Flashpoints Signal Hidden Inherent Instabilities in Land Use Planning

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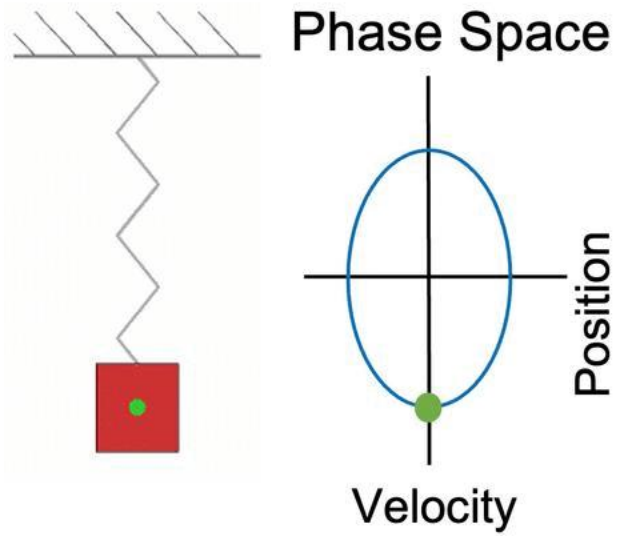
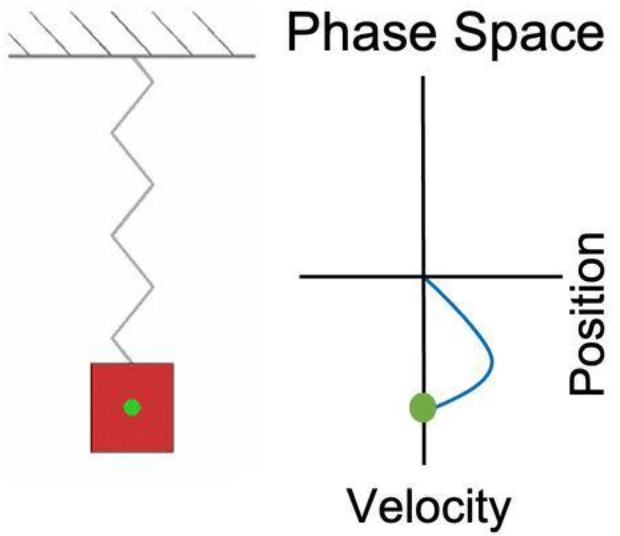
Physics of Design Problems → Hyperoptimization

- Optimization thinks about the optimal solution.
- Physics thinks about the whole solution space!

PHYSICS



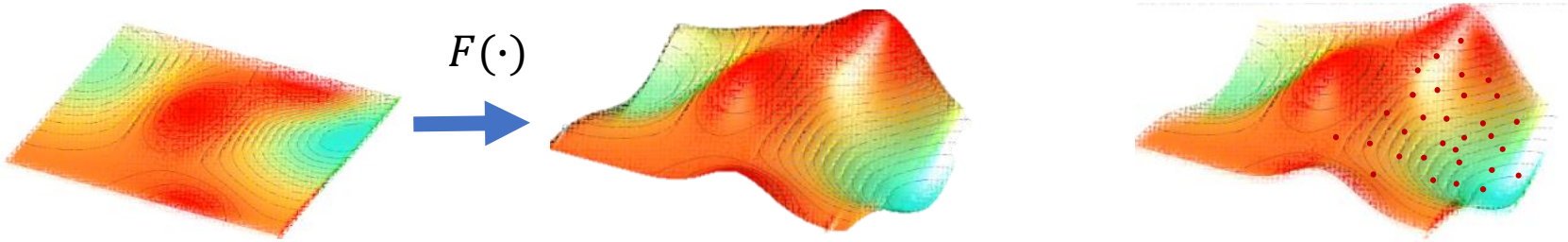
OPTIMIZATION



How? Landscape exploration

Solution Space | Landscape | Exploration

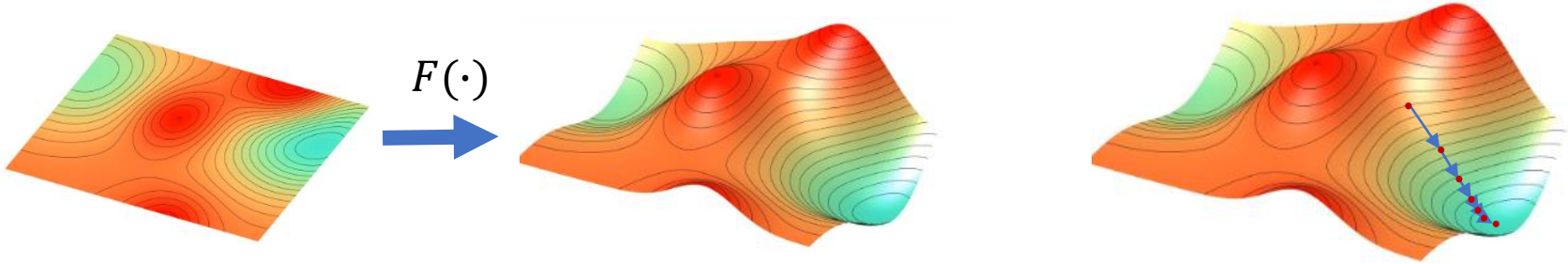
Discrete Domain



Method:
Markov Chain Monte Carlo

Problem of interest:
Multi-objective Land Allocation

Continuous Domain



Method:
Molecular Dynamics

Problem of interest:
Topology Optimization

"Hyperoptimization insight for computational morphogenesis"

