola Valley
- Nepal Middle Hills
- 27.5º50’N 85º20’E
- 20km N of Kathmandu



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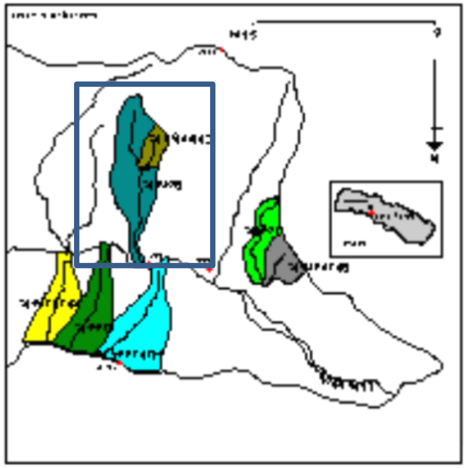
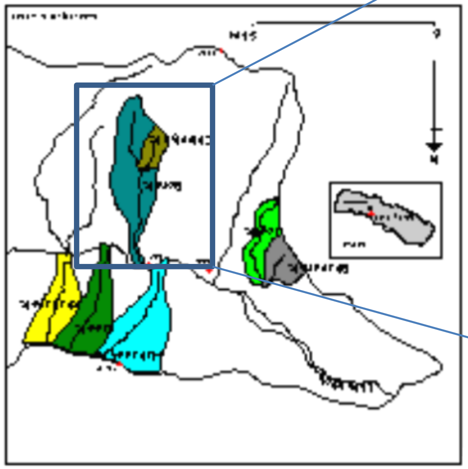
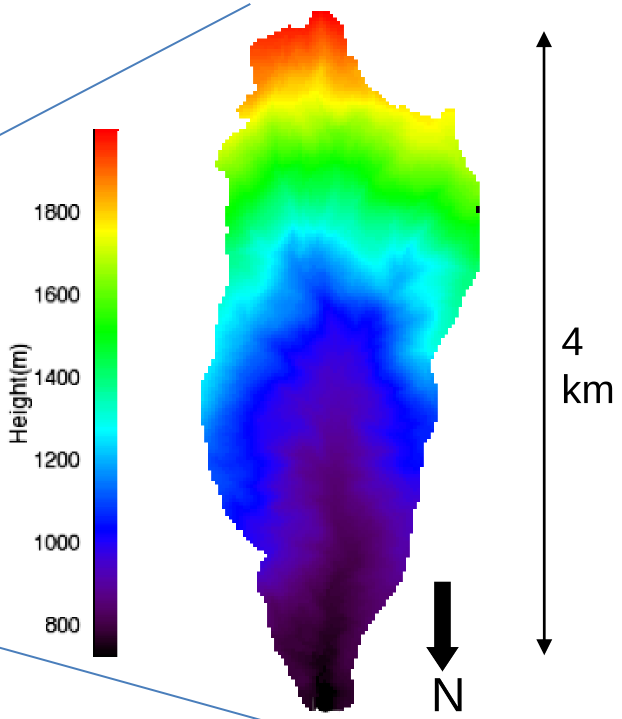


Forest Model – a specific example

- 4km square catchment
- Height data at 20m horizontal resolution, 10m in vertical
- Overall relief approx. 1000m

