Wildlands facing global warming : the landscape connectivity dilemma

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Bingo #1

Motivation

- Biodiversity is vulnerable to climate change and extreme weather conditions (*IPBES-IPCC, 2021*) through various mechanisms :
    - Reproduction success is impaired and survival reduced (*Gauziere et al, 2016*)
    - Mismatch between habitat availability and bioclimatic niches (*Devictor et al, 2008)* and range shifts (*IPCC, 2002)*: damsels, dragonflies, grasshoppers etc

- Need to maintain *landscape structural connectivity (Taylor et al, 1993)*, in the form of habitat corridors, landscape links, to support ecosystems and avoid local extinctions.

Motivation

- Climate change increases the likelihood, severity and magnitude of wildfires (*Abatzoglou & Williams, 2016*) :
  - Role of environmental factors: droughts, reduced fuel moisture
  - Notion of fire deficit, in Northern California (*California Carbon Plan*, *2016*)

- Wildfires come at high cost:
  - Ecological : severe wildfire decrease forest resilience and threaten ecosystem shifts
  - Human :
    - Destroyed assets and supply chain disruption (*Wang et al*, *2021*)
    - Smoke exposure : health (*Heft Neal et al*, *2023*), outdoors recreation (*Gellman et al*, *2022*)

→ Fuel treatments reduce fire spread and limit both extent and severity of wildfire (*North et al*, *2012*)

Research question

- As fuel treatments reduce wildfire impacts, they also reduce wildlife habitat connectivity : this is the *landscape connectivity dilemma*
- The trade-off depends on the *heterogeneous & relative* importance of a land patch in wildfire spread **and** in landscape structural connectivity
- Given limited resources and an initial landscape configuration

➔ **How should a land planner allocate treatments in landscapes to minimize wildfire damages while maintaining habitat connectivity?**

Literature and approach

- Economic studies for the optimal location and timing of treatments in a forest providing multiple ecosystem services under threat of catastrophic fire (*Warziniack et al., 2019*)

- Specific case studies (*Rachmawati et al., 2015, 2016*) with large gridded landscapes (225 cells) to optimally assign treatments, without outlining structural mechanisms

- We simulate :
    - the evolution through time
    - of **all** the initial conditions of theoretical landscapes of varying size
    - subject to treatments
    - to uncover guiding principles in the landscape connectivity dilemma

Outline

- Theoretical landscape model & computational experiment
  - Simplified ecological processes
  - Leveraging graph theory to frame the landscape connectivity dilemma
- Results :
  - The efficiency frontier
  - Extensive and intensive margins in spatial treatment allocations
- Discussion & perspectives

Modeling framework

- Landscapes are grids of size *n*
- Each cell *i* is characterized by a vegetation age, with dynamics:

$$A_i(t+1) = \max\big((A_i(t)+1)(1-x_i(t)), 2\big) \text{ for } t \in \{0,1,\ldots,T\}$$

