

Modélisation et analyse d'écosystèmes à l'aide de méthodes formelles discrète

Modelling and analysing ecosystems using discrete formal methods

Franck Pommereau¹ Cédric Gaucherel²

¹ IBISC, University of Évry / Paris-Saclay

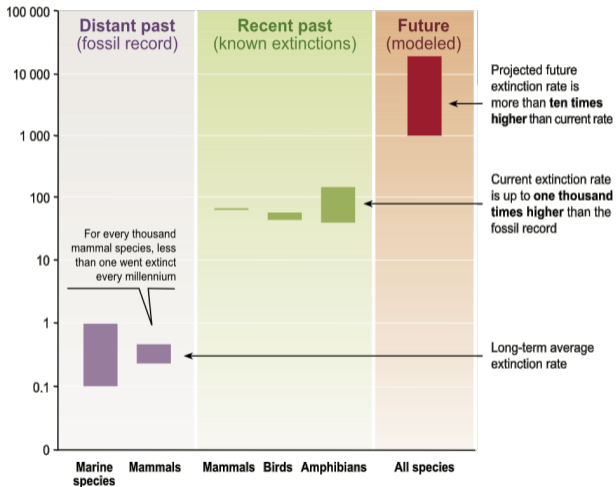
² AMAP—INRA, CIRAD, Montpellier

Un monde, une santé — June 16th 2023

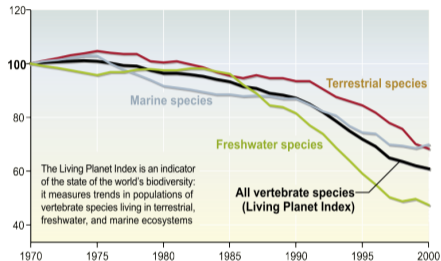


Context, goals

Extinctions per thousand species per millennium



Population Index = 100 in 1970



Ecosystems and human well-being. Biodiversity synthesis.
Millennium Ecosystem Assessment. 2005. (Fig.3.3 P.44 / Fig.3.7 P.57)

- ▶ **understanding** ecosystems ⇒ management
- ▶ using **formal methods** ⇒ explanations
- ▶ **exploring** behaviour ⇒ interactive

