Linking metapopulation modelling and Information Theory for area-wide pest management

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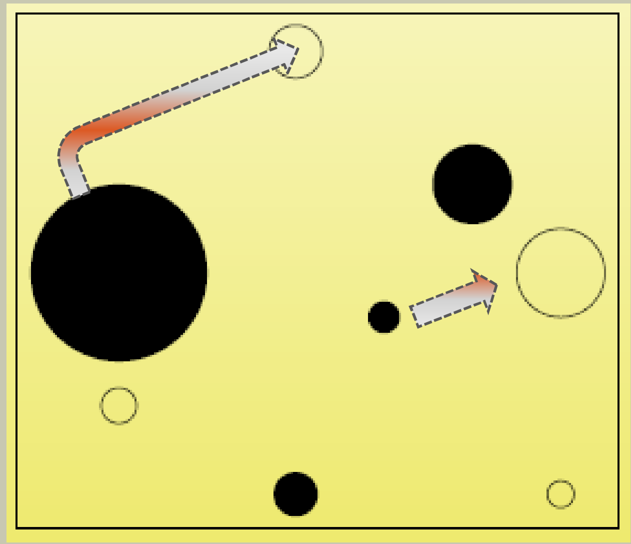
Non statistical terms …

- **Metapopulation** :[*s*]et of local populations within some larger area, where typically migration from one local population to at least some other patches is possible (Hanski and Simberloff, 1997).



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- **Pest**: organisms (rats, insects, etc.) which may cause illness or damage or consume food crops and other materials important to humans. An organism that is considered a nuisance to man, most usually having pathogenic properties (Biology-Online.org dictionary)

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- **Area-wide pest management**: Management of localized populations is the conventional or most widely used strategy, wherein individual producers, other operators and households practice independent pest control. However, since individual producers or households are not capable of adequately meeting the challenge of certain *very mobile and dangerous pests*, the area-wide pest management strategy was developed.

… & statistical problems

Quantitative evaluation of management strategies

Metapopulation models should be embedded in a **decision-making** framework to give managers the capability of **ranking** alternative decisions (Westphal et al., 2003). This means that the **objectives** of the management should be explicitly and clearly stated **in terms of metapopulation model variables** (Possingham et al., 2001).

… & statistical problems

Optimization

stochastic dynamic programming (SDP) has been recently applied in pest management, coupled with a spatially ***implicit*** metapopulation model, e.g. for invasive species control optimization (Bogich and Shea, 2008), or for biological control release strategies optimization (Shea and Possingham, 2000). However, SDP is computationally complex and its applicability limited to ***small metapopulations*** (Nicol and Chadès, 2011). Borrowing from epidemiology, a susceptible-infected-susceptible (SIS) model and a finite Markov decision process have been proposed to manage diseases, pest or endangered species in small (<25 nodes) network motifs (Chadès et al., 2011)

The idea

- **Spatially explicit** stochastic processes to **predict** metapopulation dynamics under the effects a given strategy

- **Kullback-Leibler divergence** to “compare predictions”

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- The best: optimization ⇐ **NON LINEAR PROBLEM**

The idea

- **Spatially explicit** stochastic processes to **predict** metapopulation dynamics under the effects a given strategy
- **Kullback-Leibler divergence** to "compare predictions"
- The best: optimization
- In practice: evaluation of a **finite set** of options

The idea

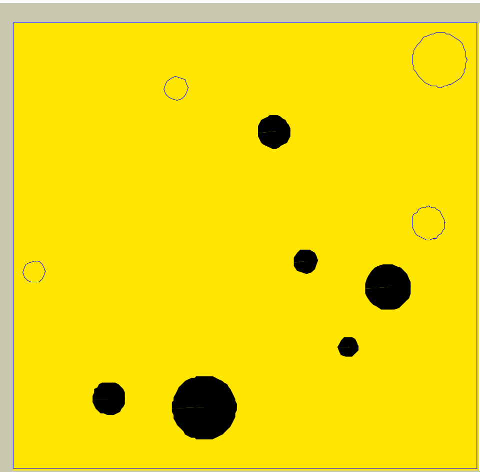
- The **Incidence Function Model** (Hanski 1994) is the only one spatially explicit metapopulation model in the literature. It has been used to predict metapopulation dynamics in terms of *presence/absence* of the species.

- The **KL divergence** has been introduced (Gilioli et al. 2008) to evaluate the strategies effects at time *T* in terms of divergence of the predicted dynamic at time *T* from the total extinction.

The idea in formula

- The **IFM.**

  Multivariate Markov chain: patches either empty or occupied



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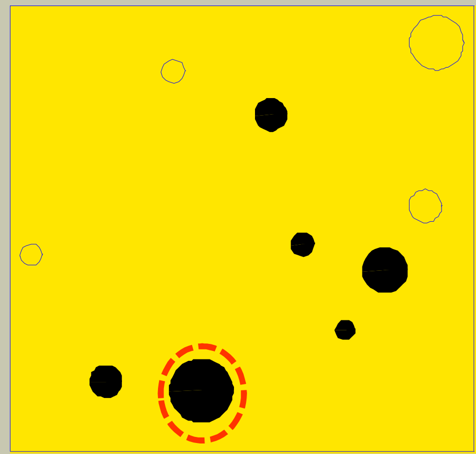

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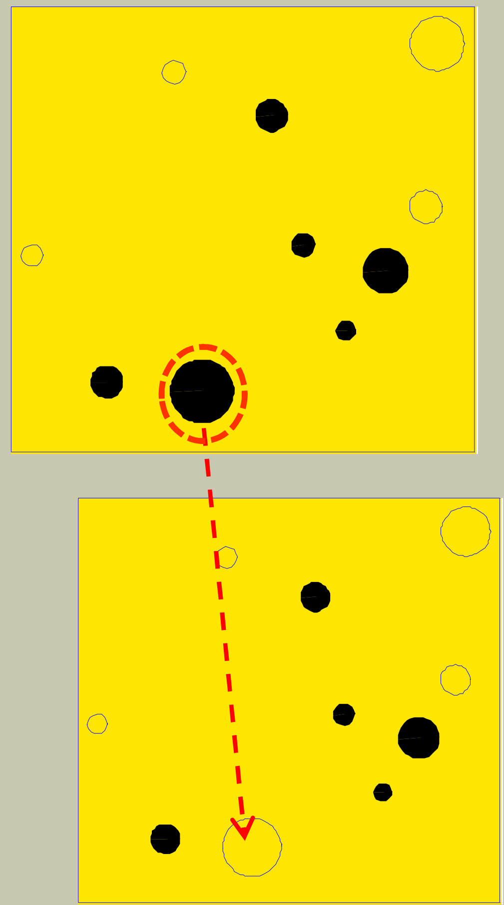

$$E_i = P(X_i(t) = 0 \mid X_i(t-1) = 1, \boldsymbol{X}_{-i}(t-1)) = \left(\frac{A_i}{A_0}\right)^x$$

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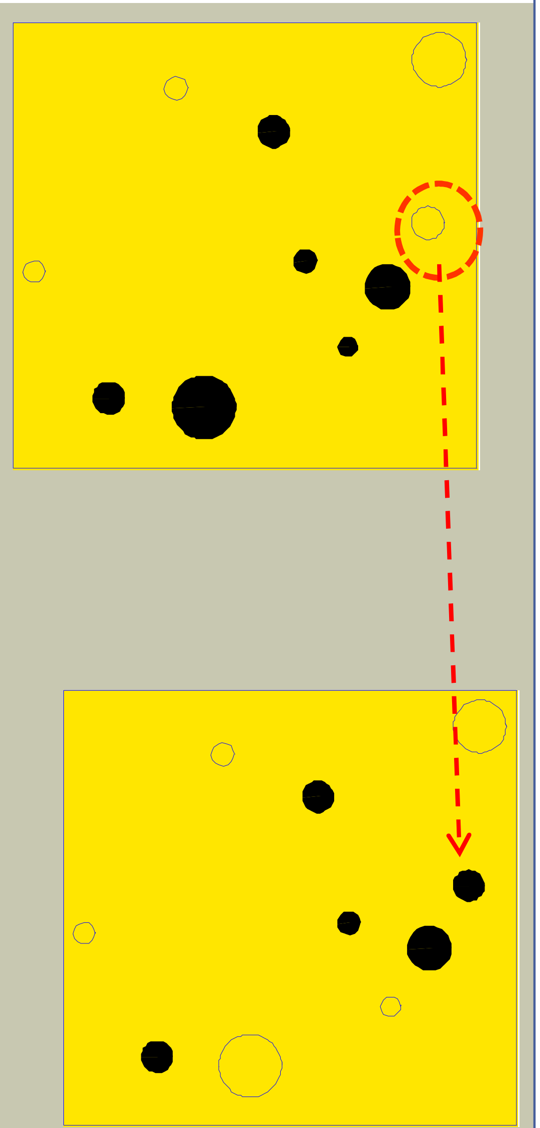


The idea in formula

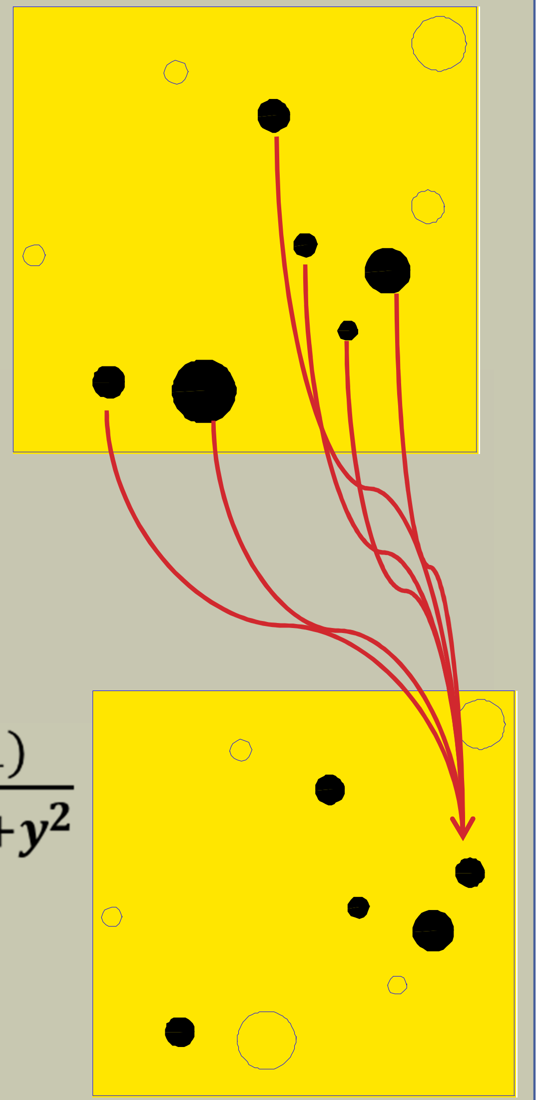
- The **IFM.**

  Multivariate Markov chain: patches are either empty ◯ or occupied ●

$$E_i = P(X_i(t) = 0 \mid X_i(t\text{-}1) = 1, \mathbf{X}_{-i}(t\text{-}1)) = \left(\frac{A_i}{A_0}\right)^x$$

$$C_i(t) = P(X_i(t) = 1 \mid X_i(t\text{-}1) = 0, \mathbf{X}_{-i}(t\text{-}1)) = \frac{\Delta_i^{\,2}(t-1)}{\Delta_i^{\,2}(t-1) + y^2}$$