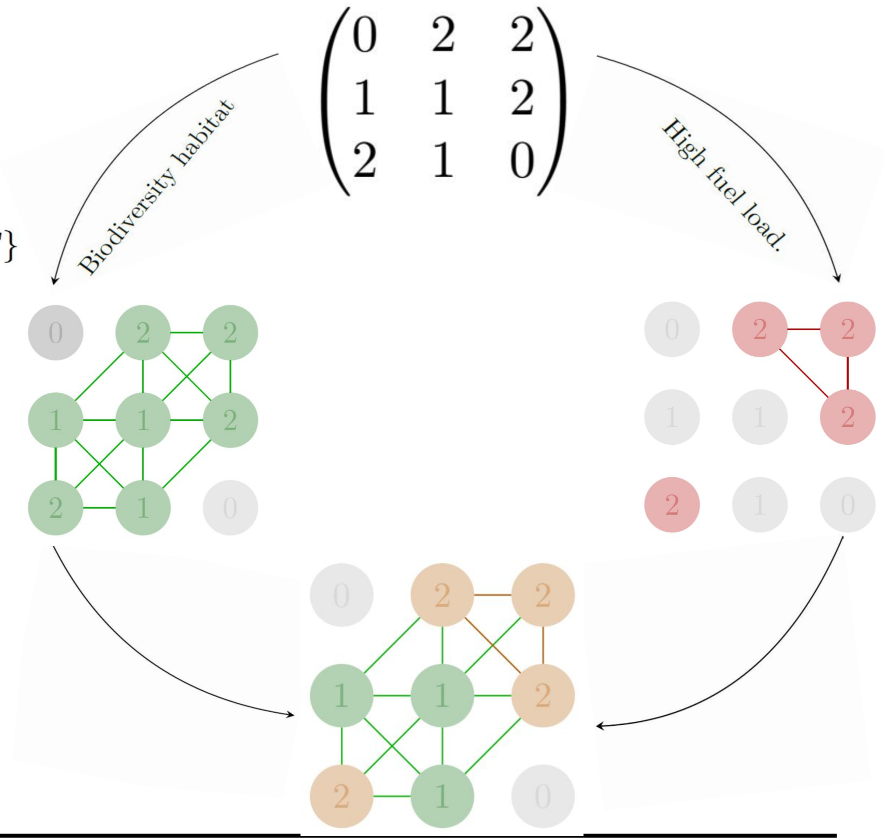
Where *x* is the treatment status, in {0,1}.

- A cell is *mature* to host biodiversity if $A_i(t) \geq 1$
- A cell is *high fuel load* if $A_i(t)=2$

Cells are *connected* if :

- They share the same status
- are within an 8-cell neighborhood

Connected cells form a *graph* G_j, with vertices V_j and edges E_j : in our set-up, $G_F \subset G_B$



Critical Node Detection

- A *graph* is a mathematical object, characterized by nodes and edges, amenable to optimization
- “optimization problem that consists in finding the set of nodes, the deletion of which maximally degrades network connectivity according to some predefined connectivity metrics” (Lalou et al, 2015)
- Taking :
    - *High(A(t))* to be the vector of *high fuel cells* in the landscape (i.e, $H(A(t)) \in \{0,1\}^{n^2}$)
    - *Mature(A(t))* to be the vector of *mature cells* in the landscape
- We define *high fuel load connectivity (H)* and *biodiversity habitat connectivity (M)* as :

$$H(A(t)) = card(V_F) + 2 \times card(E_F) \quad M(A(t)) = card(V_B) + 2 \times card(E_B)$$

The land planner’s problem

- The aim of the land planner is to :
    - Minimize the landscape fuel connectivity (Critical Nodes Detection)
    - Over a time horizon of 20 periods
- Such that :
    - Vegetation grows according to our dynamics
    - Biodiversity habitat connectivity is larger or equal than *Biod*
    - Treatment costs are homogeneous (*=1* in every cell) and the sum of treatment costs across the landscape at time *t* does not outweigh the *Budget*
    - For a given initial landscape *A(0)*

We run those simulations for **all** the possible initial conditions for landscape size $n \in \{3, 4\}$ and *Budget* $\in \{1, 2, 3, 4\}$, to uncover **general and systematic results**.