CAP 2023

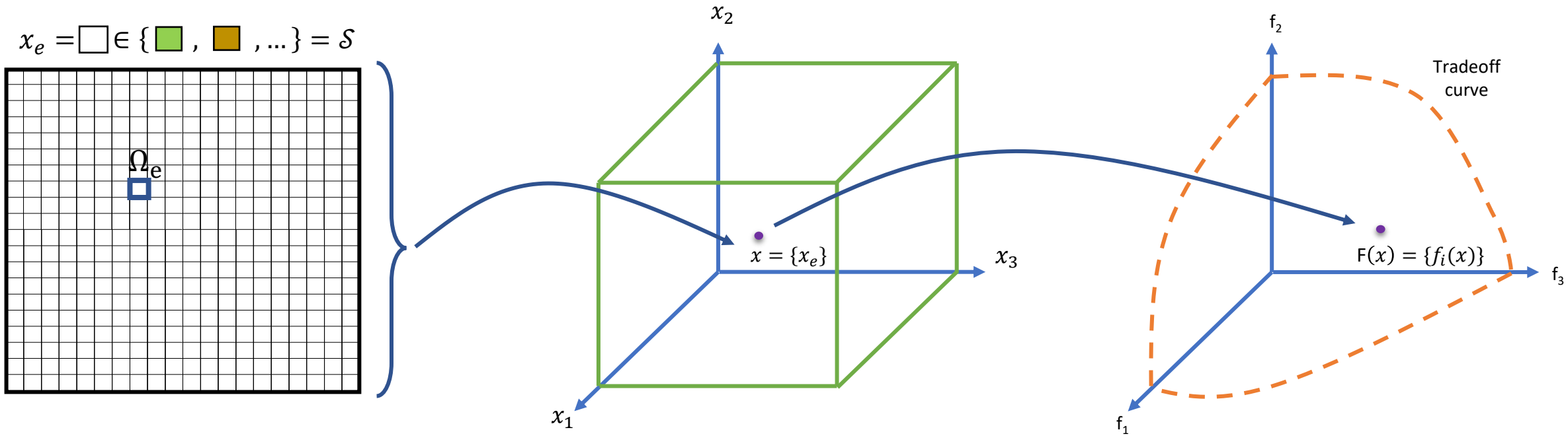
Antoine Jay et al., **J. Chem. Theory Comput.**, 2020

Allocation Design Problems

$$\min_{\{x_e\}\in\mathcal{D}} \quad F(\{x_e\}) = \sum_{i=1}^{I_f}\sum_{e=1}^{N_e}\int_{\Omega_e} w_i f_i(x_e)\,d\Omega_e$$

$$s.t. \quad \sum_{e=1}^{N_e}\int_{\Omega_e} G_{j_e}(x_e)\,d\Omega_e - c_{j_e} = 0, \ \text{for } j_e = \{1,2,\dots,I_e\}$$

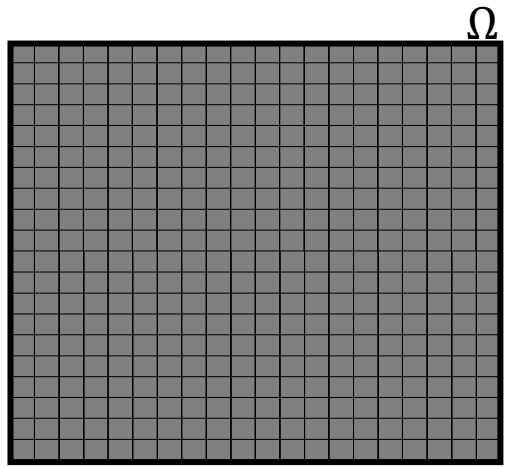
$$\sum_{e=1}^{N_e}\int_{\Omega_e} G_{j_{ine}}(x_e)\,d\Omega_e - c_{j_{ine}} \le 0, \ \text{for } j_{ine} = \{1,2,\dots,I_{ine}\}$$



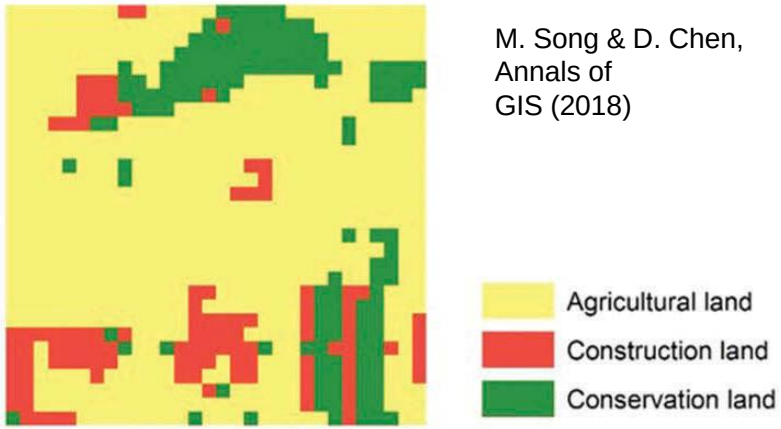
Design Domain (Ω) Solution Space ($\mathcal{D}$) Design Space

Multi-Objective Land Allocation (MOLA)

- What is the best way to allocate land uses in a prescribed domain in order to find the best performance?