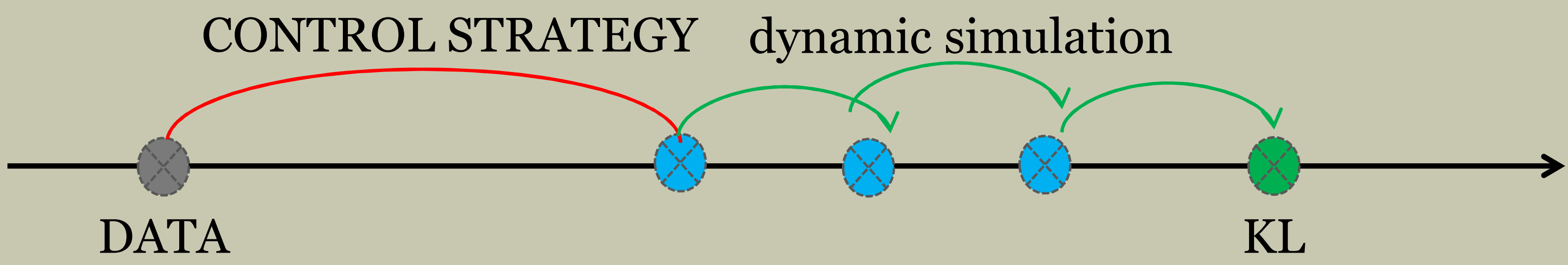
$$\Delta_i(t\text{-}1) = \sum_{j=1, j \neq i}^{n} X_j(t\text{-}1)\, A_j e^{-\alpha d_{ij}}$$ ***connectivity***

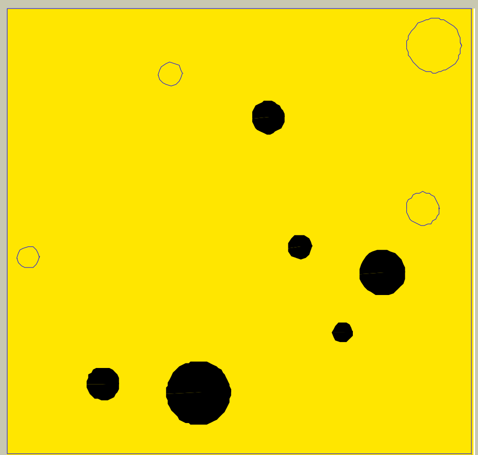


For insect pest, t means *generation*.

The idea by graphics

- The **KL** for strategy evaluation. **Purely spatial:**





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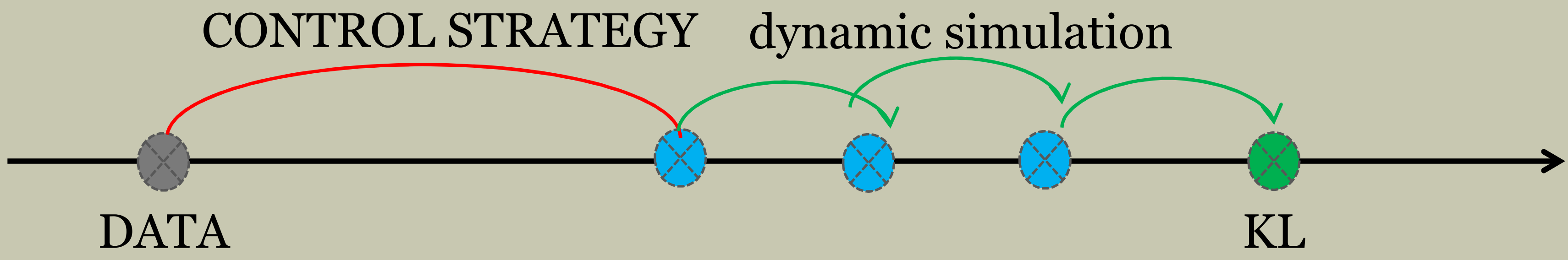

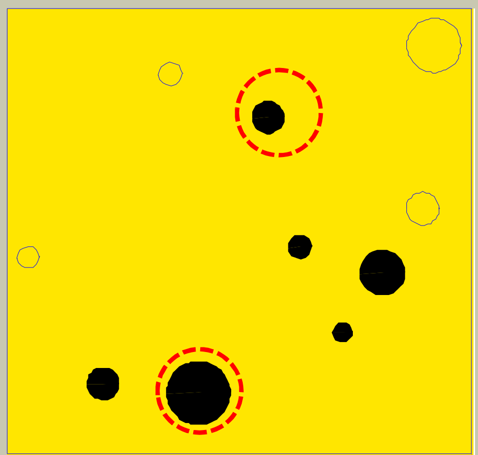

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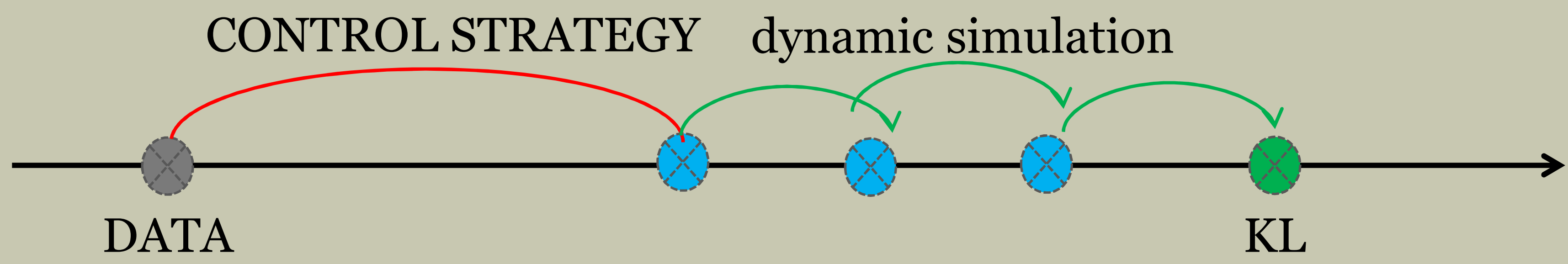

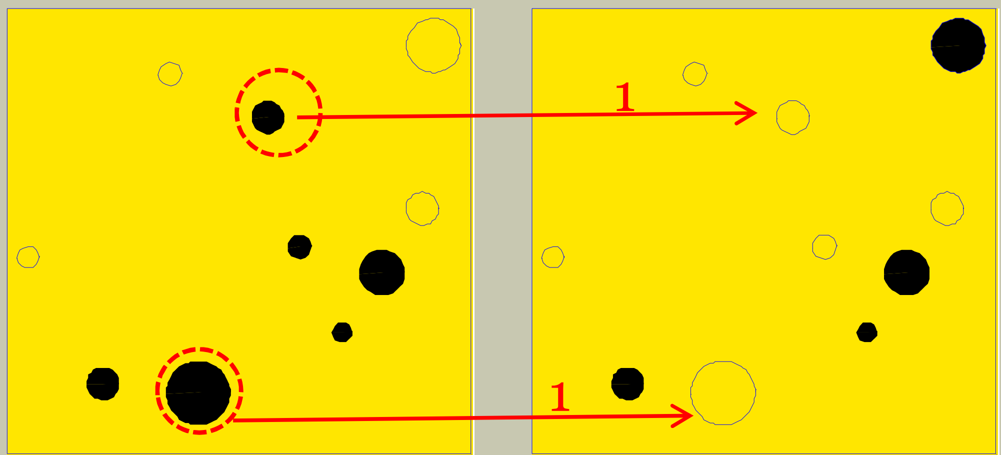

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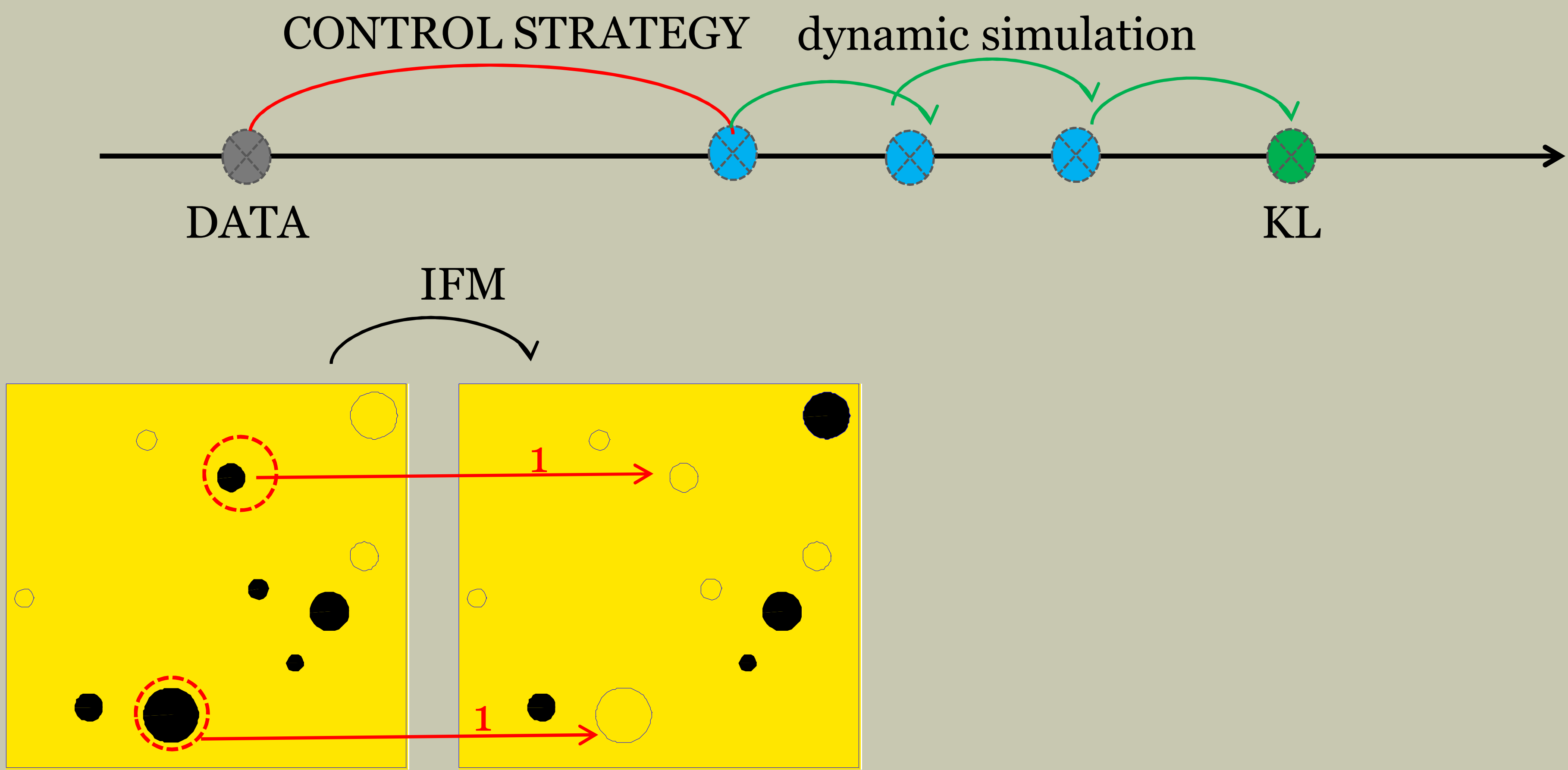