Optimal long term landscapes

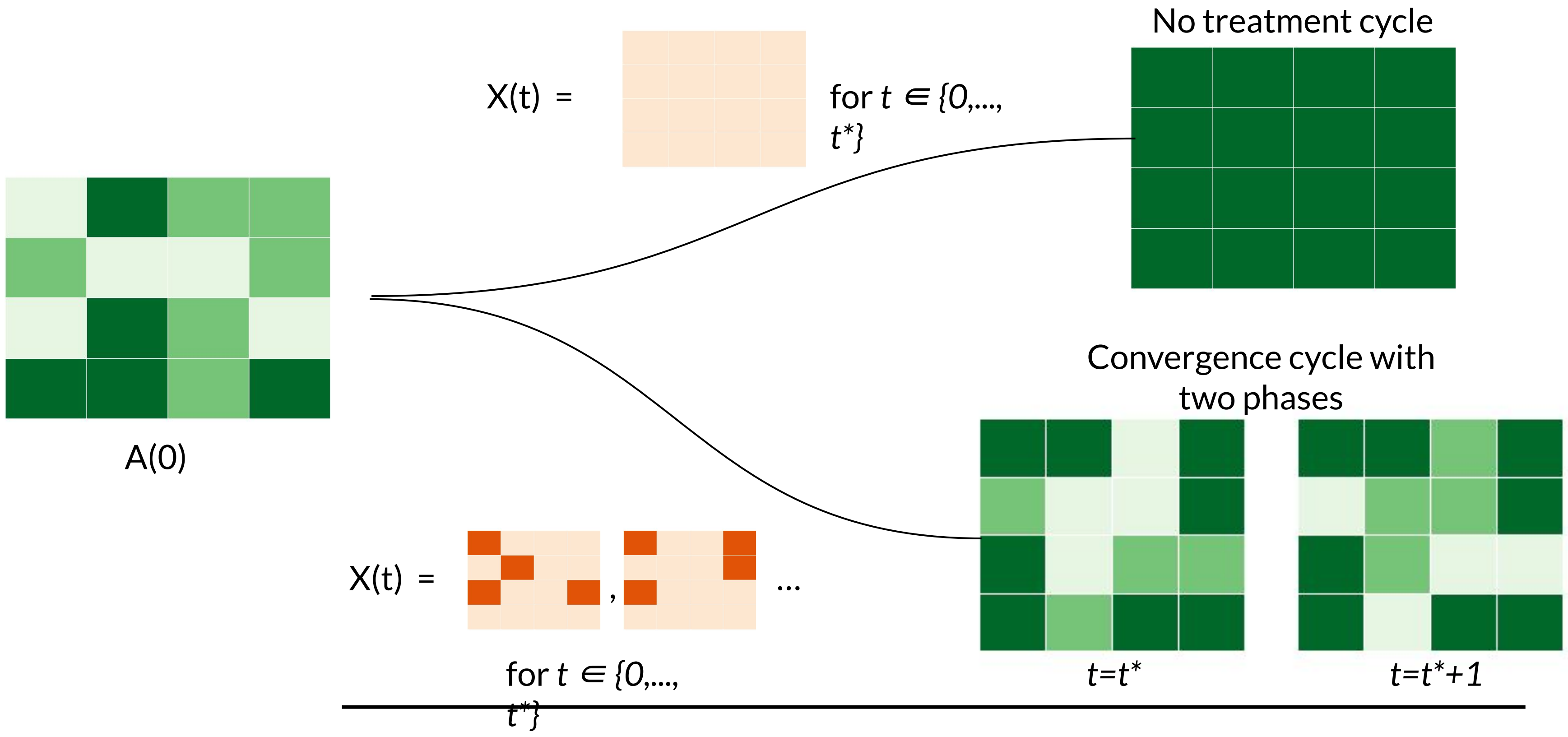
Landscape size	3x3	4x4	5x5
Number of initial conditions	19, 683	43, 046, 721	847, 288, 609, 443
Number of unique landscapes	2, 861	5, 398, 082	?
Number of steady state cycles	33 (0.2%)	61 (1.4×10^{-4}%)	?