Optimization →



M. Song & D. Chen, Annals of GIS (2018)

$$\min_{\{x_e\}\in\{0,1,2\}^N} \quad F = P_c O_c + P_s O_s$$

MOLA

Suitability $O_s = -\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{M} W_k S_{ijk} x_{ijk}$

Compactness $O_c = -\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{M} b_{ijk} x_{ijk}$

$b_{ijk} = (\sum_{\alpha,\beta=\{-1,0,1\}} x_{i+\alpha,j+\beta,k}) - x_{i,j}$

Change notation →

$O_s = -\sum_i S(i)\delta(s_i, i)$ External field

$O_c = -\sum_{\langle ij\rangle} \delta(s_i, s_j)$ Interaction

Potts Model

M. Song & D. Chen, Annals of GIS (2018)

Problem:

There are no unique agreements on priorities

- Preferences, at the human level, play a significant role in the “optimized” solution.

⇨ <u>Optimization is not the best solution!</u>

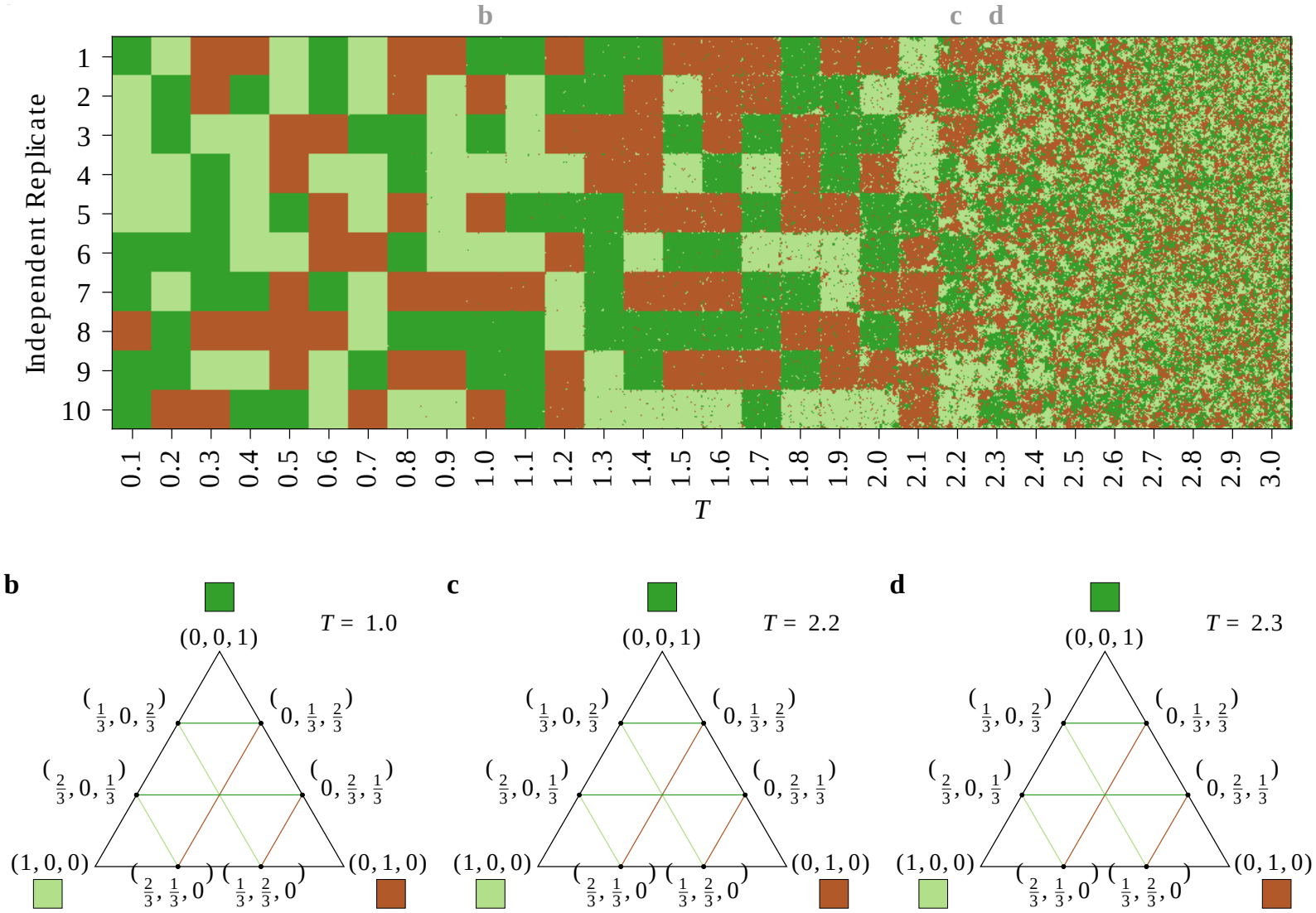
Question:

How do land-use patterns depend on MOLA weights?