Topography





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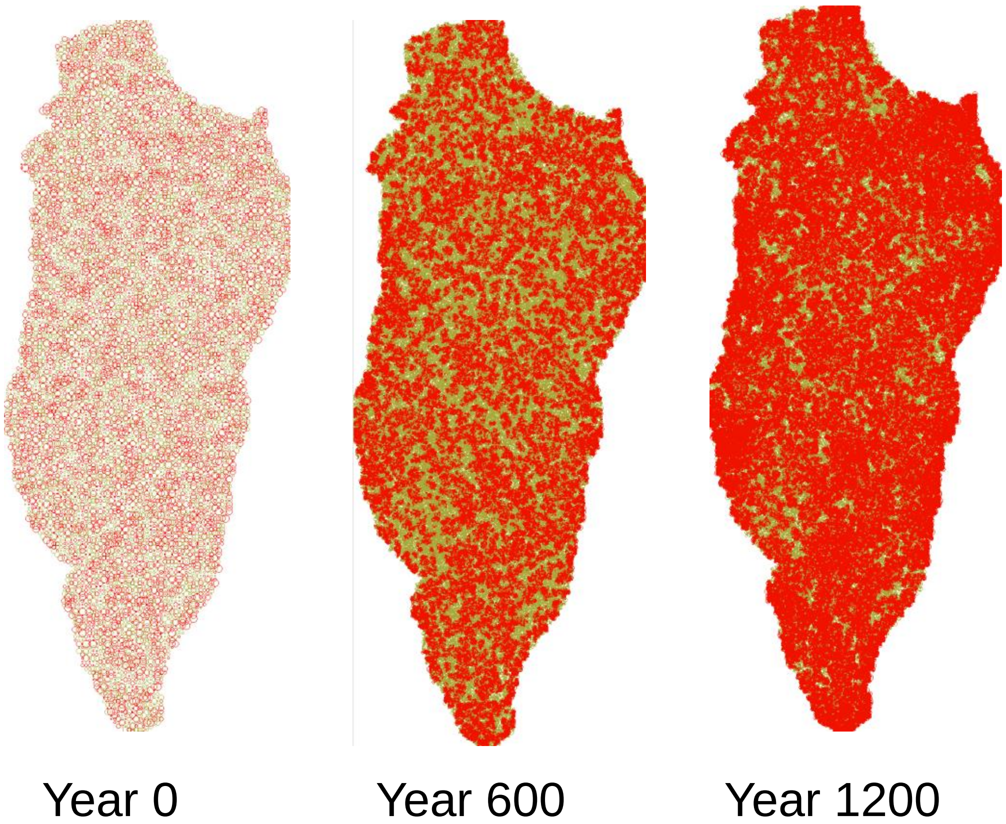
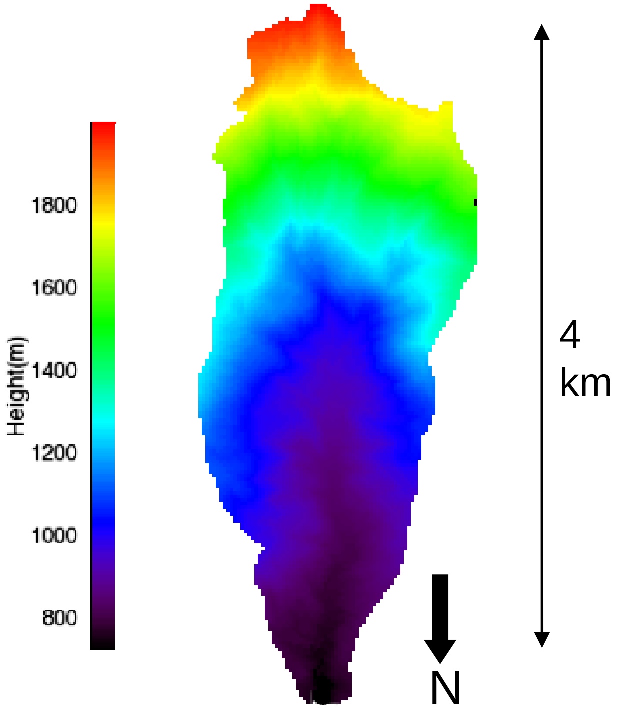
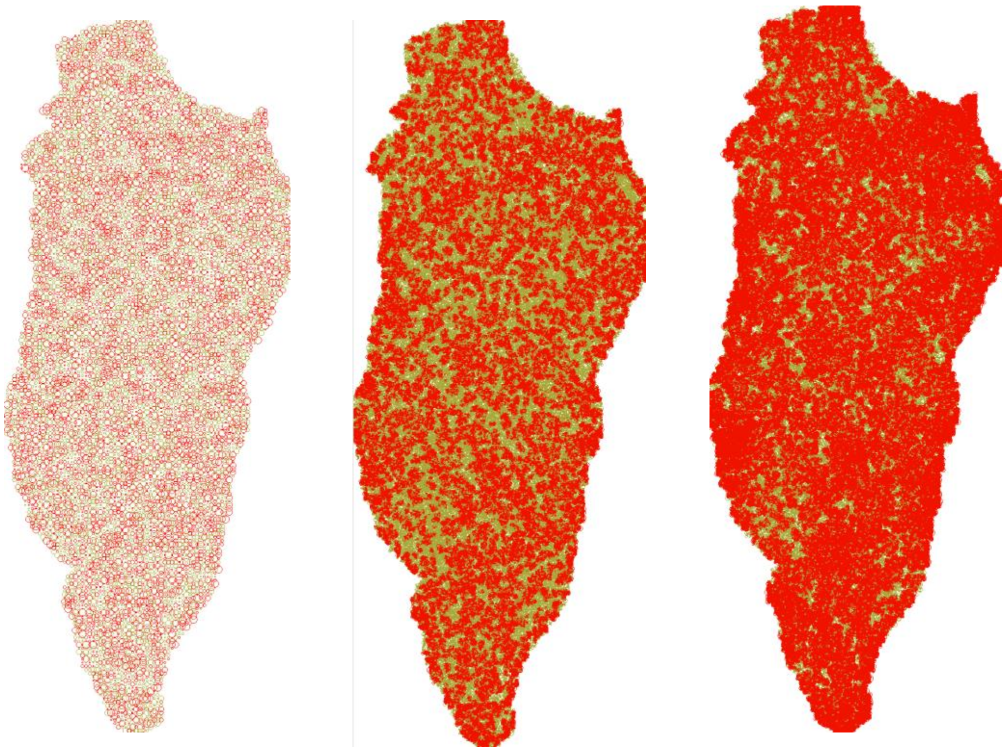


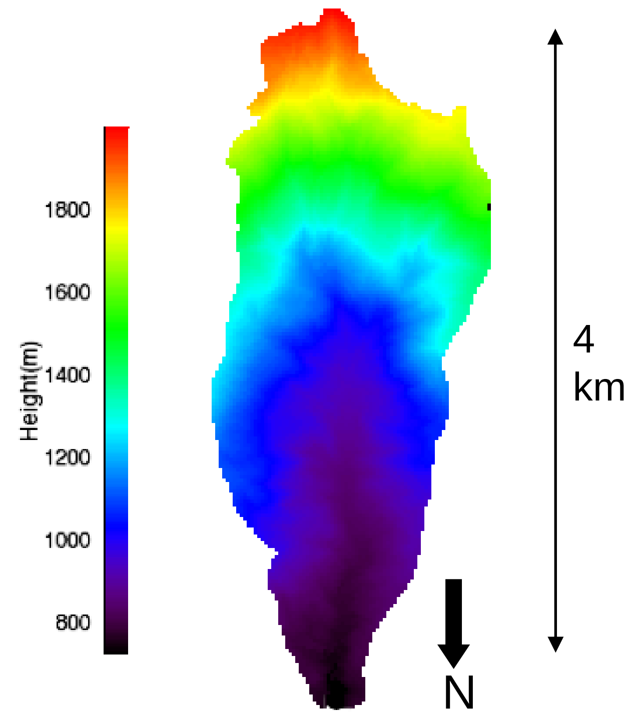


- Tree density accumulates over time

Forest Model – a specific example



Year 0 Year 600 Year 1200



- Tree density accumulates over time
- Now we send people out into the forest

Increasing Complexity

Discrete Element Models

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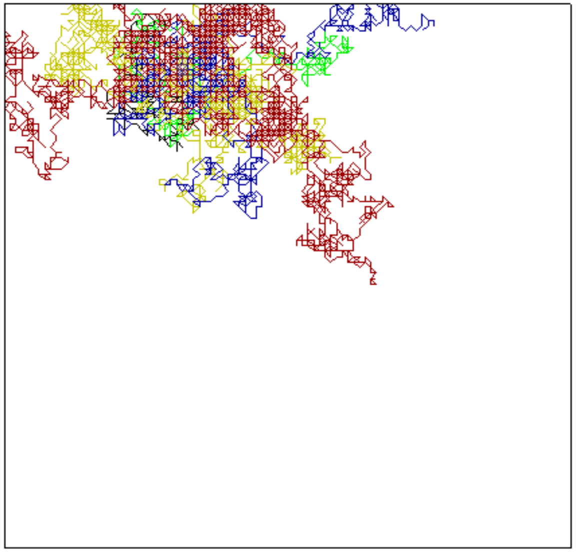
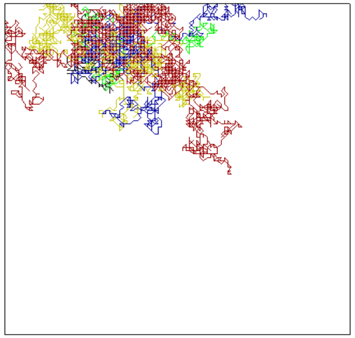
Foraging