Approach: incremental exploration

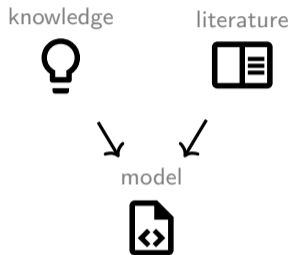
knowledge



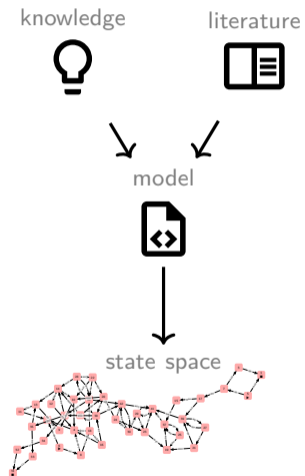
literature



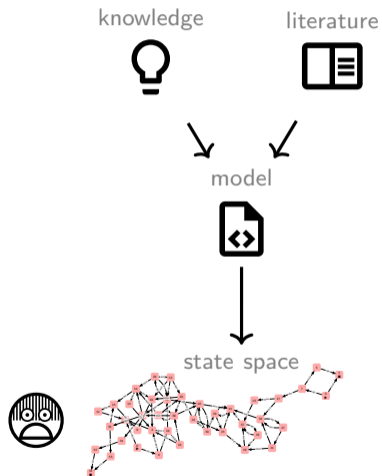
Approach: incremental exploration



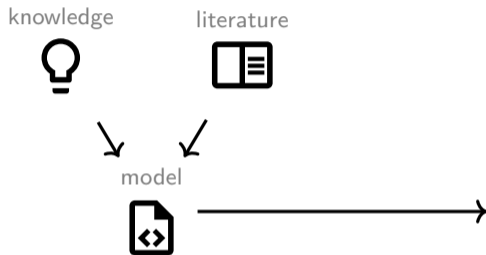
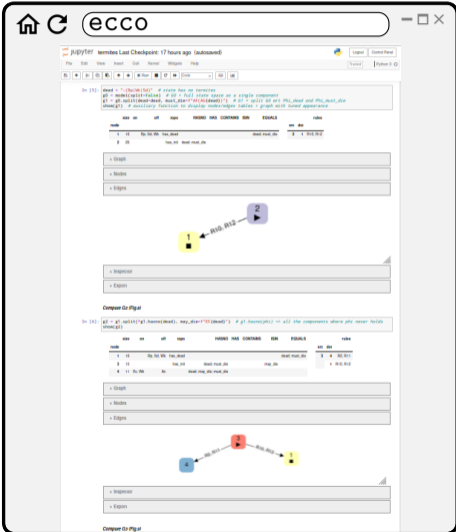
Approach: incremental exploration



Approach: incremental exploration



Approach: incremental exploration

The screenshot shows a JupyterLab interface with a notebook titled "ecco". The notebook contains two code cells. The first cell defines a network graph with nodes and edges, and displays a graph visualization with two nodes (1 and 2) and a directed edge from 2 to 1. The second cell computes a path and displays a graph visualization with three nodes (1, 2, 3) and edges connecting them in a path (1-2-3).

```

In [12]: from ecco import *
         graph = Graph()
         graph.add_node(1)
         graph.add_node(2)
         graph.add_edge(2, 1)
         graph

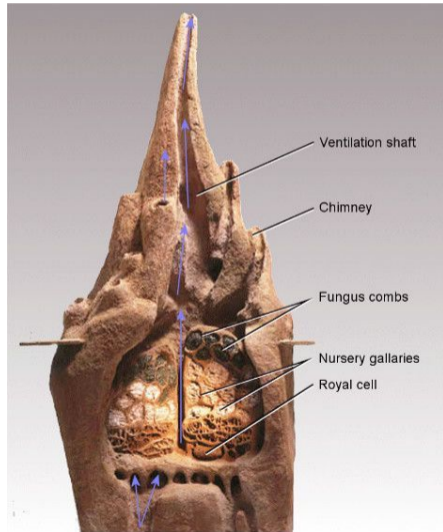
Out[12]:
graph LR
    2 --> 1
  
```

```

In [13]: path = shortest_path(graph, 1, 3)
         path

Out[13]:
[1, 2, 3]
  
```

Example: a termites colony



Example: a termites colony

inhabitants:

Rp+: reproductives

Wk-: workers

Sd-: soldiers

Te-: termitomyces (fungi)

structures:

Ec-: egg chambers

Fg-: fungal gardens

resources:

Wd-: wood

competitors:

Ac*: ant competitors

Example: a termites colony

inhabitants:

Rp+: reproductives

Wk-: workers

Sd-: soldiers

Te-: termitomyces (fungi)

structures:

Ec-: egg chambers

Fg-: fungal gardens

resources:

Wd-: wood

competitors:

Ac*: ant competitors

constraints:

Fg- >> Te- # C1

rules:

Rp+ >> Ec+ # R1

Rp+, Ec+ >> Wk+ # R2

Wk+ >> Wd+, Te+, Fg+, Ec+ # R3

Wk+, Wd+ >> Sd+, Rp+ # R4

Wk-, Te+ >> Wd- # R5

Wk+ >> Wd- # R6

Wd- >> Te- # R7

Wk- >> Fg-, Sd- # R8

Wk-, Rp- >> Ec- # R9

Ac+, Sd- >> Wk-, Rp- # R10

Sd+ >> Ac- # R11

Te- >> Rp-, Sd- # R12

Example: a termites colony

inhabitants:

Rp+: reproductives

Wk-: workers

Sd-: soldiers

Te-: termitomyces (fungi)

structures:

Ec-: egg chambers

Fg-: fungal gardens

resources:

Wd-: wood

competitors:

Ac*: ant competitors

constraints:

Fg- >> Te- # C1

rules:

Rp+ >> Ec+ # R1

Rp+, Ec+ >> Wk+ # R2

Ac+, Sd- >> Wk-, Rp- # R3

Wk+, Wd+ >> Sd+, Rp+ # R4

Wk-, Te+ >> Wd- # R5

Wk+ >> Wd- # R6

Wd- >> Te- # R7

Wk- >> Fg-, Sd- # R8

Wk-, Rp- >> Ec- # R9

Ac+, Sd- >> Wk-, Rp- # R10

Sd+ >> Ac- # R11

Te- >> Rp-, Sd- # R12

“in the absence of soldiers, ants may kill workers and reproductives”

Building explanations

1. Can the termite colony collapse?

split: $AF AG \varphi_{dead}$ where: $\varphi_{dead} \stackrel{df}{=} \neg(Rp \vee Wk \vee Sd)$

#0 (all) \Leftrightarrow #1 (dead) / #2 (alive)

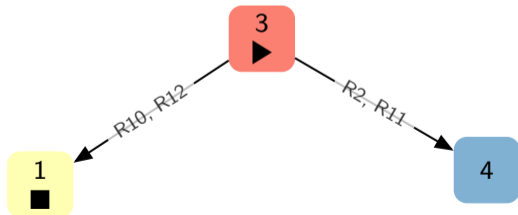


Building explanations

1. Can the termite colony collapse?
2. Can the termite colony avoid to collapse?

split: $EF \varphi_{dead}$

#2 \Rightarrow #3 (may die) / #4 (stayin' alive)

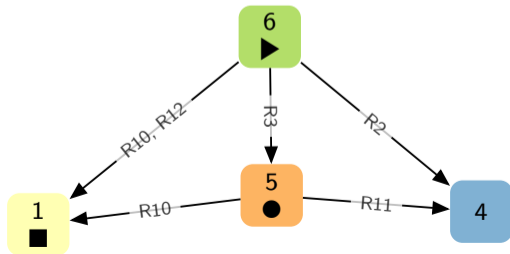
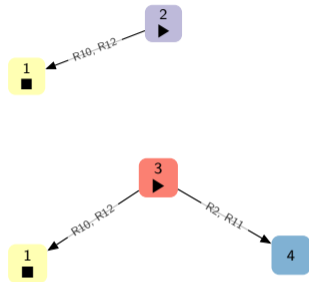


Building explanations

1. Can the termite colony collapse?
2. Can the termite colony avoid to collapse?
3. Can the branching between the two fates be delayed forever?

split: SCC hull

#3 \Rightarrow #5 (persistent) / #6 (transient)

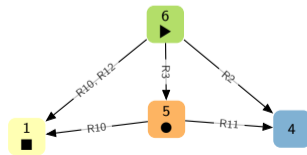
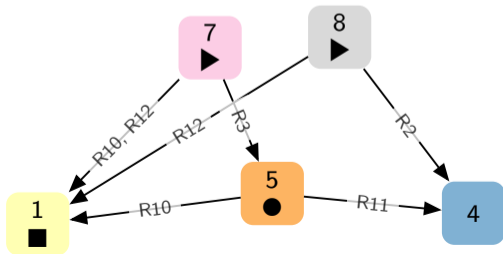


Building explanations

1. Can the termite colony collapse?
2. Can the termite colony avoid to collapse?
3. Can the branching between the two fates be delayed forever?
4. What is the role of ants?

split: Ac

#6 \Rightarrow #7 (with ants) / #8 (no ants)



Use cases

- ▶ bush encroachment in Borona zone (south Ethiopia)
- ▶ biodiversity in Camargue (south France)
- ▶ risk assessment and recovery after a volcanic eruption (north Tanzania)
- ▶ ...