for *n>4:*

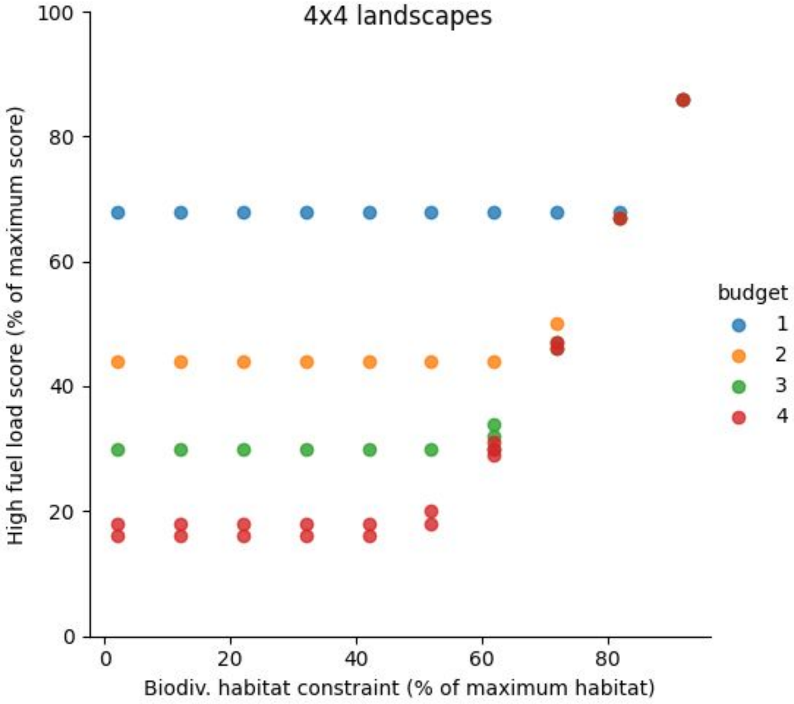
Conjecture 1 : if the distance between the maturity and high fuel load thresholds (*fire return interval*) is finite, landscapes reach steady state cycles.

→ Focus on steady state cycles

Methods : comparing steady states with the counterfactual



Results : the efficiency frontier



Results : the efficiency frontier

Results are established for landscapes of size $n \in \{3,4\}$.

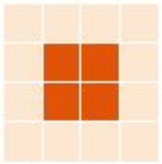
For landscapes of size $n \geq 5$:

Conjecture 2 : the land planner can achieve risk reductions and moderately important ecological requirements with a positive budget

Conjecture 3 : increasing the available budget reduces high fuel load connectivity at a decreasing rate. This rate tends to 0 as budget and/or biodiversity habitat requirements increase