We imagine a gatherer of forest products searches randomly in part of the domain, degrading the forest over time

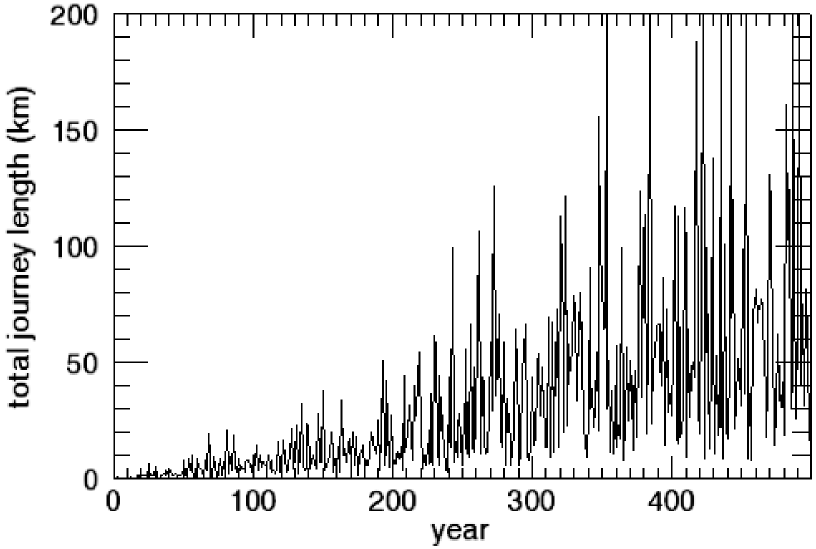
Random search is very inefficient !



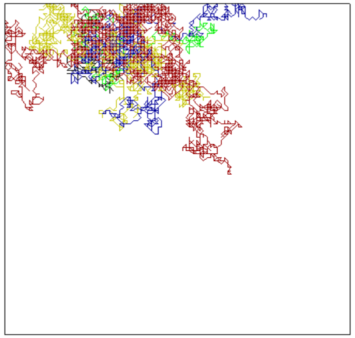
Foraging



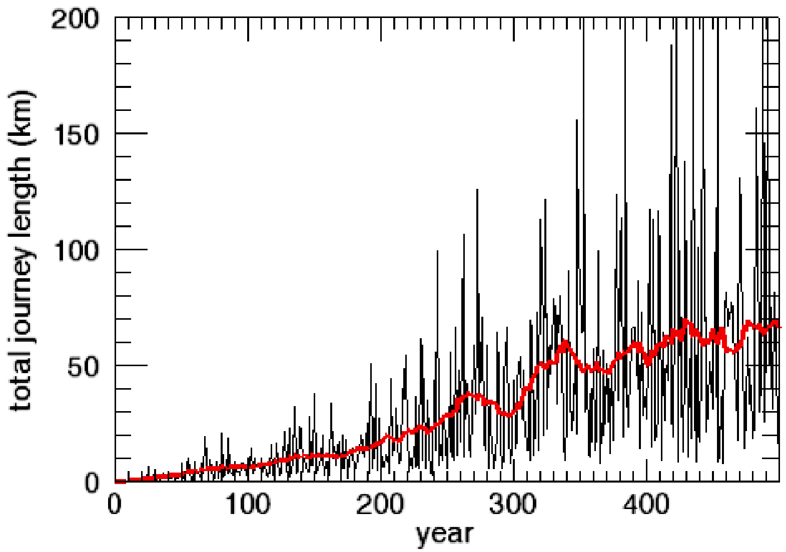
Large fluctuations are experienced in the total travel distance

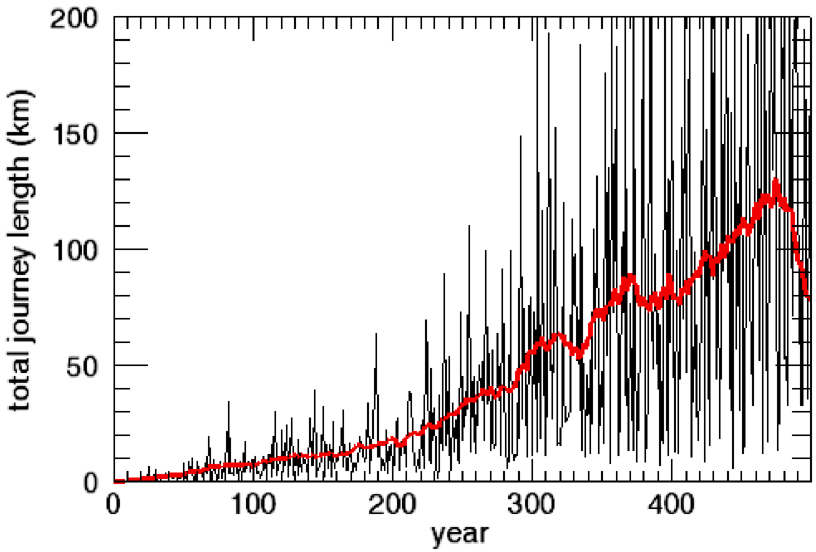


Foraging



Returning home increases the difficulty for random search

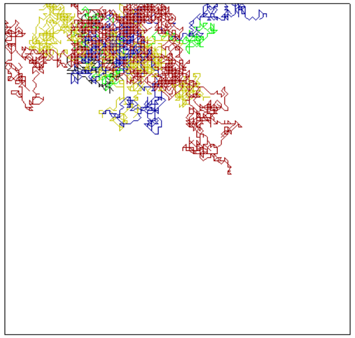


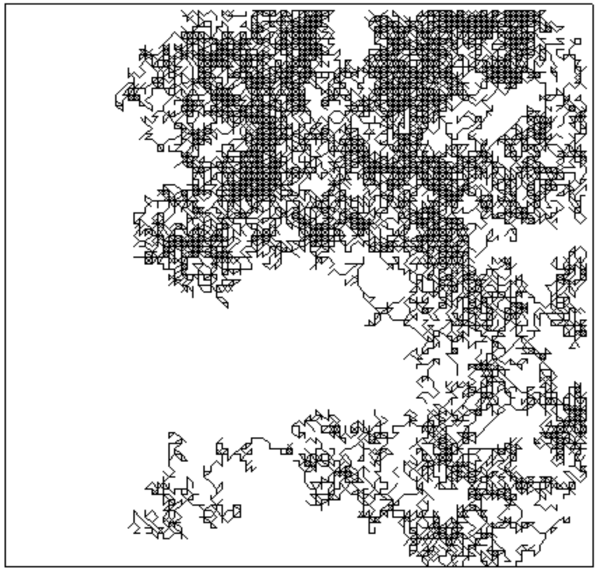


Individual excursion length limited to 25km

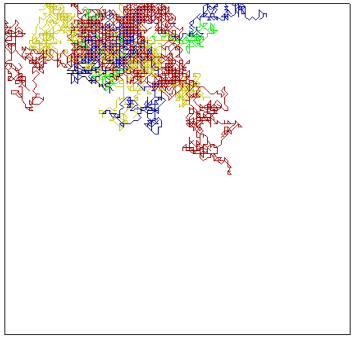
Foraging

A simple strategy of remembering the last visited increases the overall area of the domain visited