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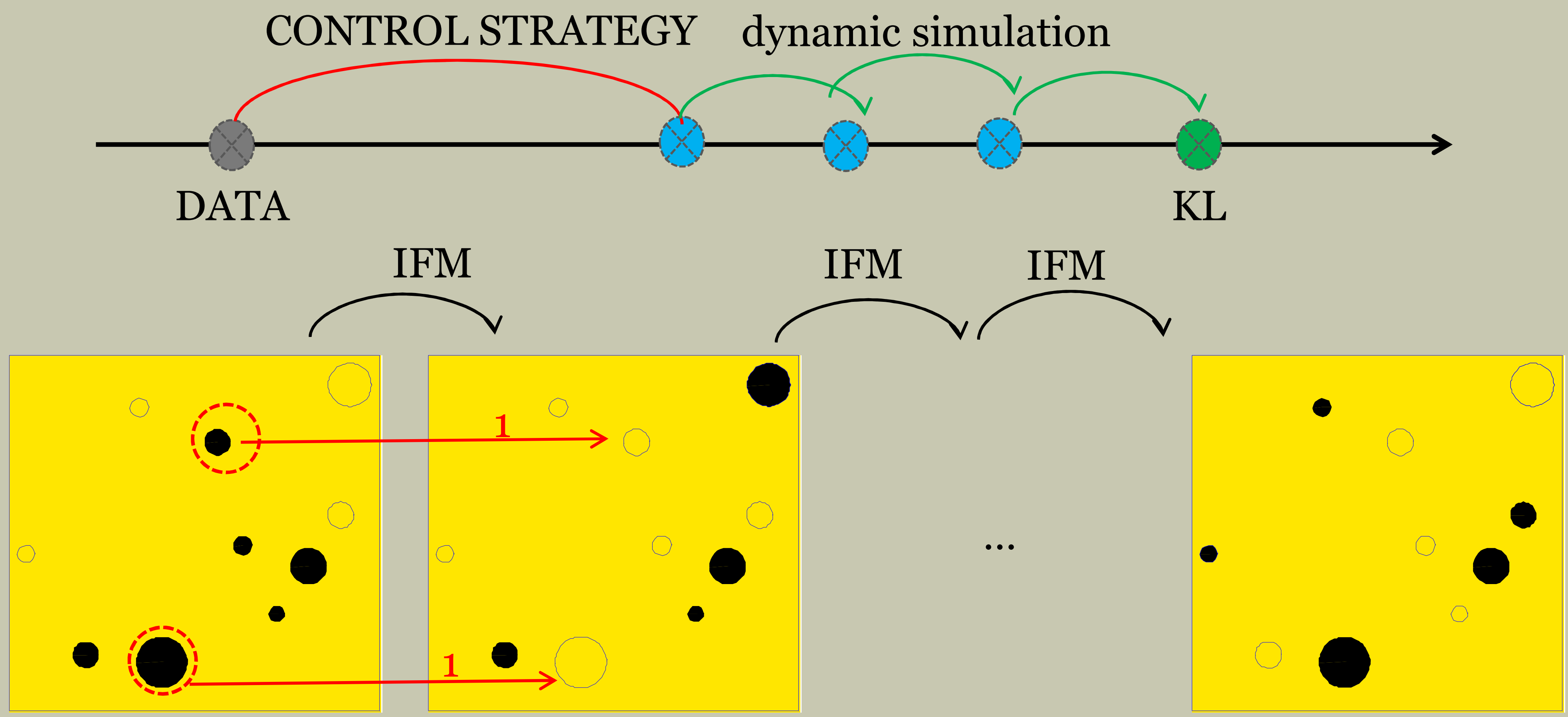
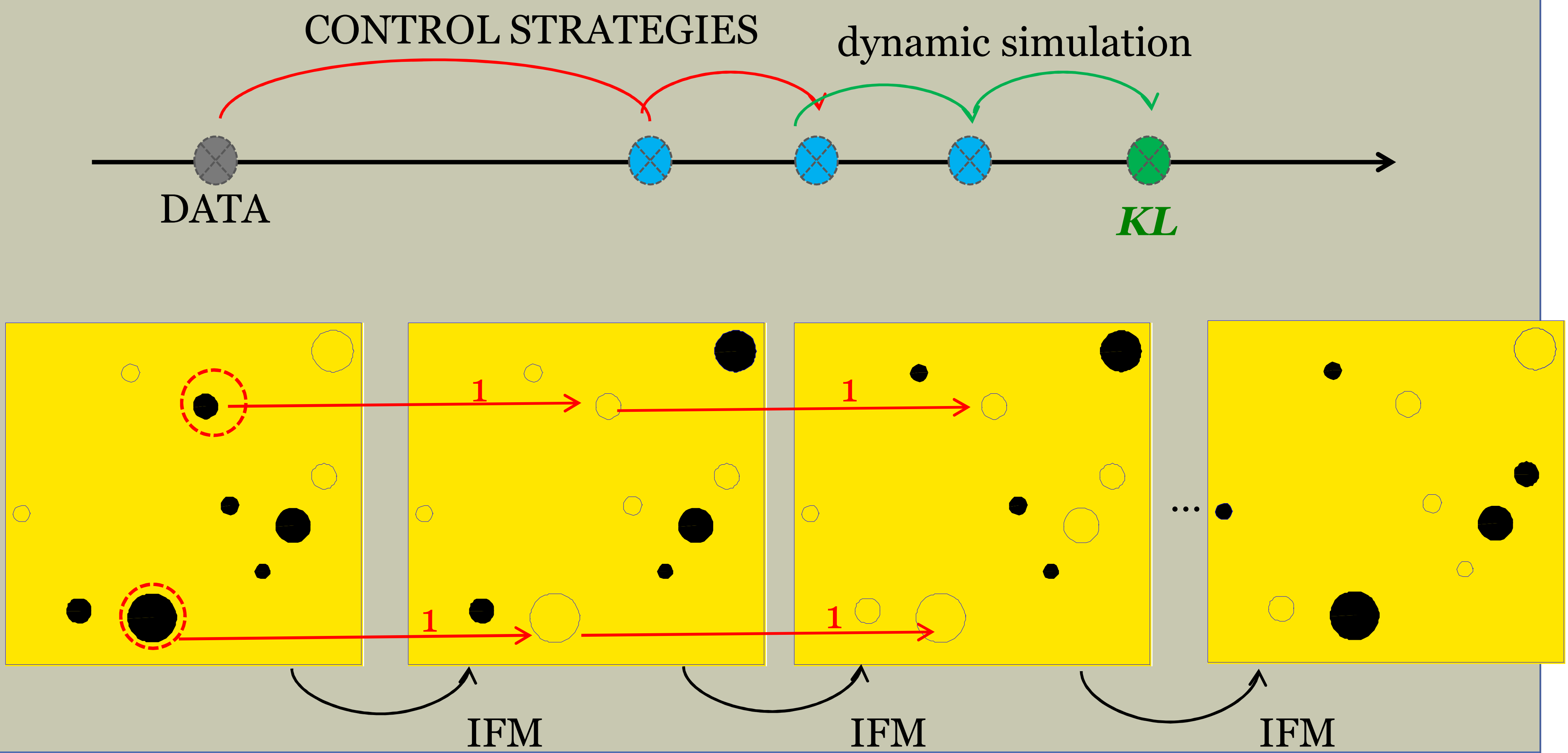


The idea by graphics

- The **KL** for strategy evaluation. **Spatio-temporal:**



The idea in formula and simulations

- The **KL of** $\boldsymbol{P}(\boldsymbol{X_T})$ from Dirac measure on $0_{\boldsymbol{n}}$: $\boldsymbol{-\ln P(X_T=0)}$
  - The lower the *KL* the better the strategy for *pest control*
  - The higher the *KL* the better the strategy for *conservation*

- **Simulations** to obtain the distribution of $\boldsymbol{X_T}$:

$$P(X_T = 0) = P(X_T = 0 | X_{T-1} = 1)\, P(X_{T-1} = 1)$$

$$+ \sum_{s \neq 1} P(X_T = 0 | X_{T-1} = s)\, P(X_{T-1} = s)$$

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explicit: $\prod_i (E_i \text{ or } C_i)$

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simulated

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explicit + simulated

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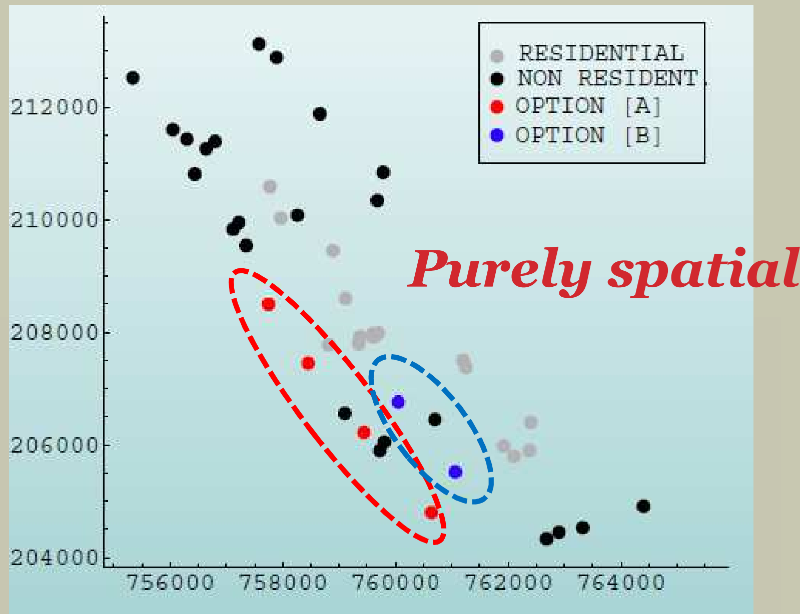
First Application

- (Amphibians) **Conservation**

Choice between 2 possible sets of new ponds.



- Only 1 year of data
- Equilibrium assumption:

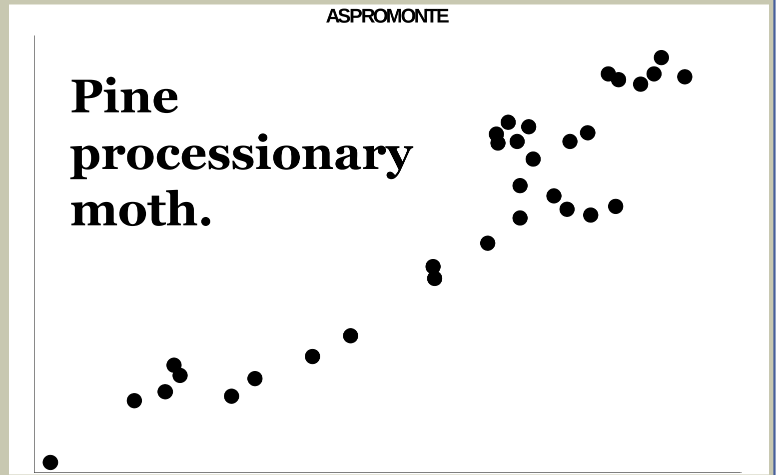
$KL(S) = -\sum_{i=1}^{n} \ln\left[1 - J_i(S)\right]$ measures the divergence of the stationary distribution coming from the strategy S, $\otimes J_i(S)$, from the total extinction.