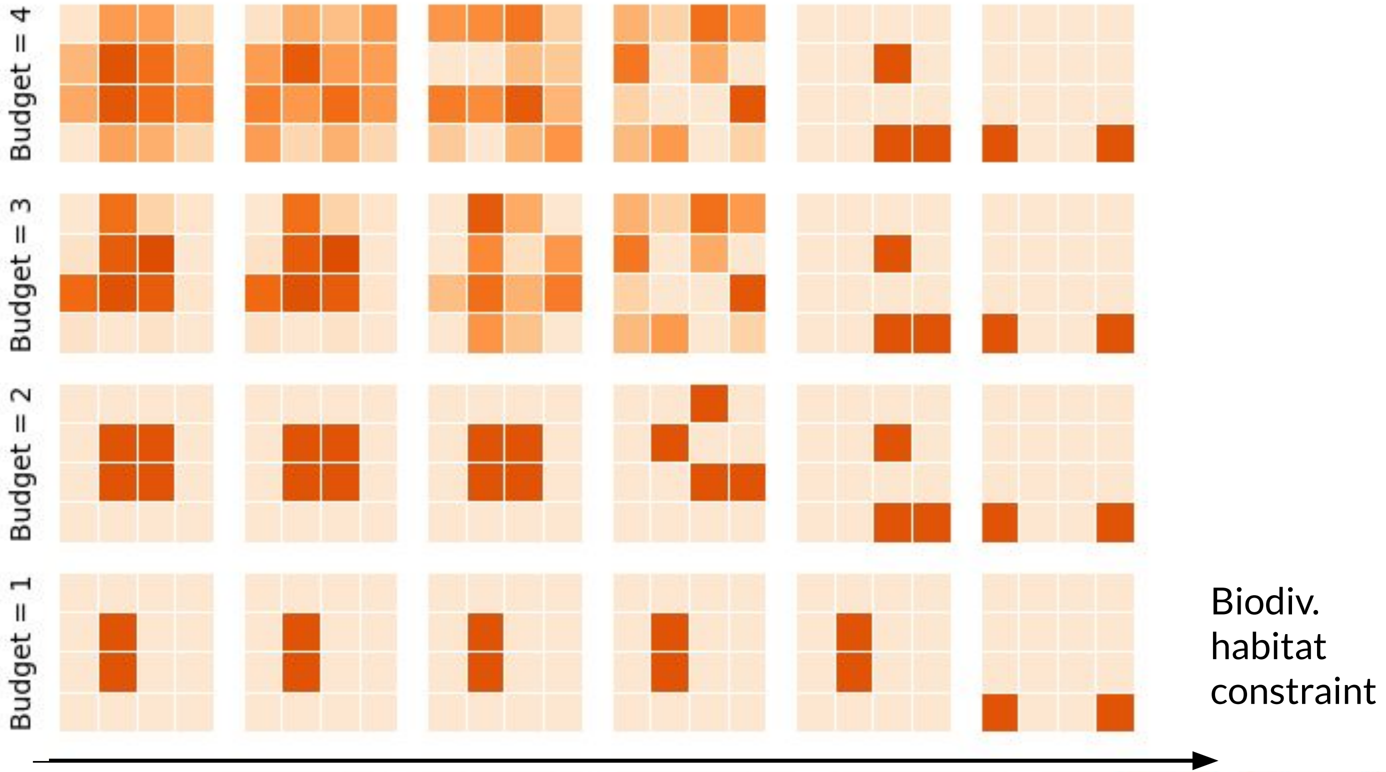
Results : optimal treatments

Budget = 2



Biodiv.
habitat
constraint

Results : optimal treatments



Results : optimal treatments

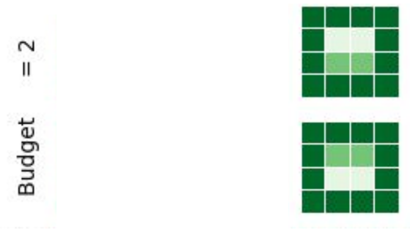
For $n > 4$, we state the following conjecture:

Conjecture 4 : treatments are allocated depending on how much they matter for habitat and high fuel load cells connectivity.

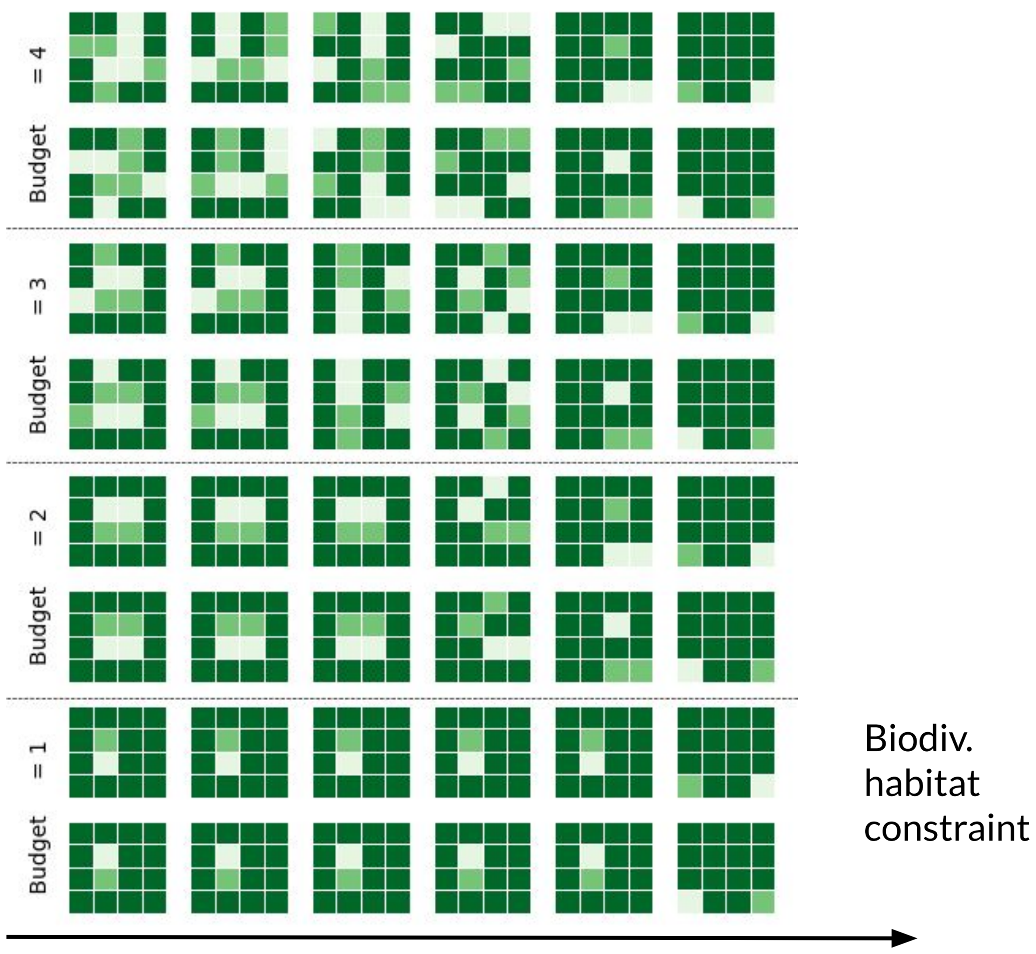
Conditional on potential location, the allocation depends on the constraints :