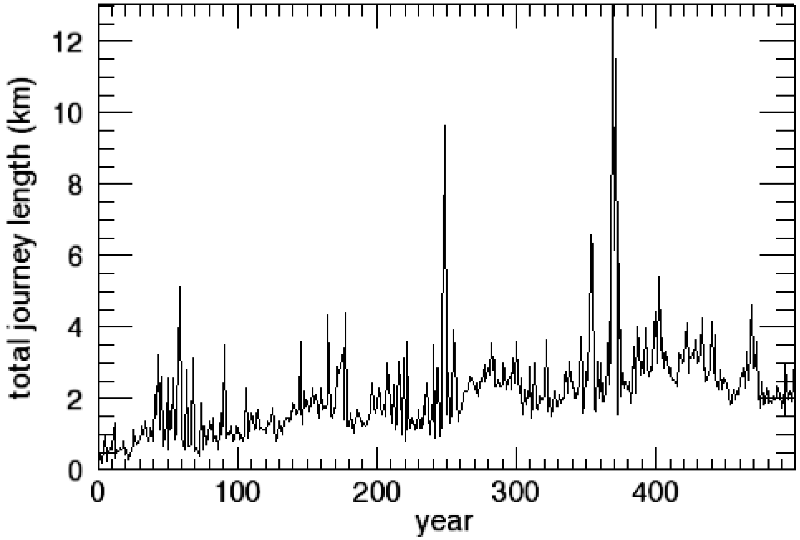


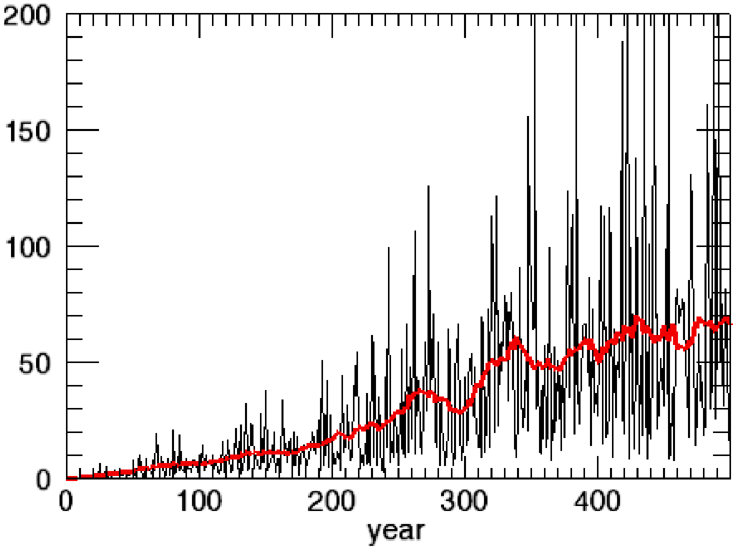


Foraging



but memory gives a huge benefit in gathering efficiency





with memory

random

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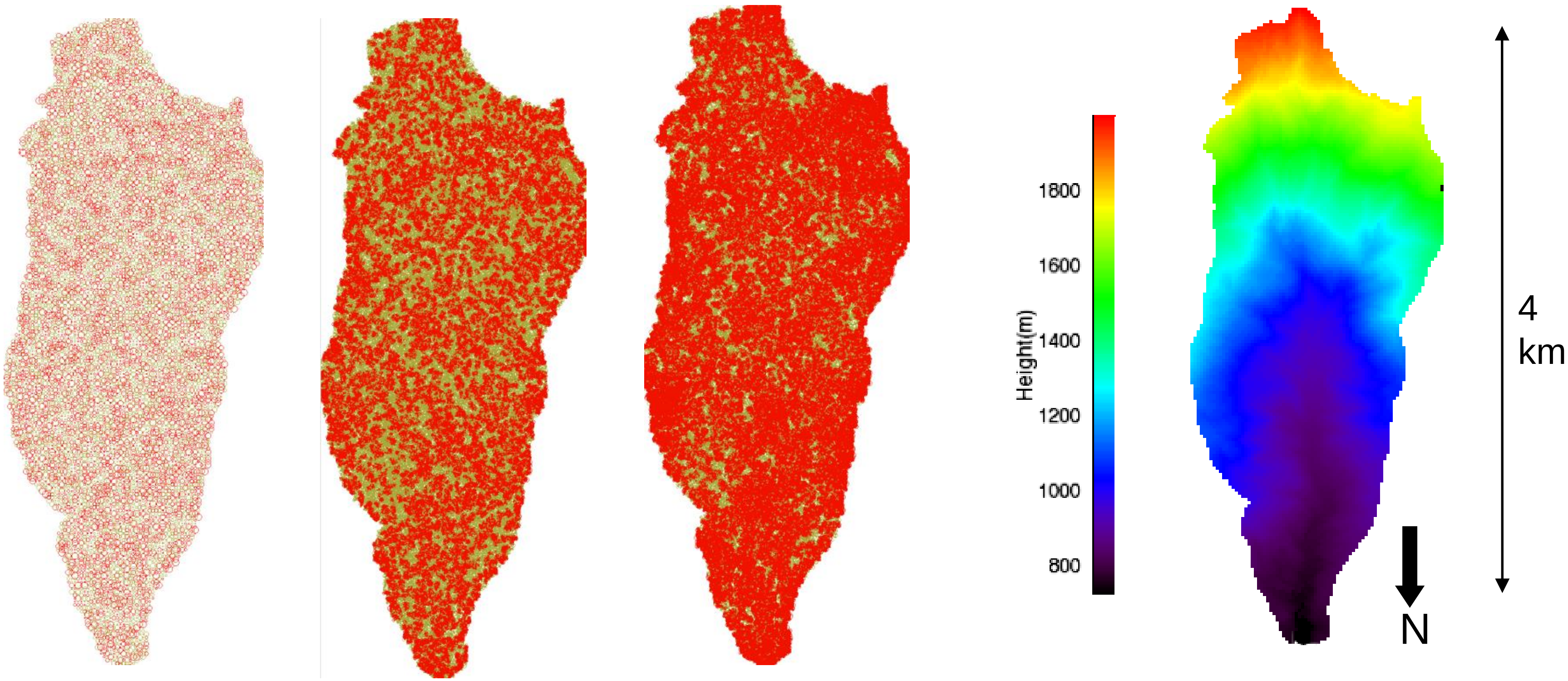