Gilioli et al. 2008

Second Application 

Gilioli et al. 2013

Pest control



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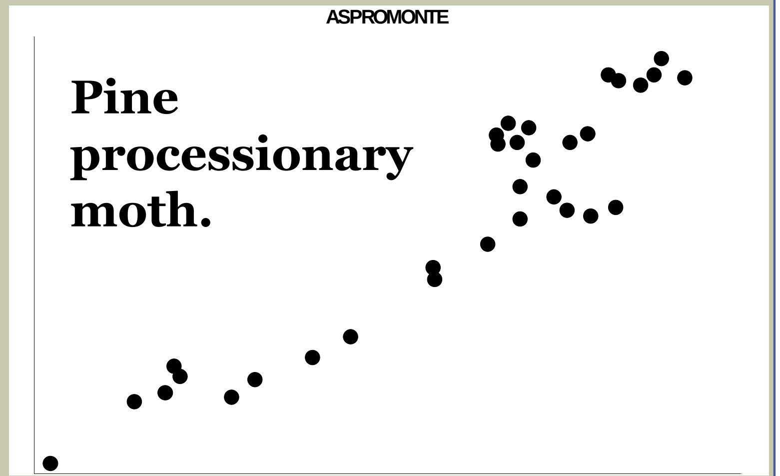

SPATIAL ANALYSIS to verify the IFM applicability to this moth.

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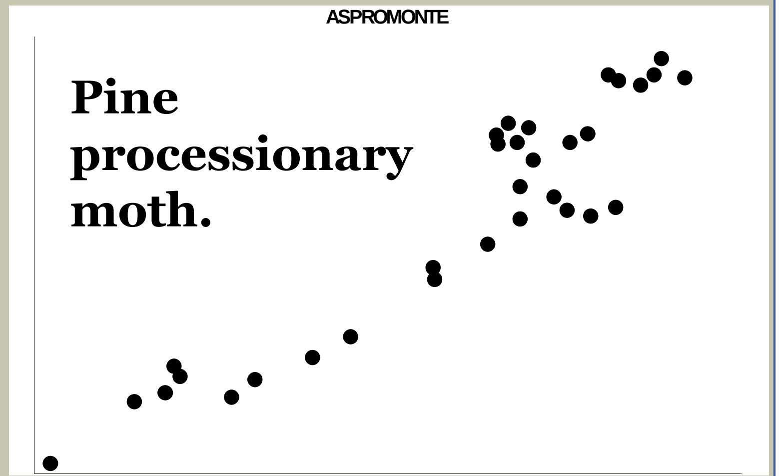

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SPATIAL STRATEGIES
(a) scattered sites
(b) close sites
(c) "in line" sites.

Three levels of intervention: 15%, 30% and 50% of the total area (low,medium and high intervention level).

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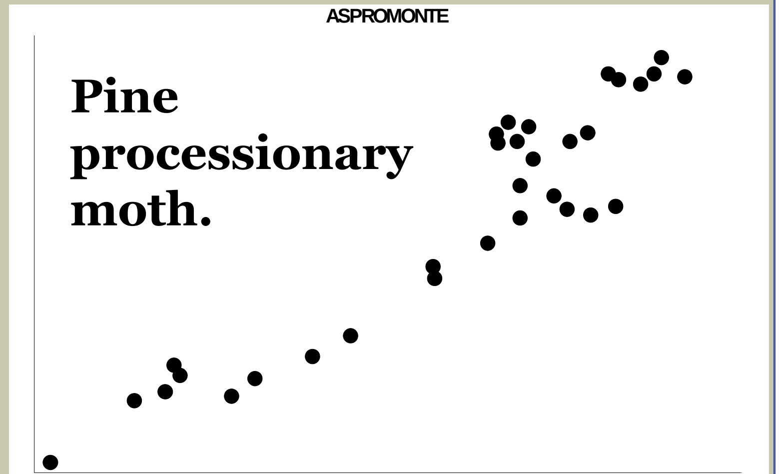

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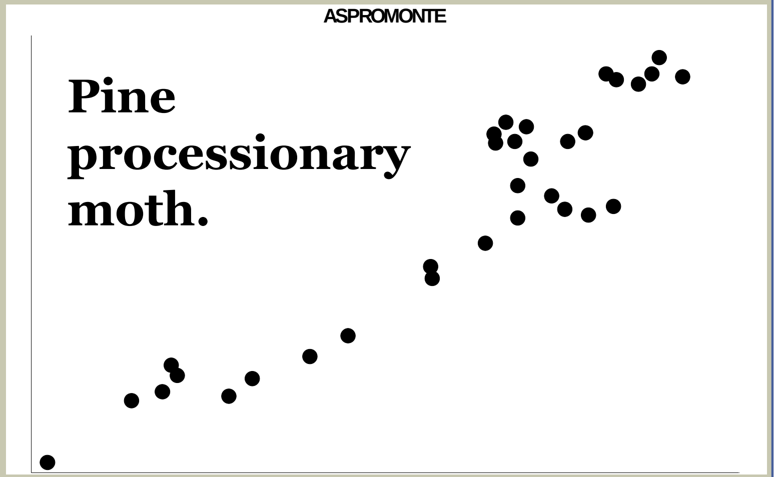

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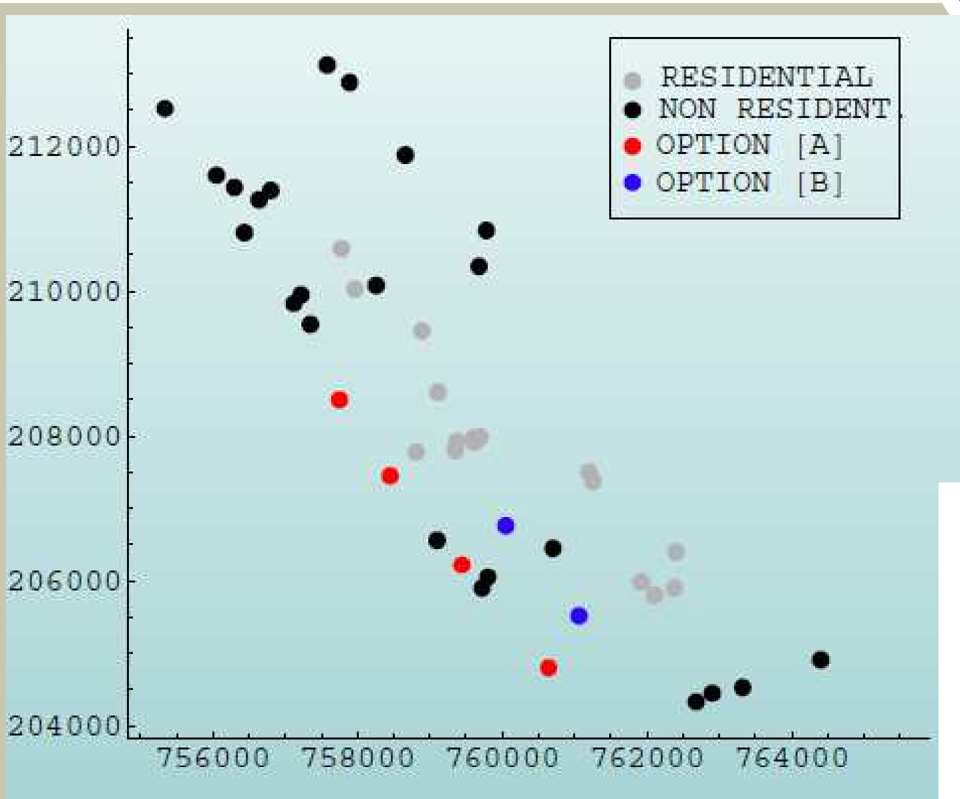
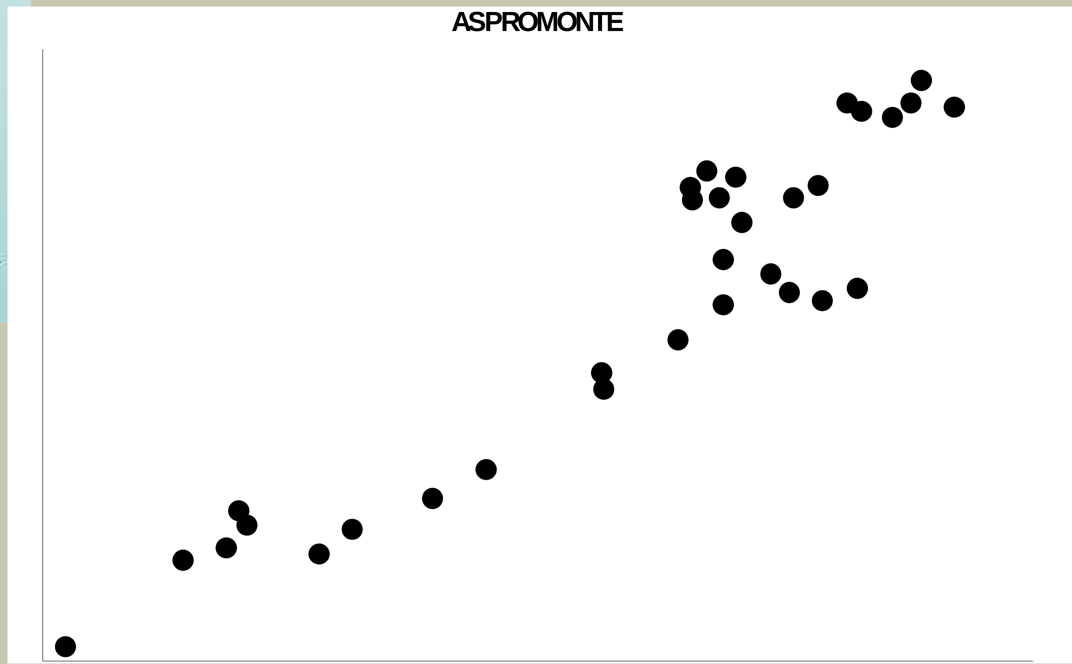
Combination of both: distributed effort for high intervention level.