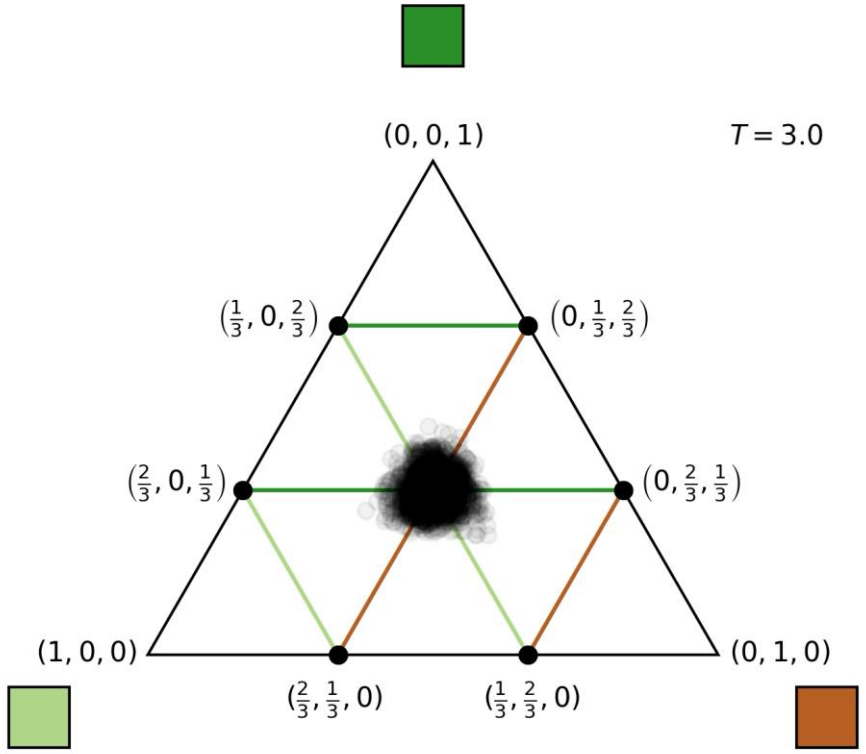
Method

- Metropolis Algorithm -> Critical slowing down -> Wolff Algorithm [Wolff Phys Rev Lett 62 361 (1989)]
- Wolff Algorithm -> No external field -> Ghost-Site Cluster MC [Kent-Dobias & Sethna Phys Rev E 98 063306 (2018)]
- Implementation
  - MATLAB for Proof of Concept
  - C++ for the main core
  - Python for the wrapper and Data management
  - Typical Run time <10 s on 2019 CPU core
  - For Annealing: more than 2300 trials
  - For Flashpoints: 82,500 trials