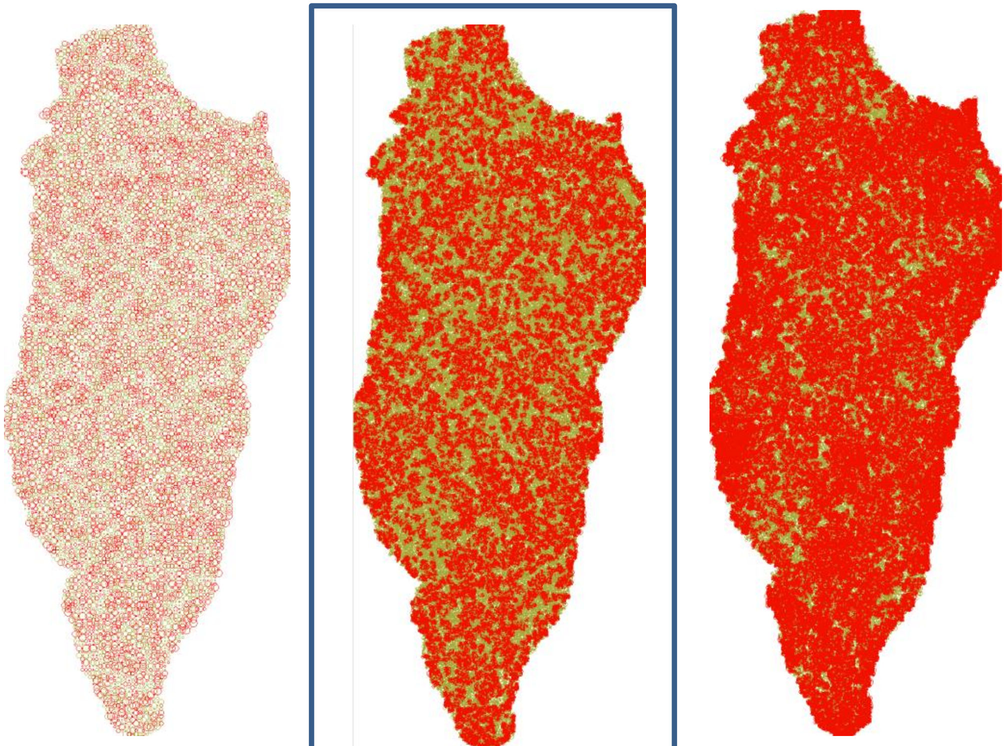
Forest Model – a specific example



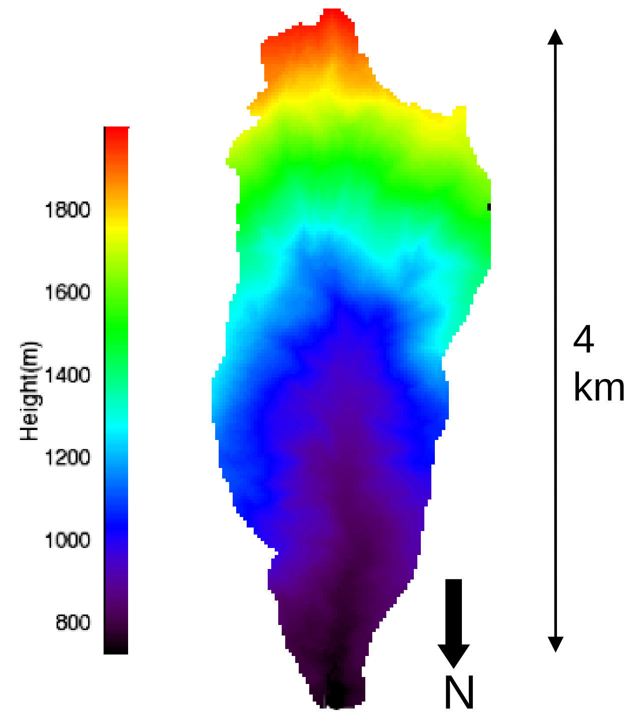
Year 0 Year 600 Year 1200

- Tree density accumulates over time
- Now we send people out into the forest
- Then people clear the forest for farming