Testing the idea



CONSERVATION

PEST CONTROL



Testing the idea

Need to

1. understand the performances of the *KL* in more general (not “linear”!!) situations
   - Different habitat configurations
   - Different types of strategies

2. provide easy interpretation for practitioners
   - Comparison of *KL* values to non probabilistic indexes

More general habitat configurations

Square of side 50 Km

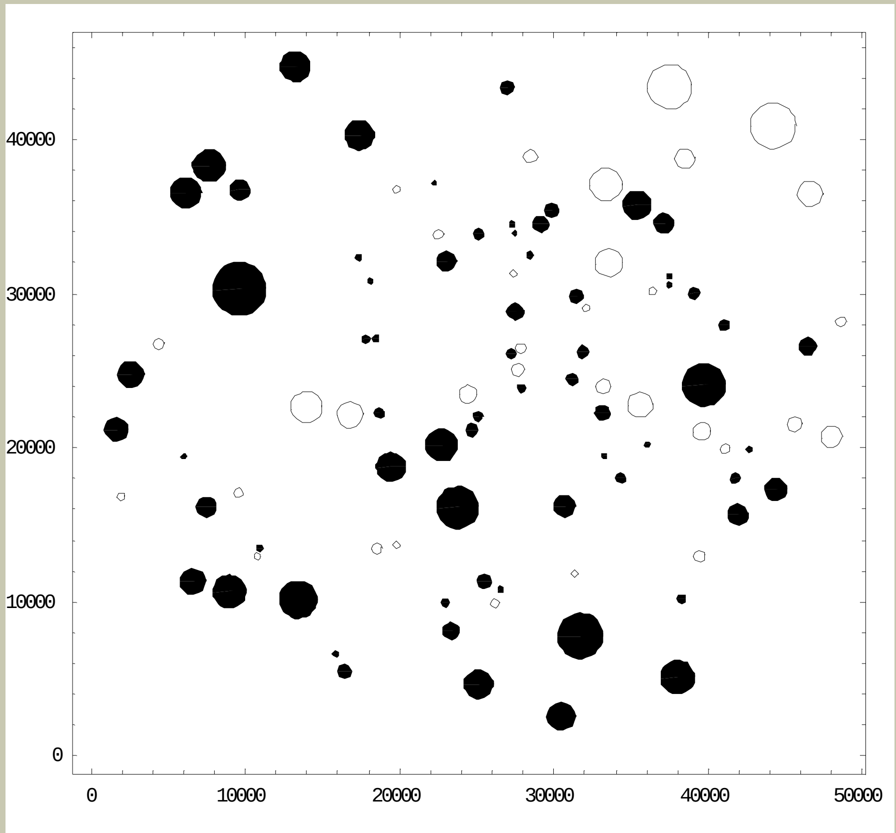
100 patches

● occupied

○ empty

IFM: $x = 0.15$, $y = 0.001$

More general habitat configurations



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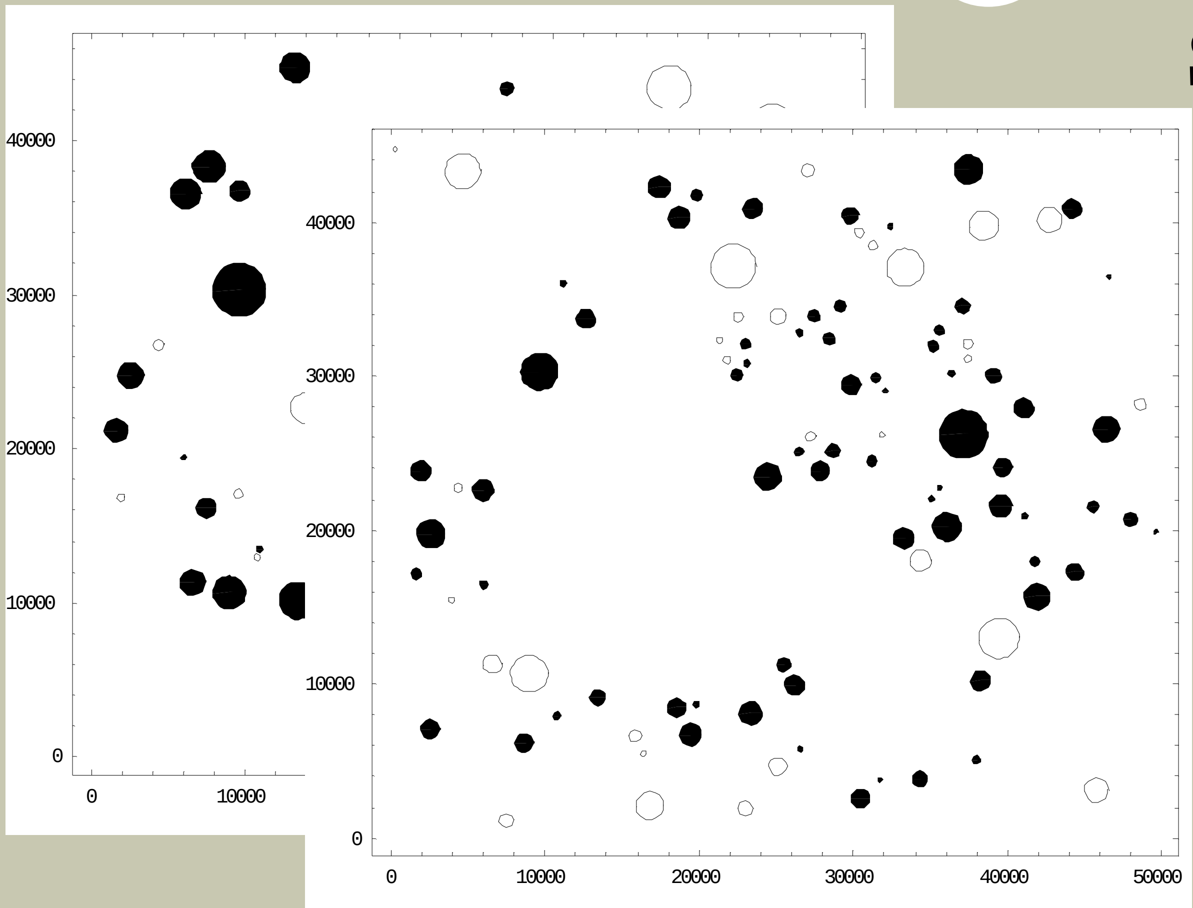

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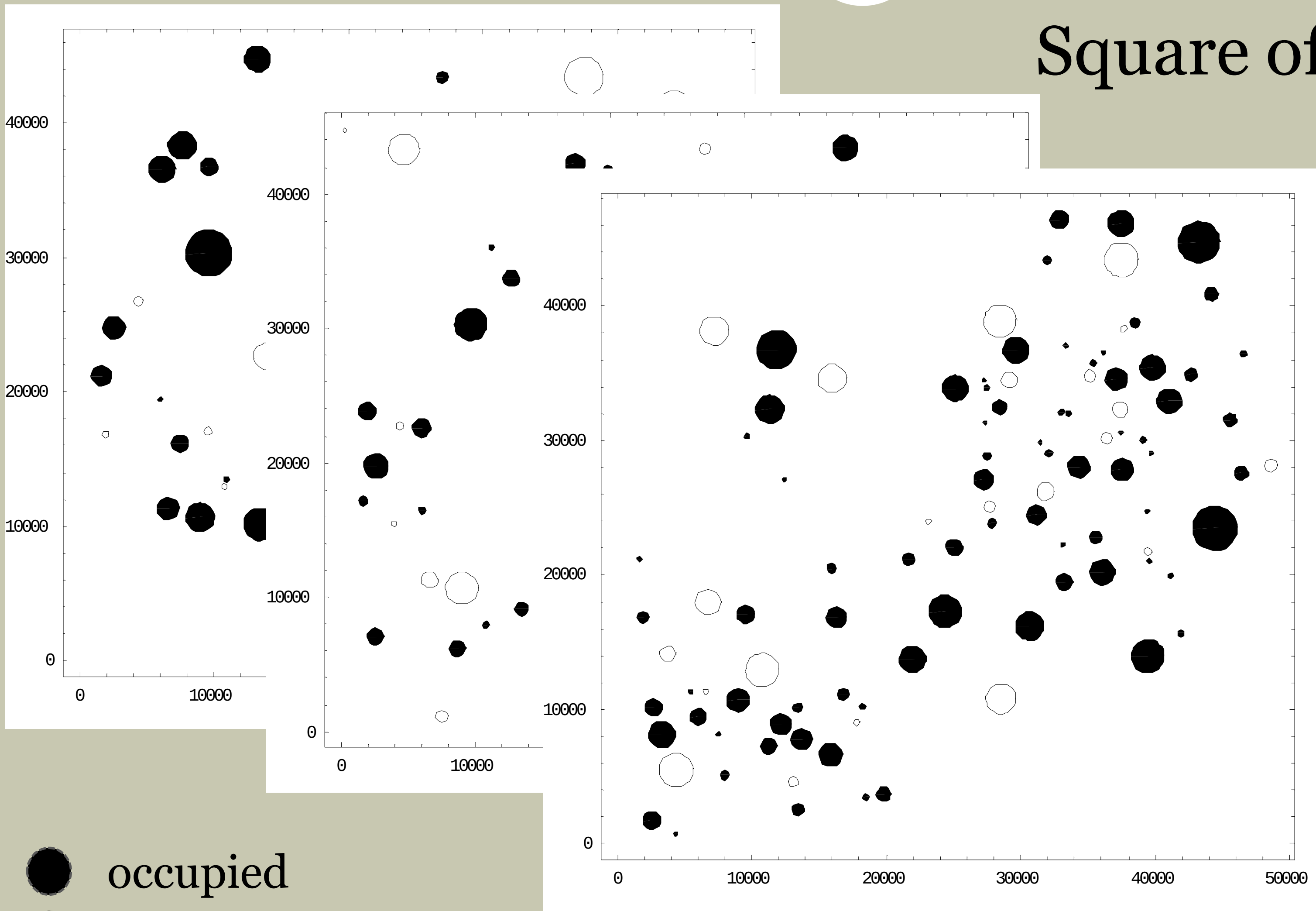

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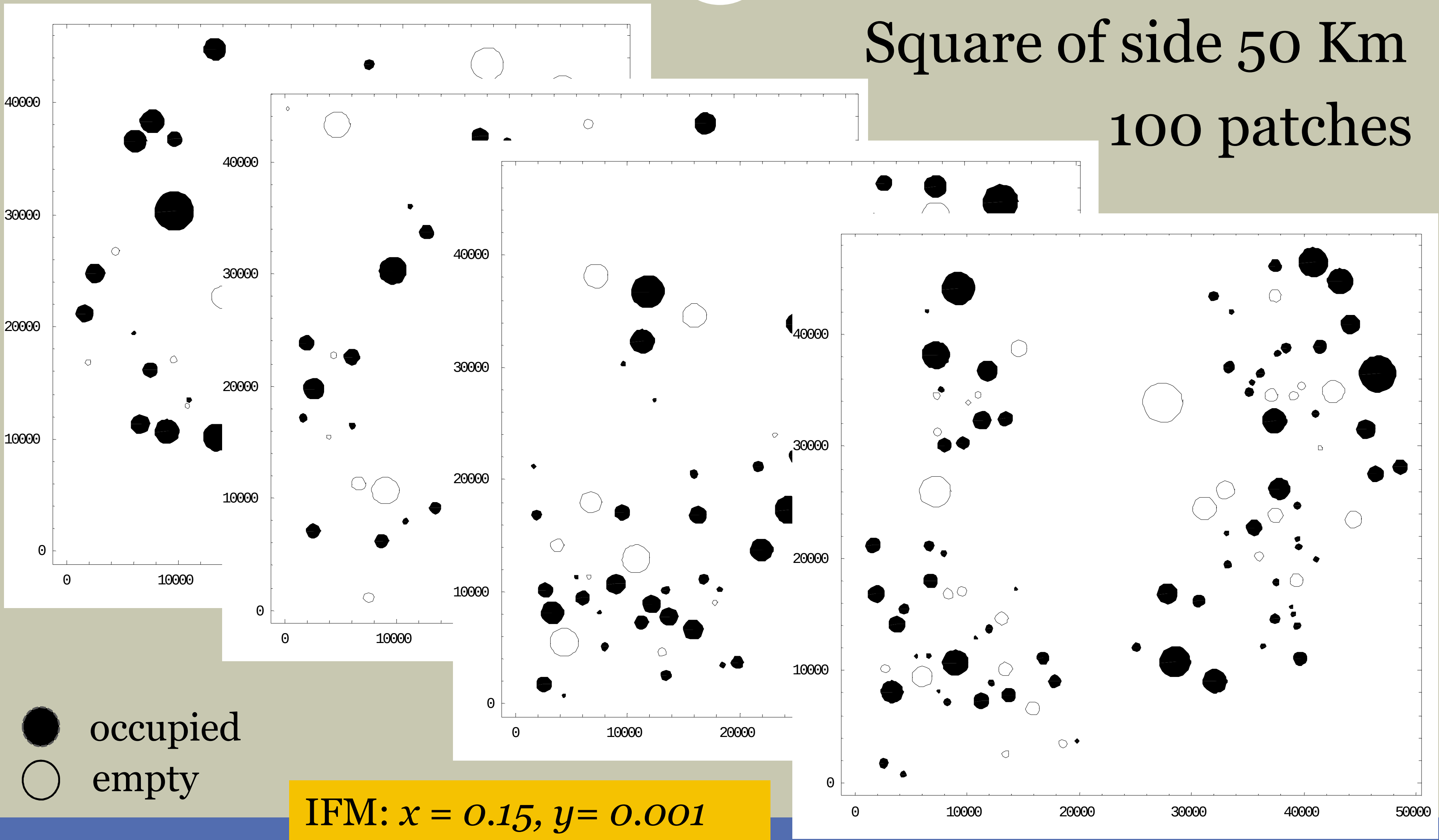