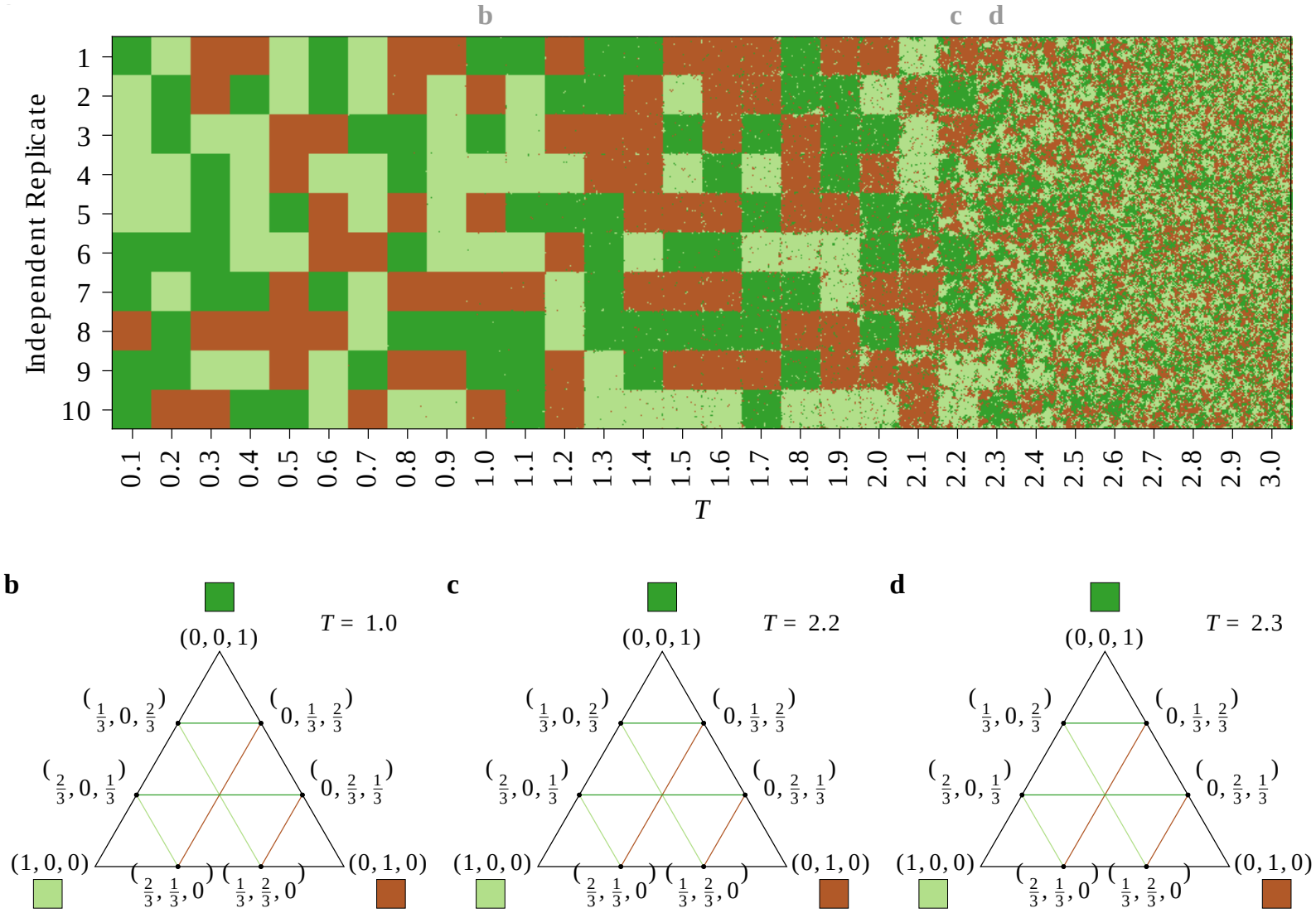
Result: Symmetry-Breaking



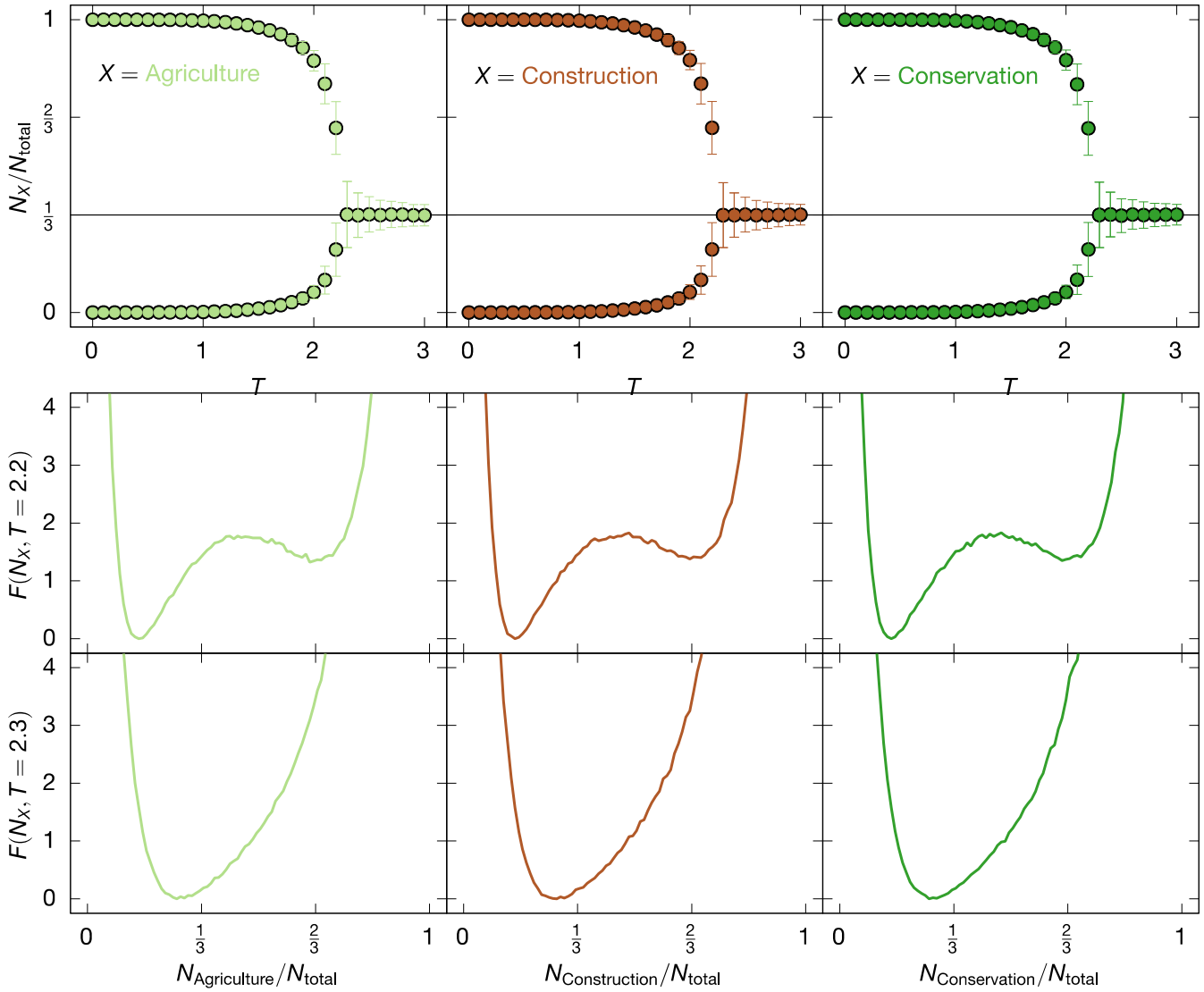
Result: Symmetry-Breaking (cont.)