Forest Model – a specific example



Year 0 | Year 600 | Year 1200



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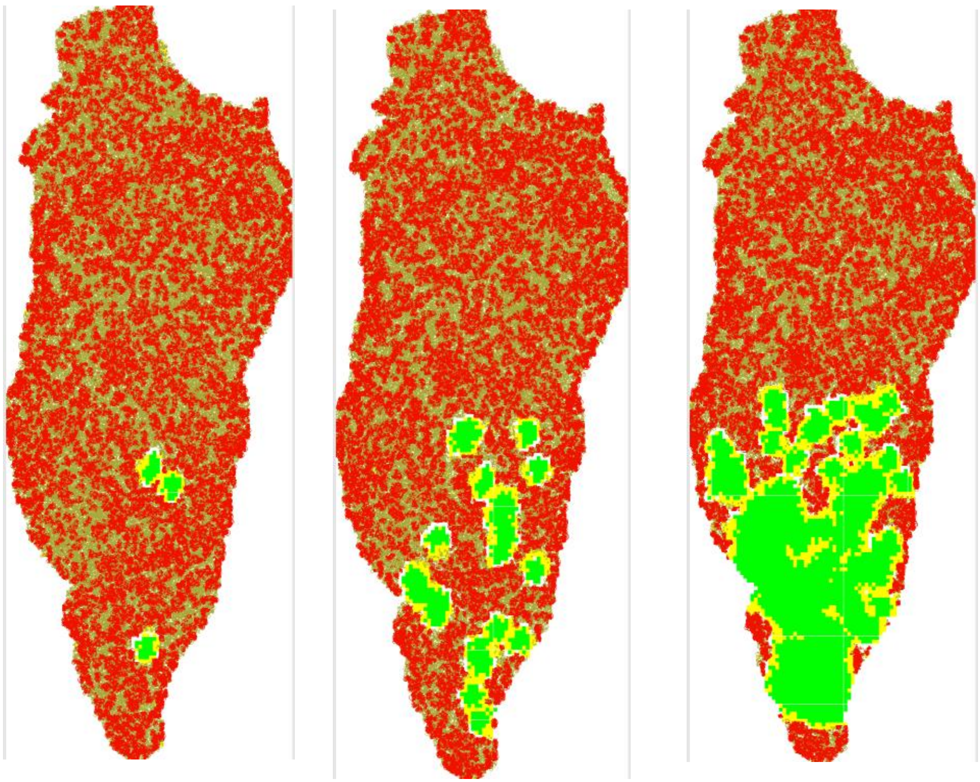
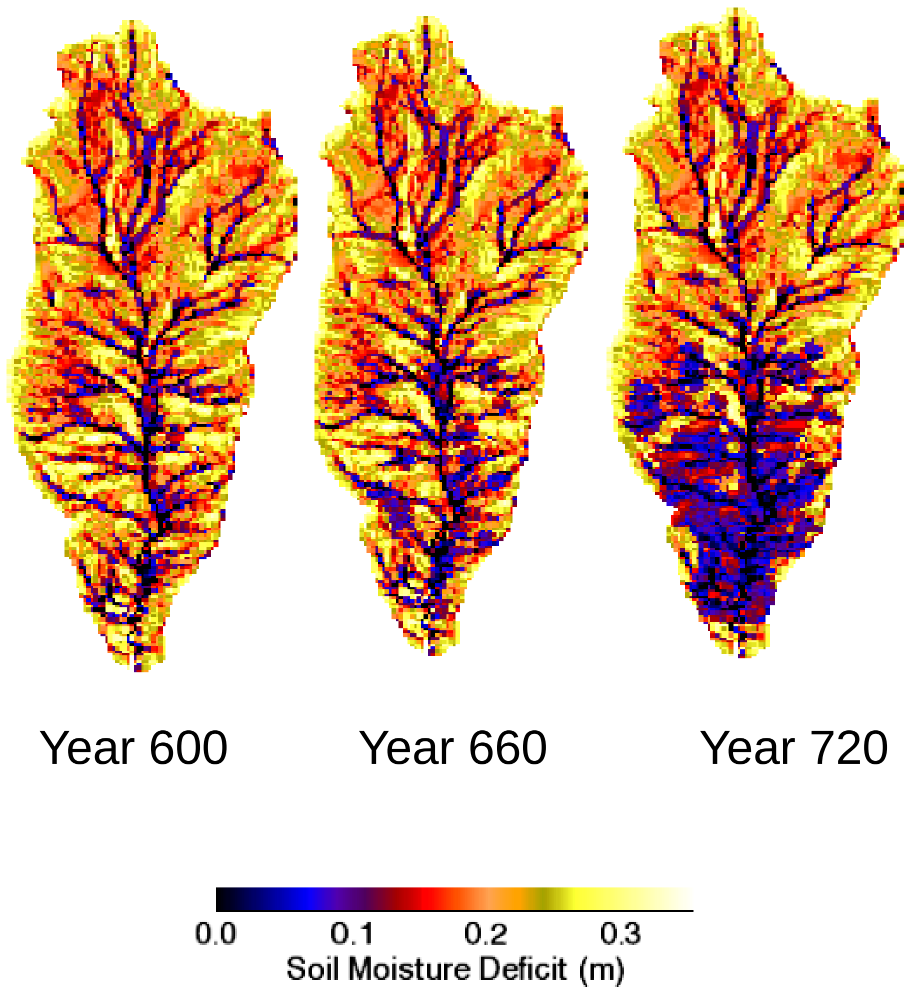
Forest with people



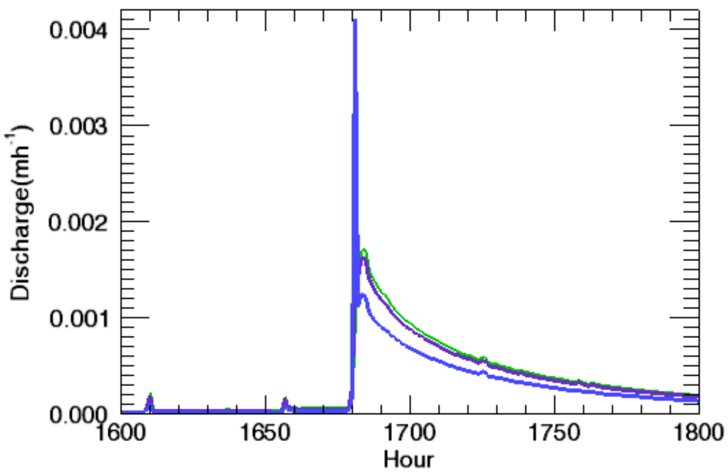
Year 600 Year 660 Year 720

- Fields Highlighted in green, degraded forest in yellow
- Farmers Exploit the lower part of the catchment first
- Trees are removed much faster then they can recover

Forest with people



- Forested areas are good at attenuating water
- Soil compaction in farmed areas increases soil saturation
- As farming increases, flash floods become more likely