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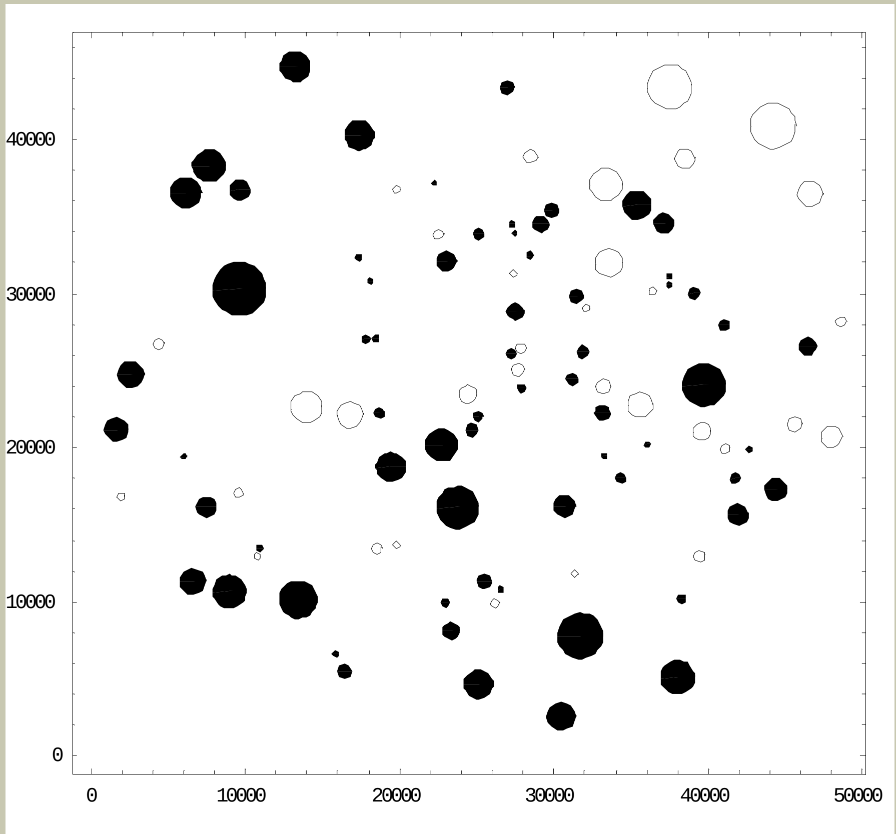
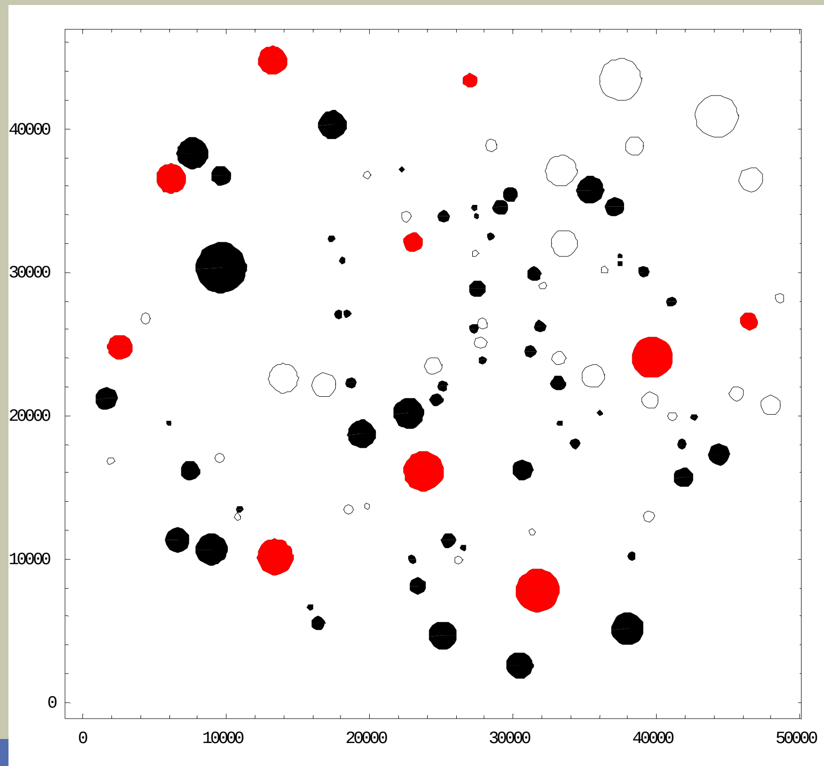
More general habitat configurations & strategies