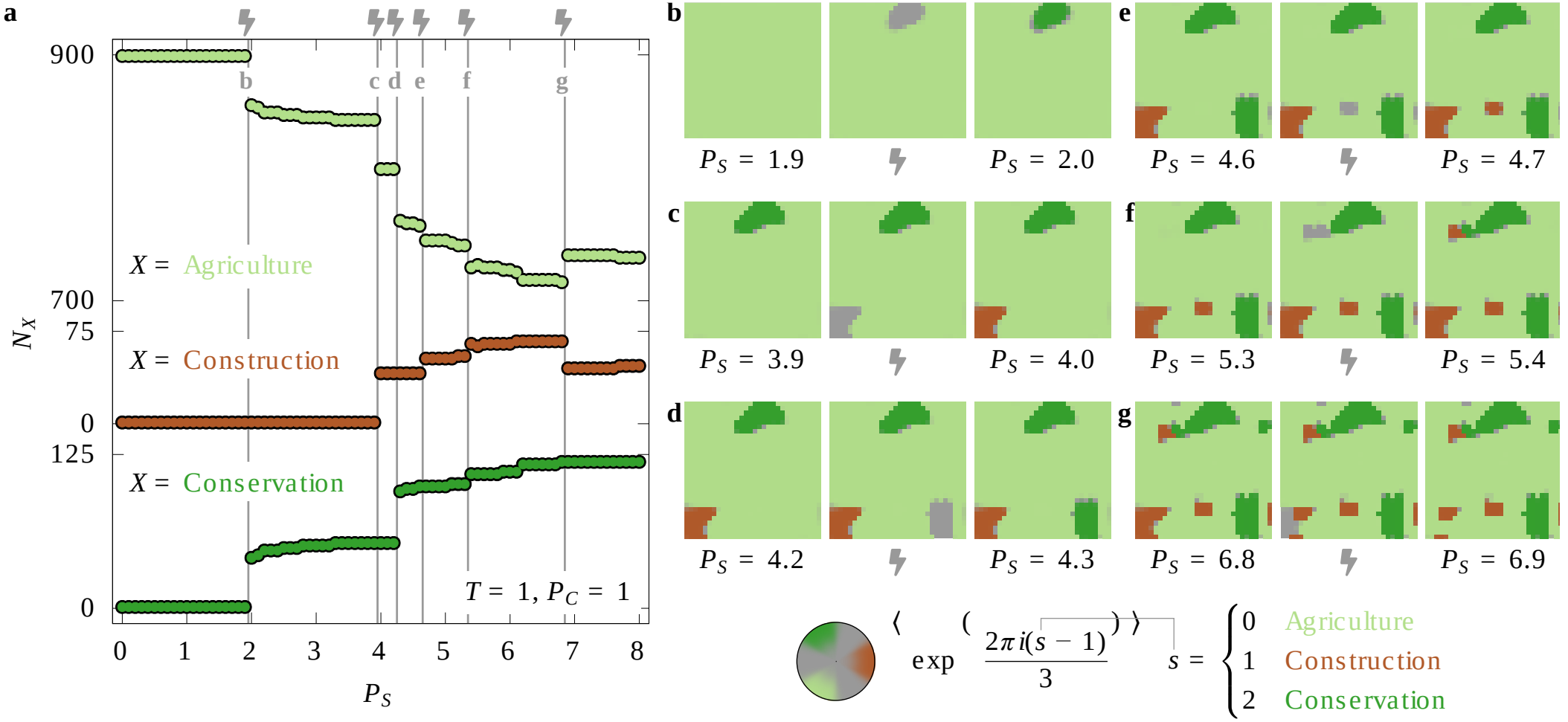
Result: Symmetry-Breaking



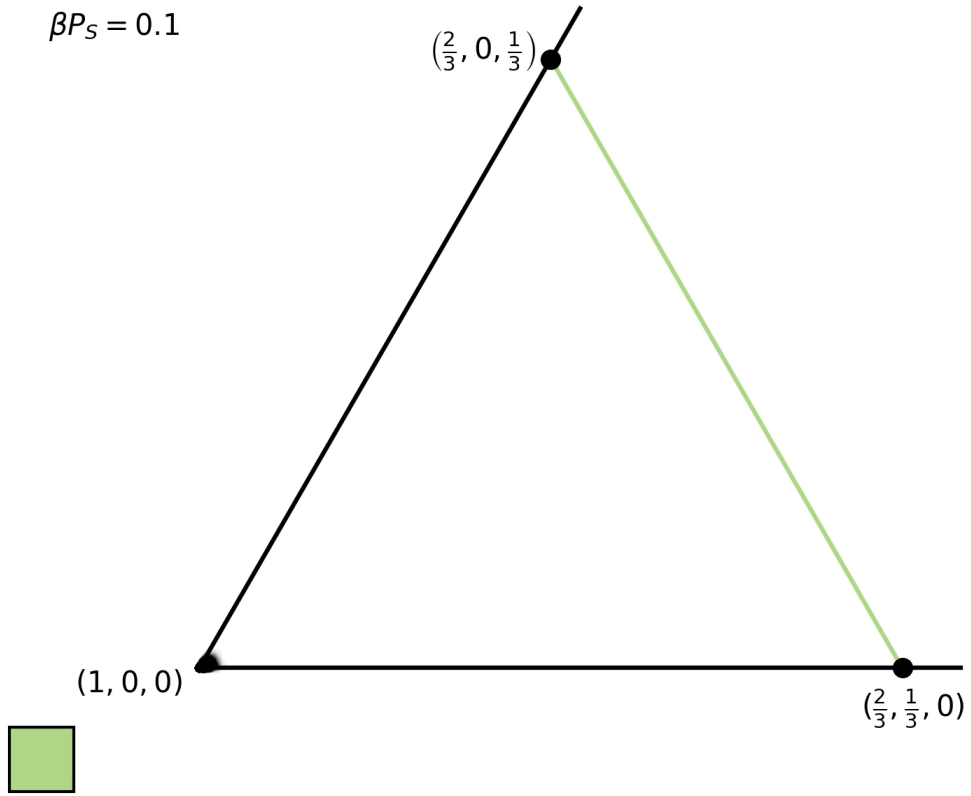
Validation: Landau Free Energy