Bithell and Brasington 2008

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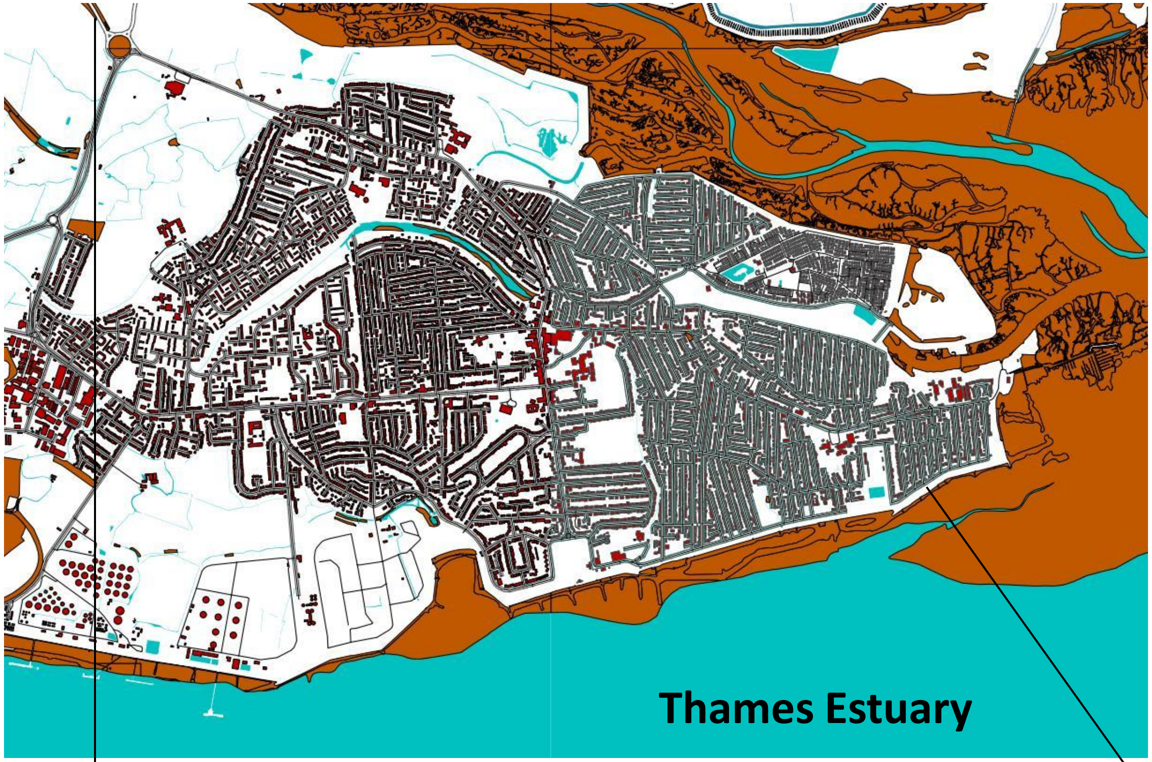


Canvey Island

In the great 1953 flood, sea defences failed.

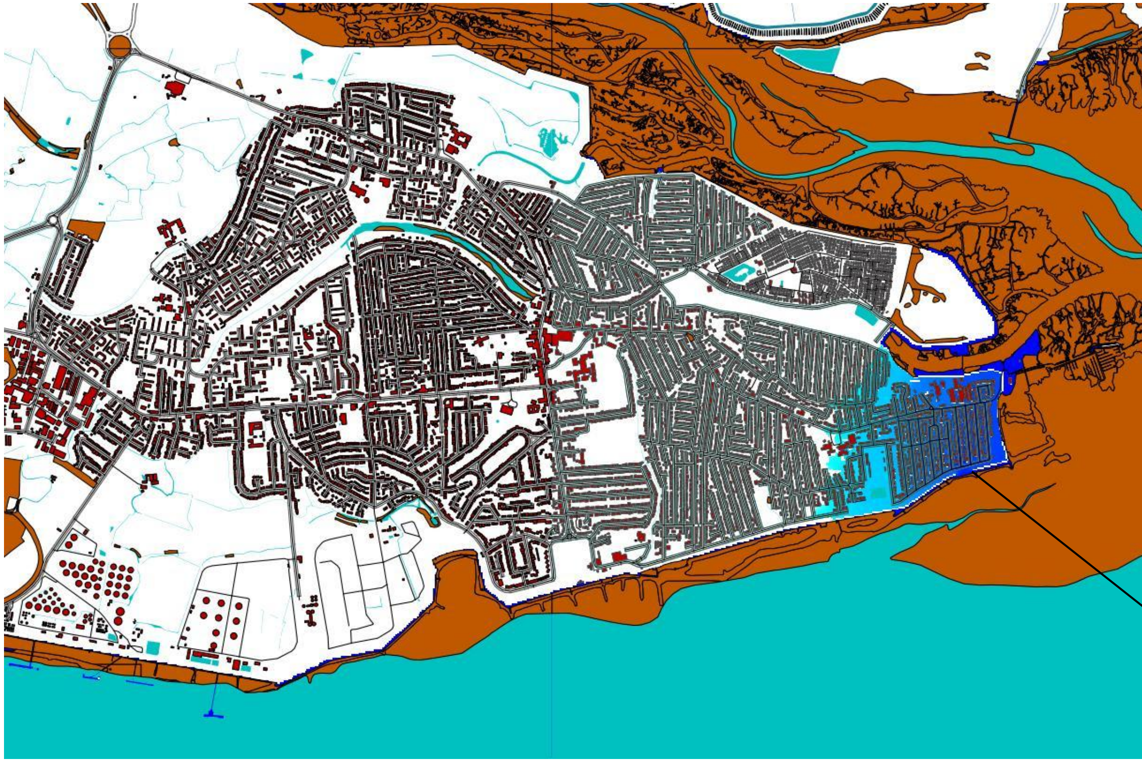
58 people died, 11000 evacuated.

Now 38000 people behind 4.66m high wall.

Only a single exit road

The illusion of safety provided by the sea wall may have encouraged settlement.

Map data: Crown Copyright/ Database right 2013 – An Ordnance Survey/EDINA supplied service. Flood modelling by James Brown
Brown, J.D, Spencer,T. And Moeller,(2007) Water Resources Research 43.



Canvey Island

In the great 1953 flood, sea defences failed

58 people died, 11000 evacuated

Simulated breach

As the climate changes, extreme events are predicted to become more likely.
Storm surges may again over- top or breach the flood barrier

Brown, J.D, Spencer,T. And Moeller,(2007) Water Resources Research 43.