Square of side 50 Km

100 patches

scattered strategy

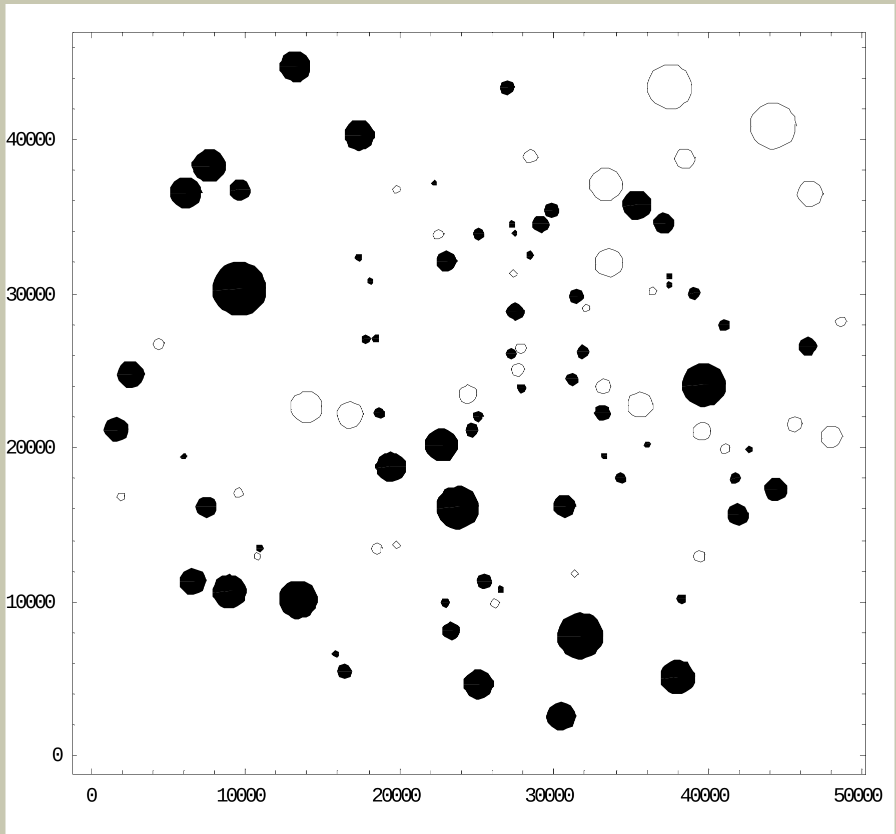


occupied

empty

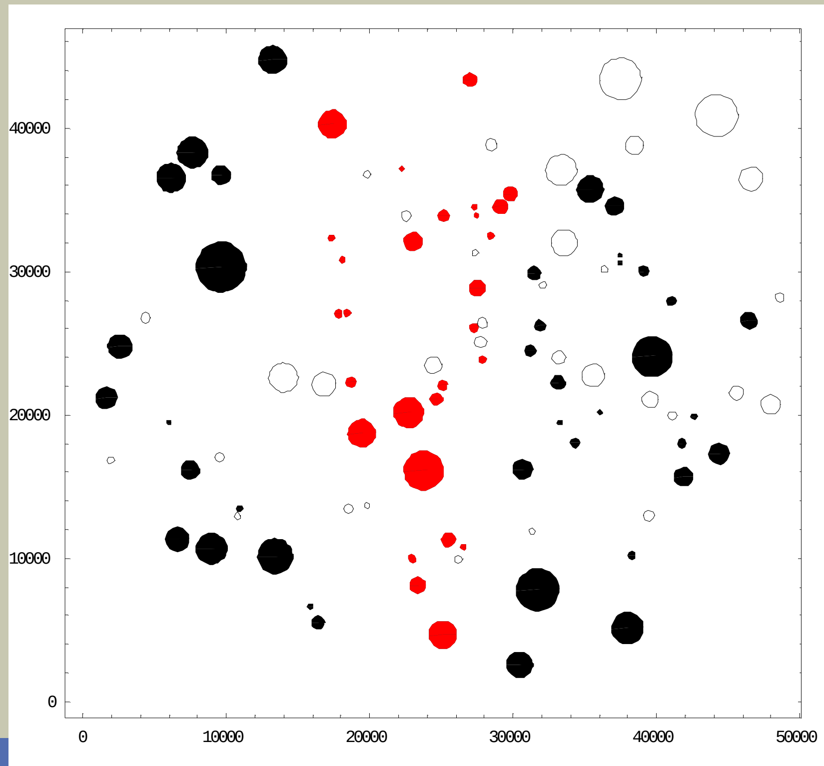
to be treated

More general habitat configurations & strategies



Square of side 50 Km
100 patches

organized strategy



occupied
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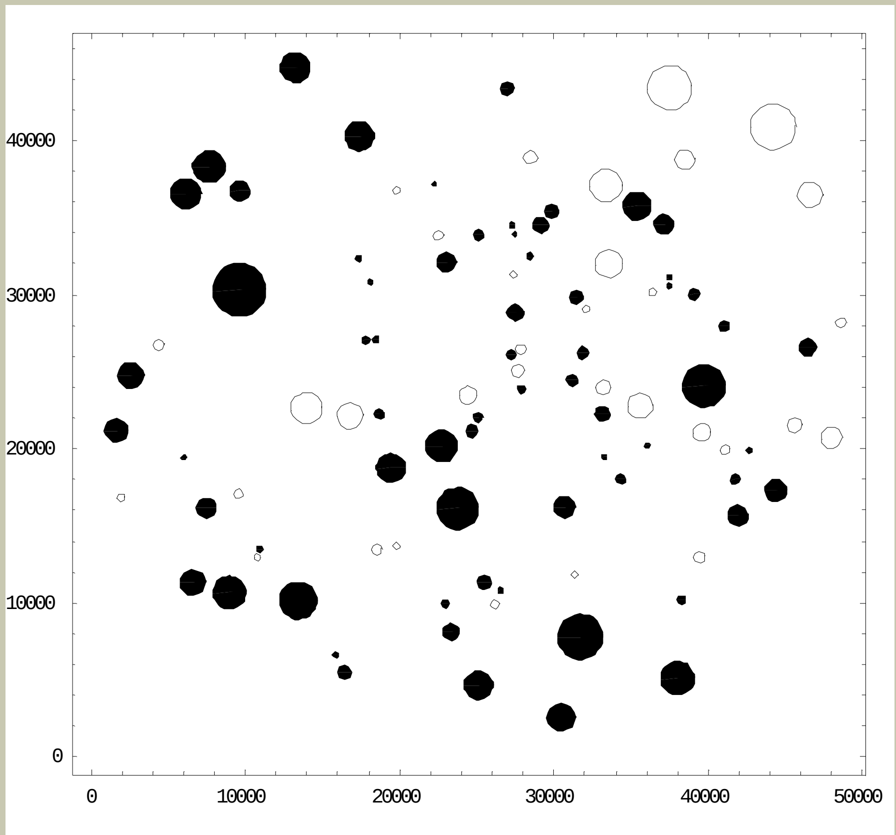
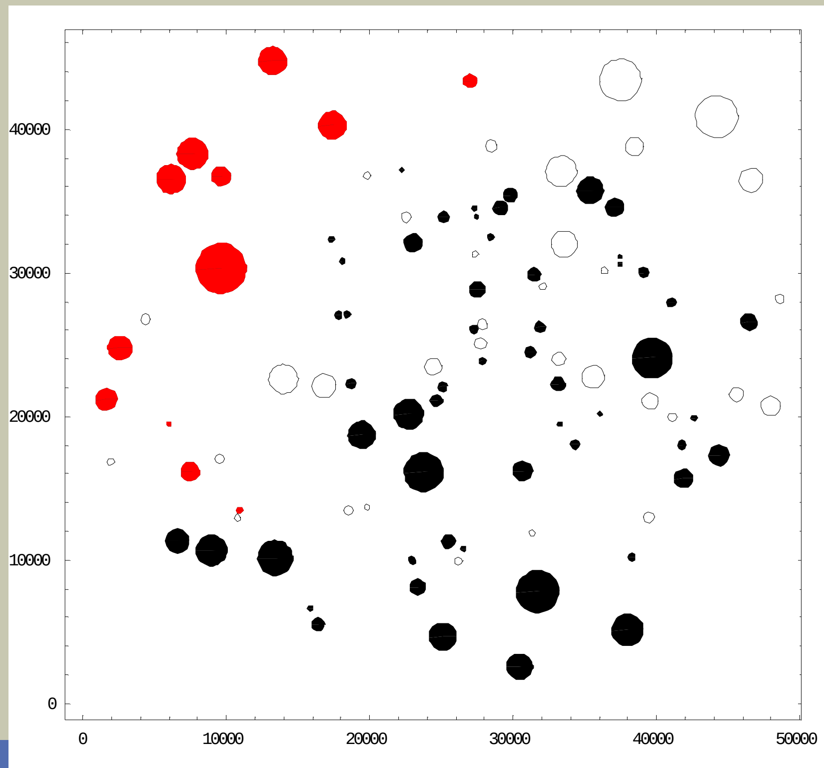
More general habitat configurations & strategies



Square of side 50 Km

100 patches

peripheral-organized strategy



occupied

empty

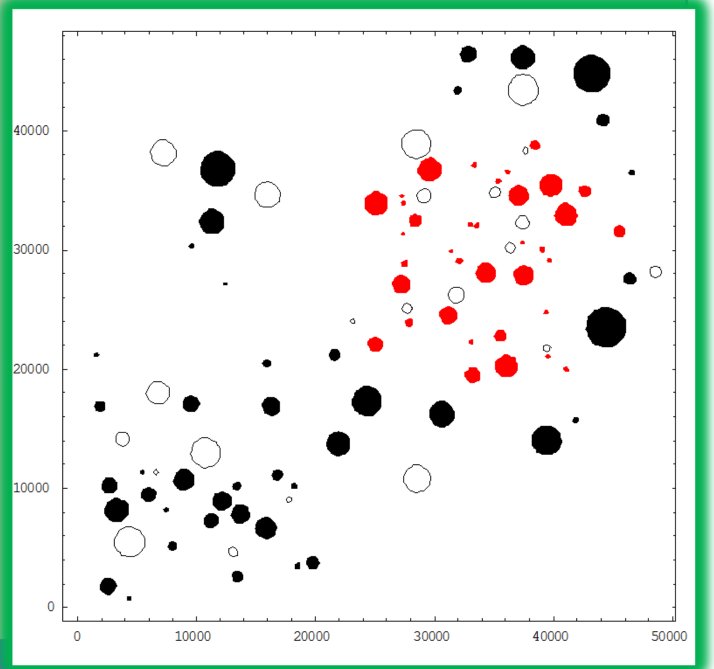
to be treated

General results: purely spatial

data:2013, KL 2016

S_0 = do nothing strategy

KL		Strategies						
		S_0	1	2	3	4	5	6
Case	True param.	**141.9**	141.0	139.7	140.3	135.4	136.6	133.1
	Estimated param.	**146.2**	146.1	144.0	141.1	139.6	140.2	137.5
T.A. (%)		**--**	**23.3**	**21.9**	**21.2**	**22.8**	**22.6**	**23.1**



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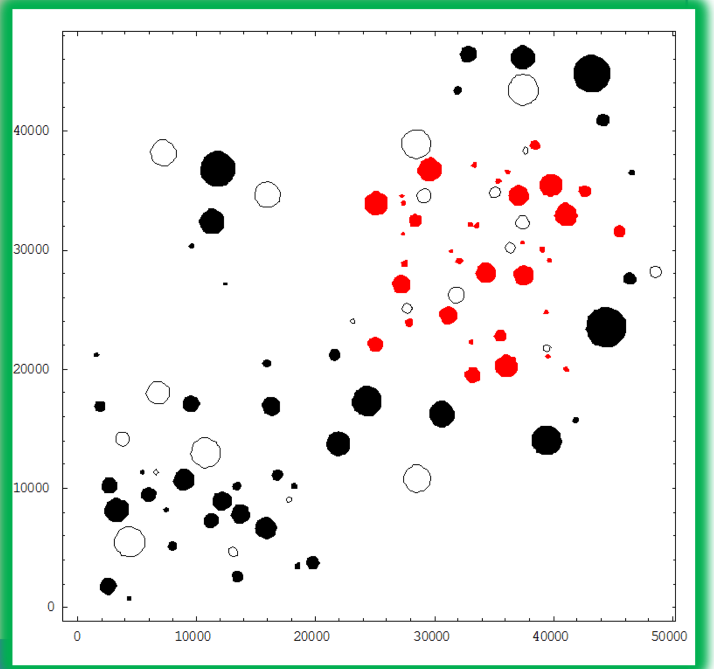
Connectivity		Strategies						
		S_0	1	2	3	4	5	**6**
Case	True param.	**0.212**	0.201	0.145	0.177	0.110	0.117	**0.087**
	Estimated param.	**0.218**	0.205	0.150	0.182	0.112	0.119	**0.088**



General results, contd.

KL		Strategies					
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Case	True param.	**143.7**	142.1	175.9	132.9	137.1	147.7
	Estimated param.	**121.0**	119.1	152.7	115.9	113.6	124.9
T.A. (%)		**--**	**24.8**	**21.3**	**21.0**	**20.6**	**27.0**

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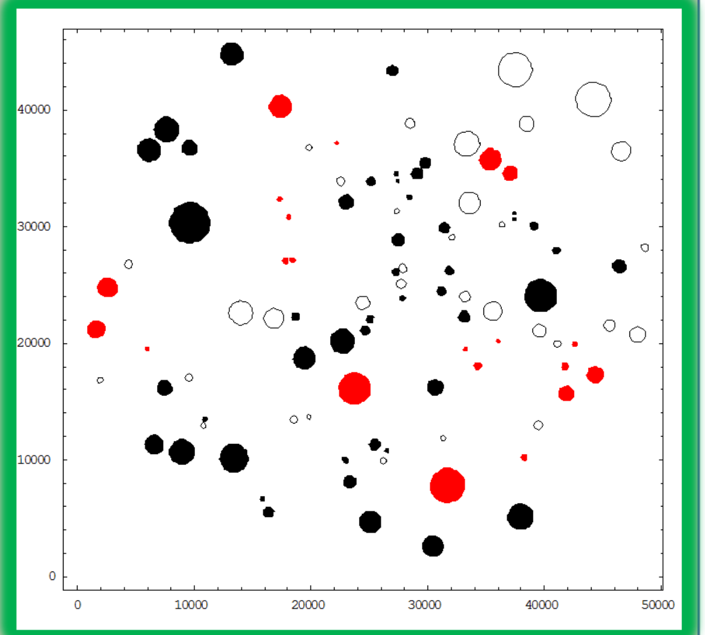