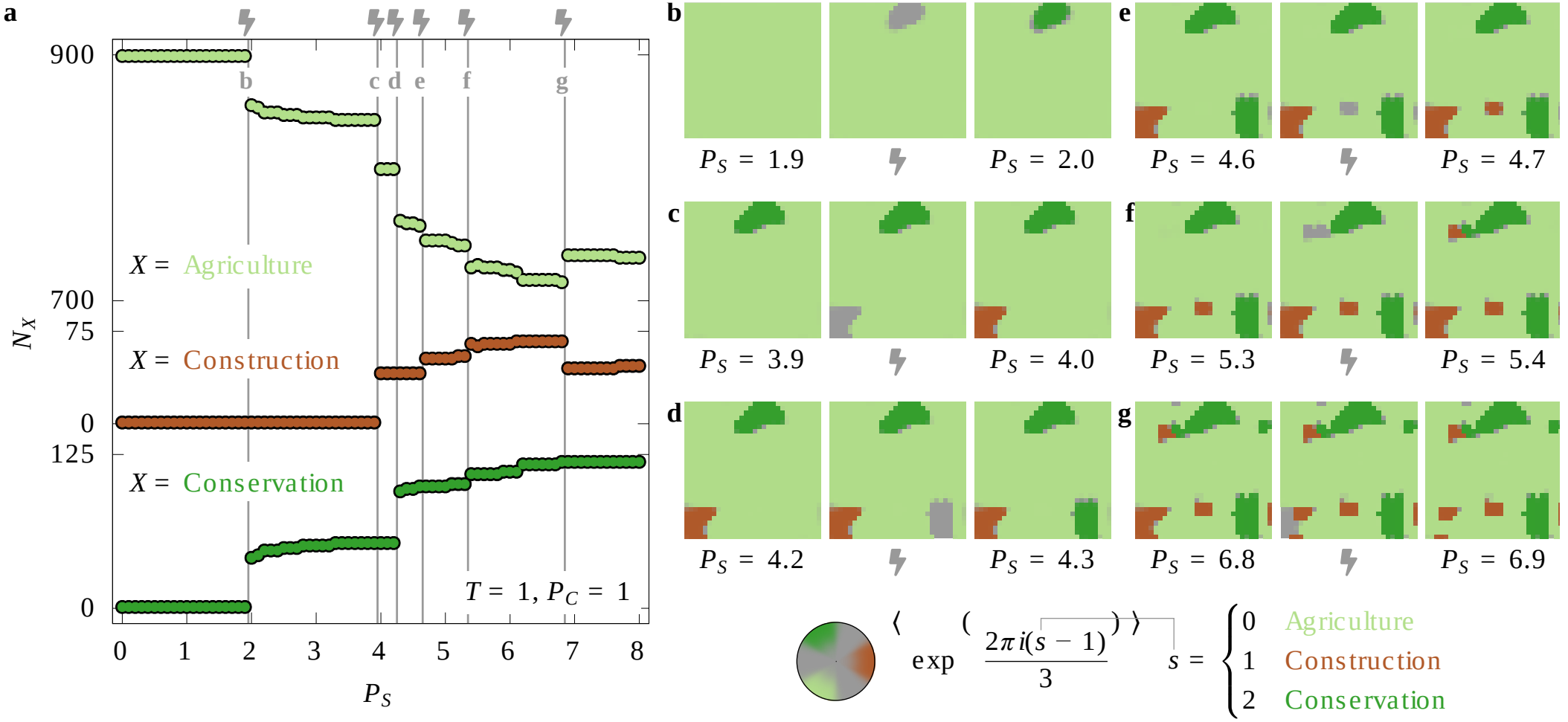
Main Result: Flashpoints!



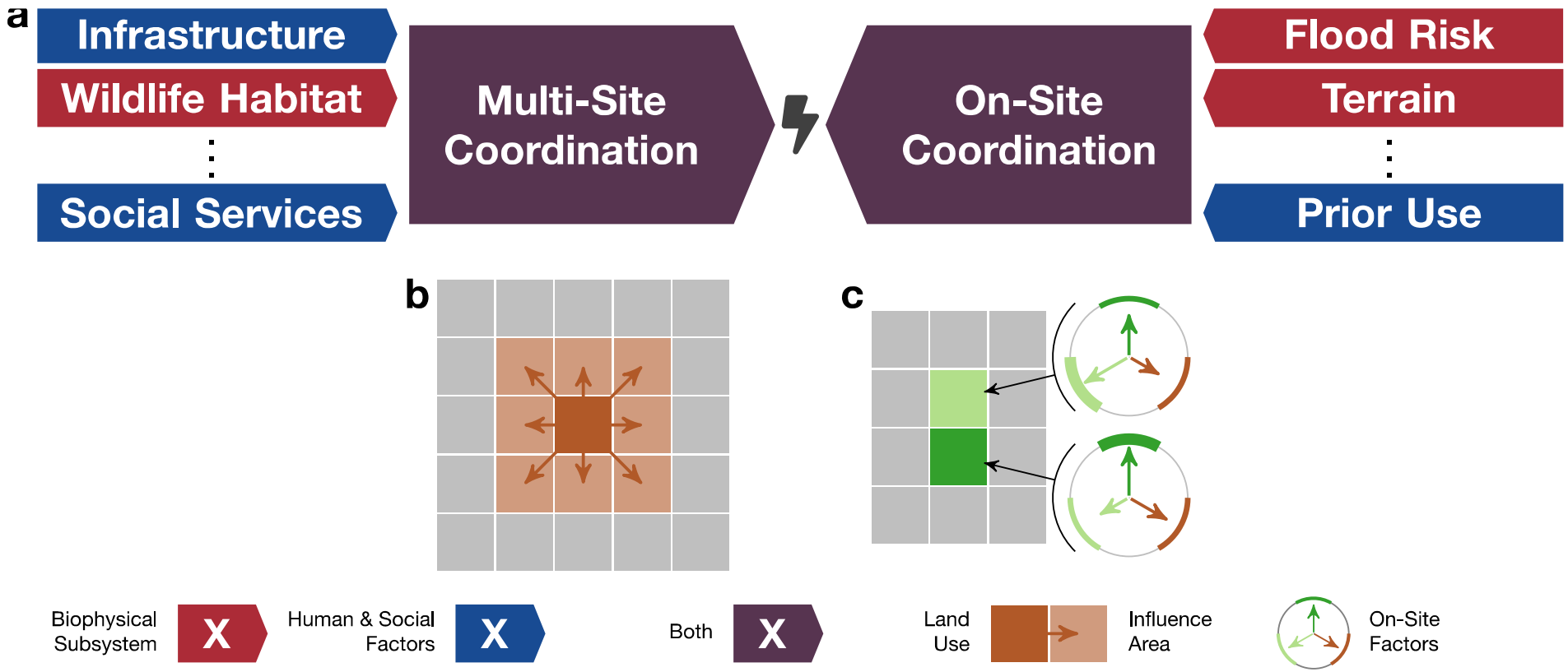
Main Result: Flashpoints! (cont.)