The island can flood in a few hours

Evacuation may be necessary

Traffic simulations can help to understand the evacuation process

Map data: Crown Copyright/ Database right 2013 – An Ordnance Survey/EDINA supplied service. Flood modelling by James Brown
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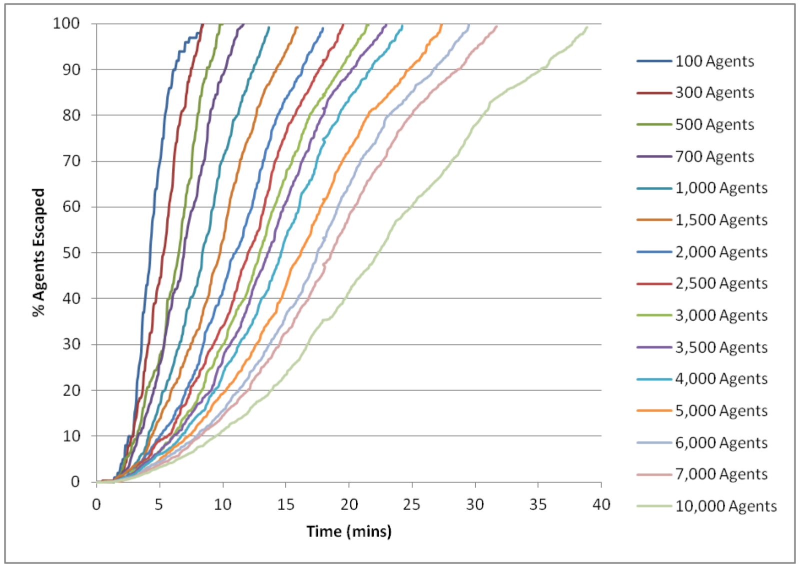
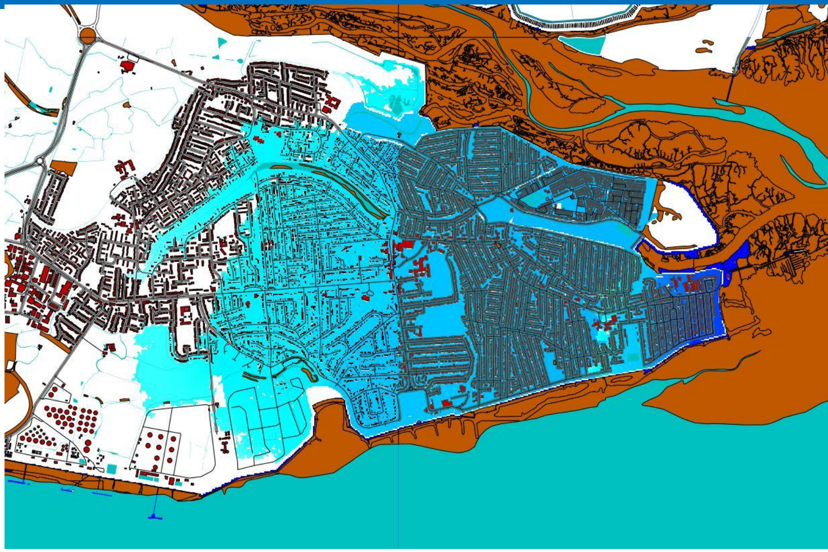
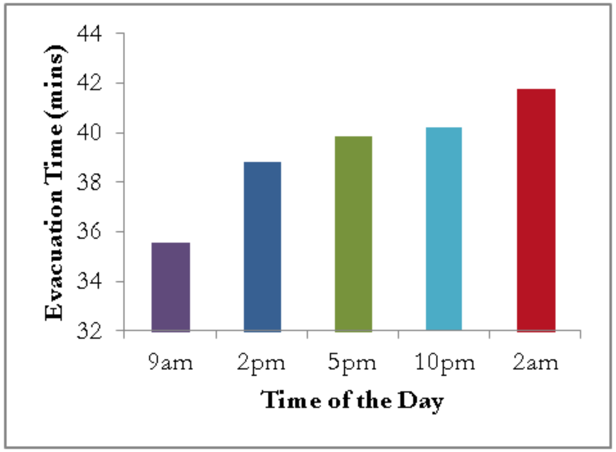
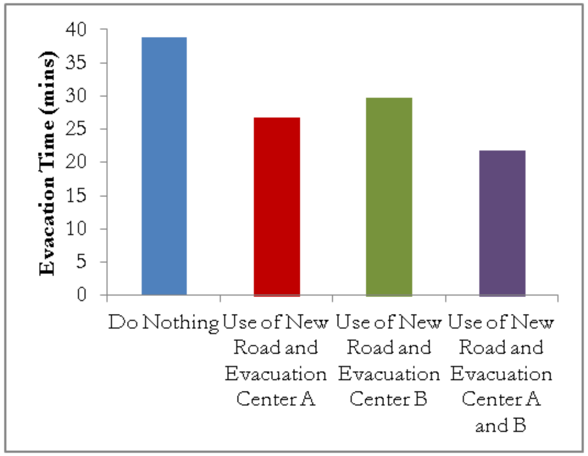
UNIVERSITY OF CAMBRIDGE
Department of Geography

Simulating Environmental Systems: The benefits of being discrete









Policy options can be tested to see what might improve evacuation times.

. Ozioma Uzoegwu 2013 Mphil. Thesis

Conclusions

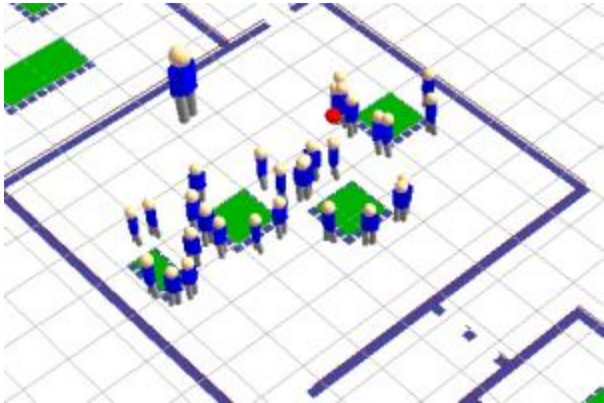
We can directly model processes in systems of discrete objects

- ❖Deal with situations where we lack analytic power
- ❖Emergent properties arise from collective interactions
- ❖Multiple coupled systems can be dealt with
- ❖Test policy options where not possible to experiment
- ❖Very visual – good for policy communication

Future

- ❖Larger scale, more complete, more complex systems
- ❖Social processes and networks in real-world situations
  - ❖Model the "Anthropocene" –
    - ❖current "Earth System Models" do not include people

➢Grand Unified Models!



Challenges

Model ownership
Democratization of knowledge
Policy assessment
Risk and environmental change

Model coupling
Cross-disciplinarity
Sharing and reproducing models/results
Joining complex dynamical models

Problem framing
What should be modelled?
Who for?

Vizualization
System size
Spatial extent
Complex interacting dynamical systems

Scaling
System size
Parameter space exploration
Processes at different scales
Micro-macro links

Validation
Reflexivity
Causality
Data integrity
Handling uncertainty

Complexity
What can be simulated?
How much complexity is "enough"?
How intelligent do agents need to be?