	Biodiversity habitat	Flexible	Stringent
Budget	*Number of treatments*	Decreasing	
Stringent	Increasing	Most central nodes	Edges & corners
Flexible		Most central nodes & edges & corners	Less central nodes, edges and corners

Results : optimal cycles



Results : optimal cycles



Results : optimal cycles

For *n>4*,

Conjecture 5: Resulting from optimal treatments, the convergence landscape can be characterized by the area of risky cells, the number of components and their diversity.

Conditional on treatment allocation, the landscape properties evolve according to the constraints:

Biodiversity habitat **Budget**	*Flexible*	*Stringent*
Flexible	Fragmented lands Low surface Diverse landscapes	Moderately fragmented to compact land Moderate to high fuel surface Relatively homogeneous landscape
Stringent	Moderate fragmentation Moderate surface Moderately diverse	Compact land High fuel surface Homogeneous landscape

Discussion

Focusing on steady states, we find general principles to guide land planners decision making

- Use a common scale for two different ecological phenomenons
- We identify the trade-offs between high fuel loads, biodiversity habitat and budget constraints
- Map the flexibility or stringency of biodiversity habitat and budget constraints to spatial arrangements

→ Need to investigate further transitional dynamics
→ Small scale results that need to be generalized to larger scales

Exponential complexity in landscape size warrants different approaches:

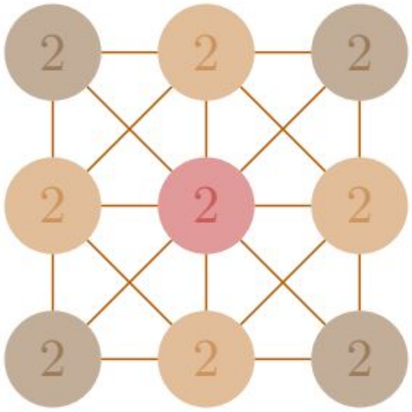
- Different *proof concepts* : from absolute to probabilistic proofs
- Different *algorithms* for more efficient computation : swarm particle optimization, heuristics based on treatment allocation mechanisms emphasized here

Discussion

- Improve on *existing* processes :
    - Account for multiple species in vegetation model, investigate the heterogeneity of *fire return intervals*
    - Simulate effects of global warming on *fire return interval*
- Add on *new* processes :
    - Economic data :
        - Treatment costs heterogeneity for prioritization (*Fried et al*, *2016*)
        - Include potential damages as an additional layer
    - Biodiversity : include multiple species and *habitat quality layer* for metapopulation models
    - Wildfires : Environmental and terrain data layer to refine spread mechanism for decision making

→ Show the need for further interdisciplinary & collaborative research!

Appendix I



$$K = \begin{pmatrix} 1 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 \end{pmatrix}$$

$$= (4, 6, 4, 6, 9, 6, 4, 6, 4)$$

In a landscape where *all cells* have reached the maximum age, the degree of vertices (i.e, their number of edges) is distributed as follows:

- 9 for red vertices
- 6 for light orange vertices
- 4 for dark orange nodes

In any graph with adjacency matrix *K*, the *maximum potential degree of a vertex k* is the sum of line or row *k*