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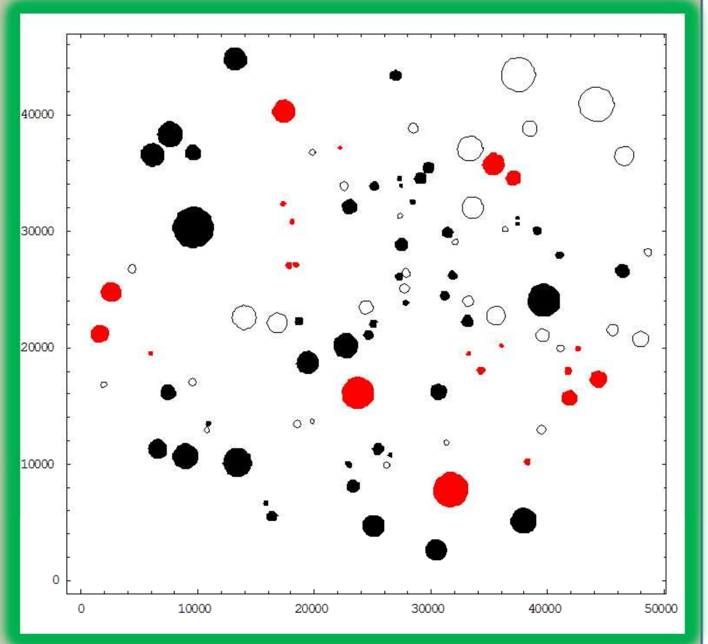
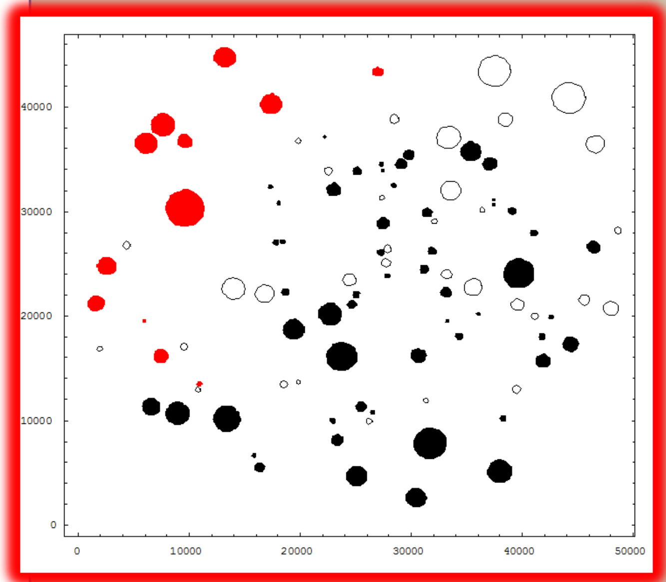
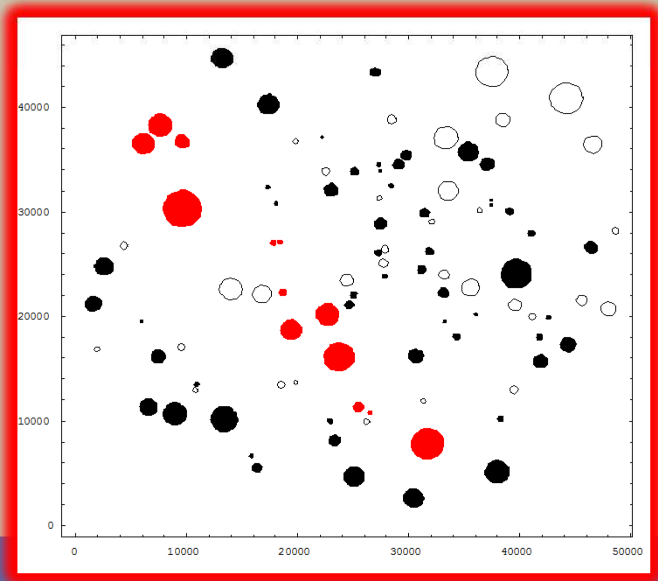
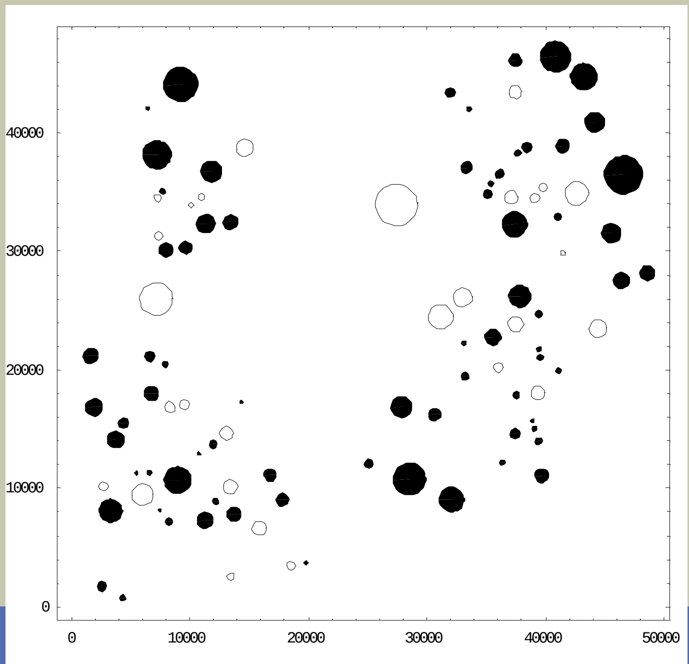






General results, contd.

KL		Strategies										
		S_o	1	2	3	4	5	6	7	8	9	10
Case	True param.	**143.1**	142.3	142.3	141.2	156.3	155.7	140.1	140.0	143.6	140.7	138.9
Case	Estimated param.	**131.5**	132.8	134.1	131.6	159.1	145.6	135.7	137.8	137.6	136.3	129.5
T.A. (%)		--	22.5	22.1	21.6	16.2	20.8	16.1	23.1	14.0	20.2	22.1



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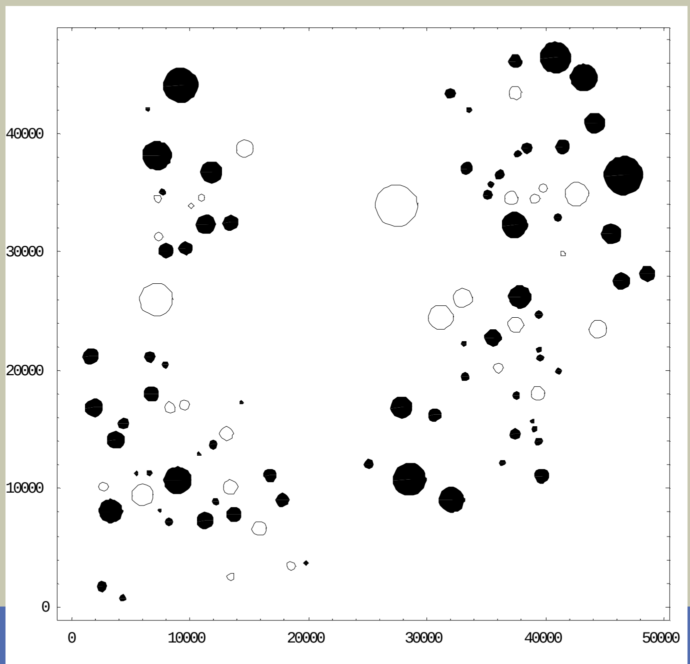

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- Is the simulated model a "biased model"?

$$C_i(t) = \frac{\Delta_i^{\,2}(t-1)}{\Delta_i^{\,2}(t-1) + y^2} \approx 1 \qquad as\ \ y^2 \approx 0 \text{ at any time } t$$

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STATISTICAL & ECOLOGICAL ISSUE

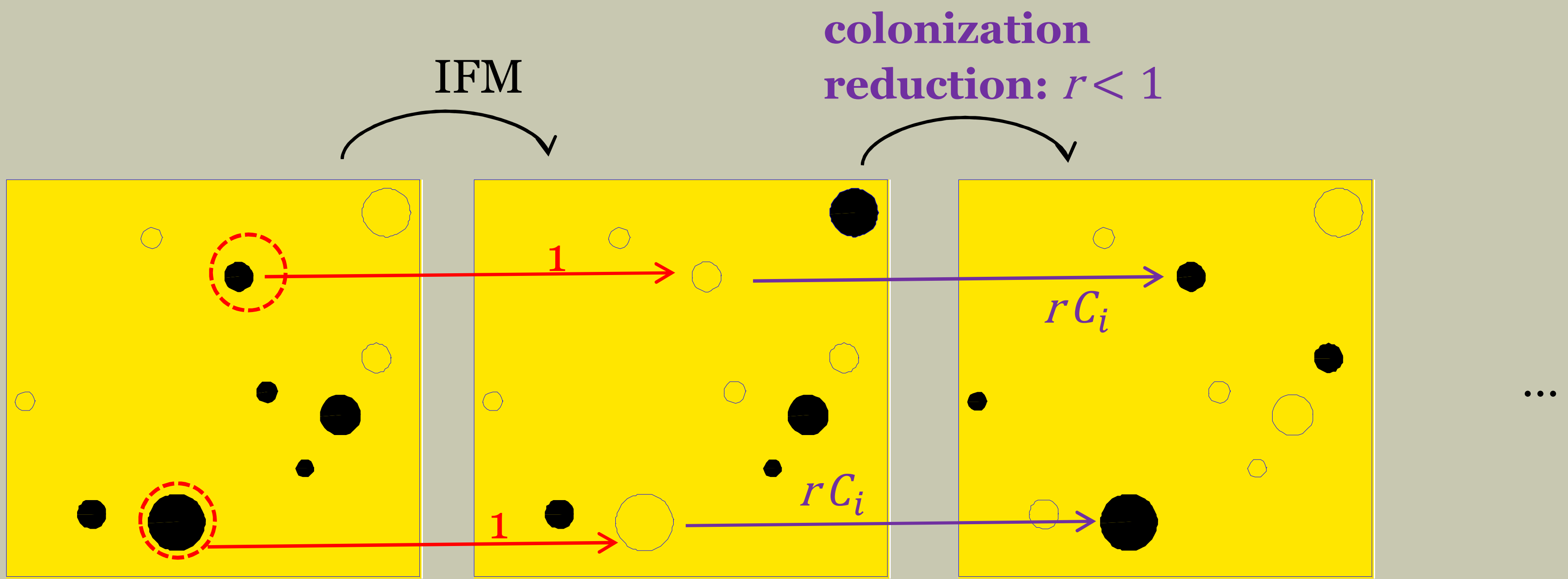
- Is the strategy effect representation adequate?
- Is the IFM a “good” model?

First possible solution…

(English translation...)

Second possible solution…

- Different representation of strategy effect: colonization reduction



A few, partial answers.

- A *good* case:
  extended treatment (59% of total area)

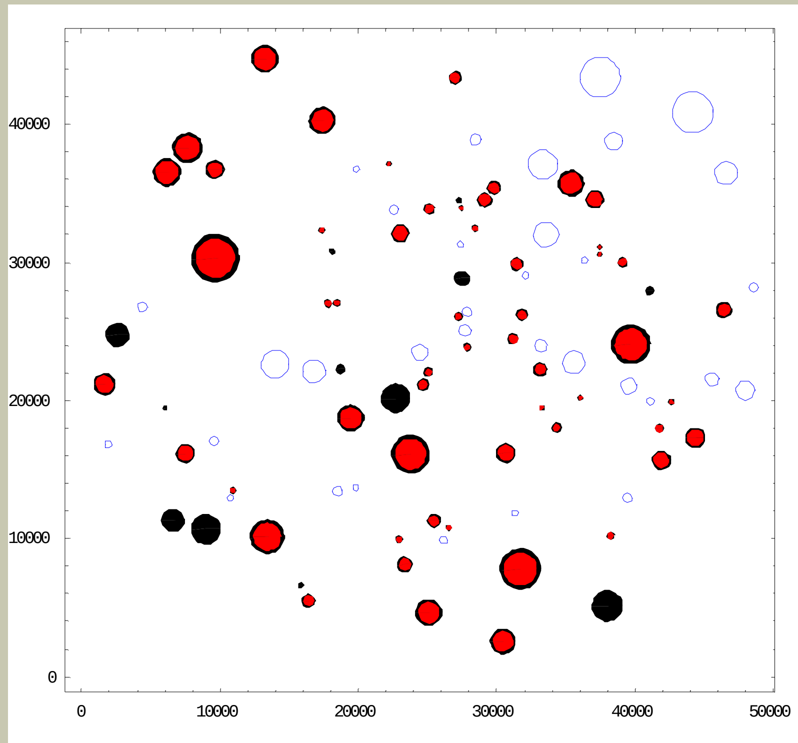
data | | | ***KL***

2013 → 2014 → 2015 → 2016

strat.

col. reduct.
r=0.5
r=0.1
r=0.1

col. reduct.
r=0.5
r=0.5
r=0.1



A few partial answers, contd.

	Do nothing	no reduction	(0.5, 0.5)	(0.1, 0.5)	(0.1,0.1)
KL	143.7	140.5	123.4	99.1	77.0

Increasing treatment effect (i.e., increasing colonization reduction)

→ decreasing *KL* (i.e. increasing probability extinction)

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Thank you very much for your attention and ***even more*** for your suggestions!