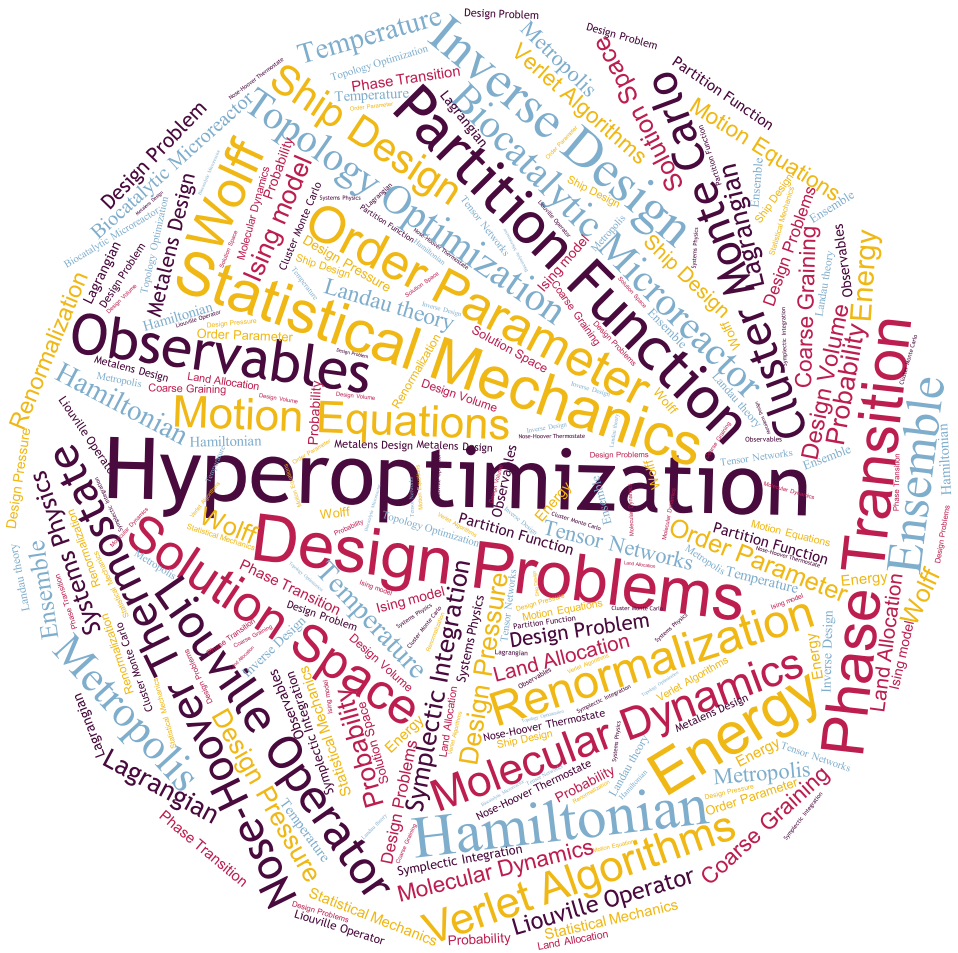
Main Result: Flashpoints!



Why?


a
Infrastructure
Wildlife Habitat
Social Services
Multi-Site Coordination
On-Site Coordination
Flood Risk
Terrain
Prior Use
b
c
Biophysical Subsystem
X
Human & Social Factors
X
Both
X
Land Use
Influence Area
On-Site Factors

Thank you!


Hyperoptimization
Partition Function
Statistical Mechanics
Observables
Inverse Design
Biocatalytic Microreactor
Ship Design
Topology Optimization
Order Parameter
Wolff
Ising model
Monte Carlo
Cluster Monte Carlo
Solution Space
Design Problem
Design Problems
Phase Transition
Ensemble
Energy
Renormalization
Molecular Dynamics
Hamiltonian
Verlet Algorithms
Metropolis
Lagrangian
Nose-Hoover Thermostate
Liouville Operator
Symplectic Integration
Coarse Graining
Land Allocation
Design Pressure
Design Volume
Probability
Motion Equations
Tensor Networks
Systems Physics
Ensemble Physics
Temperature
Metalens Design
Hamiltonian
Landau theory
Observables