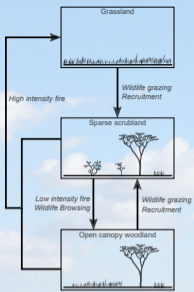


Climate Change, Agriculture and Food Security. *Ethiopian landscape.*

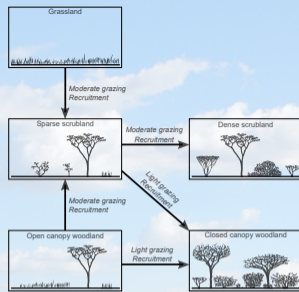
<https://www.flickr.com/photos/cgiarclimate/8547603361/>



termite colony




(a). Before livestock introduction



(b). With livestock and fire ban

- ▶ modelling with RR
- ▶ splits with CTL
- ▶ management policy

 PLOS Comp. Bio. 2022





Cédric Gaucherel. *Pink flamingos in Camargue.*

personal collection

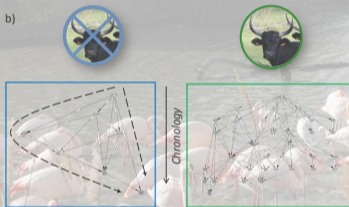
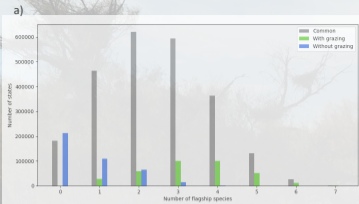


FIGURE 3

- ▶ modelling with RR
- ▶ trajectories analysis
- ▶ crucial role of grazing





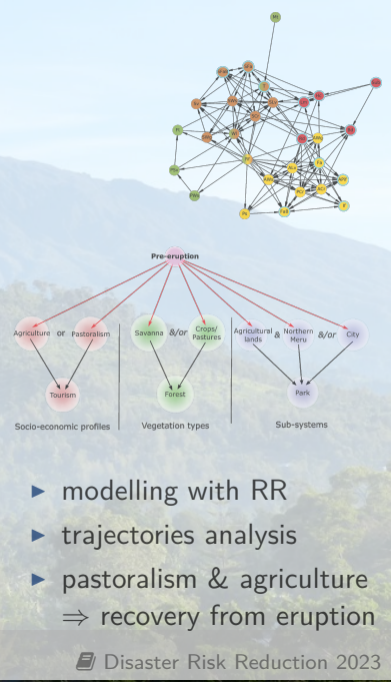
Ronam Boed. *Mount Meru in the morning.*

<https://www.flickr.com/photos/romanboed/8367494775>



Ronam Boed. *Mount Meru in the morning.*

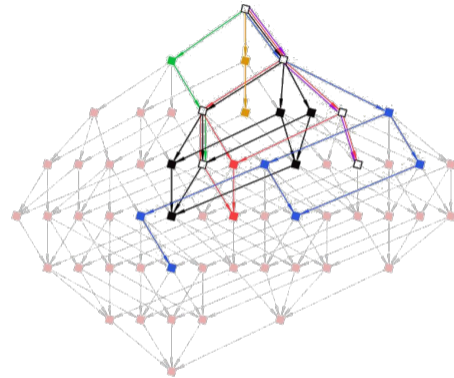
<https://www.flickr.com/photos/romanboed/8367494775>



- ▶ modelling with RR
- ▶ trajectories analysis
- ▶ pastoralism & agriculture
⇒ recovery from eruption

Future works and open questions

- ▶ more case studies (drive the development)
 - ▶ *Does the spillover exist?* (spoiler: not really)
 - ▶ meta-analysis of the concept
 - ▶ model of the epidemic emergence mechanisms
 - ⇒ spillover notion is inconsistent & incomplete
 - ▶ ...
- ▶ multivaluated variables
 - ⌚ *extra combinatorial explosion*
 - ⌚ *keep language/interface simple*
- ▶ Petri nets and unfolding-based analysis
 - ❓ *orthogonal approaches*
 - (with Stefan Haar & Giann-Karlo Aguirre-Samboni)
- ▶ model synthesis using Boolean networks
 - ❓ *concurrent approaches*
 - (with Loïc Paulevé)



📖 Gavotte & al. Environmental Research 2023