# Modèles graphiques stochastiques et optimisation pour la gestion de systèmes agroécologiques

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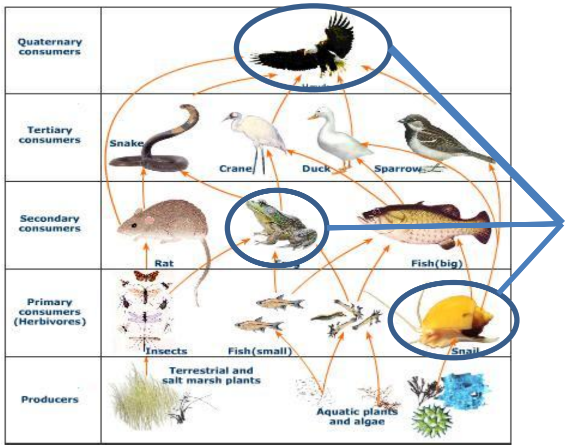
# Some AI tools for the management of stochastic processes on networks

- Tools based on Stochastic graphical models
  - Bayesian networks
  - Markov Random Fields
  - (Factored) Markov Decision Processes
- Plus the use of optimization/approximation methods
  - Dynamic programming
  - Reinforcement learning
  - Continuous optimization
  - Heuristics
- Applications in agroecological systems management
  - Biodiversity conservation
  - Spatial sampling of weeds
  - Management of services / crop health at the landscape scale

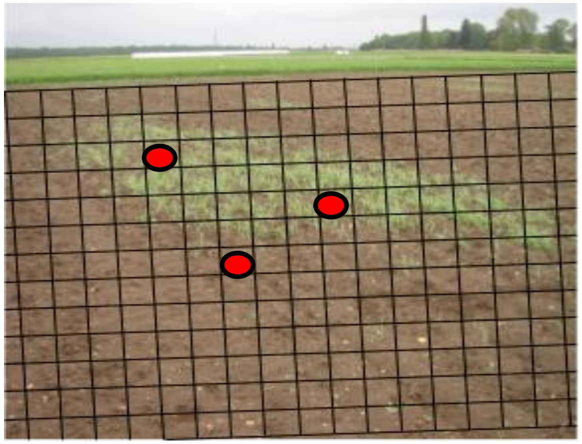
# Three example case studies/models

**Species conservation in food webs**

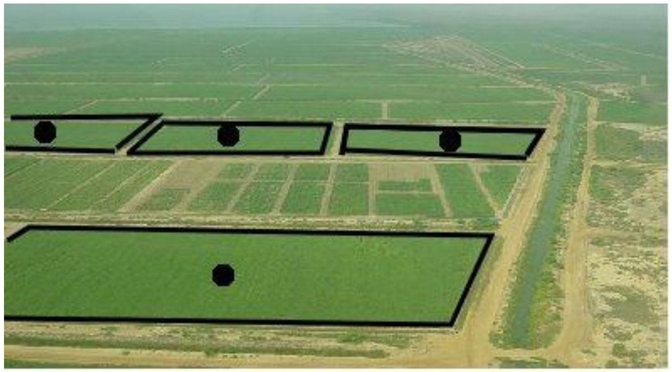



**Conservation?**

**Weeds sampling for map reconstruction**



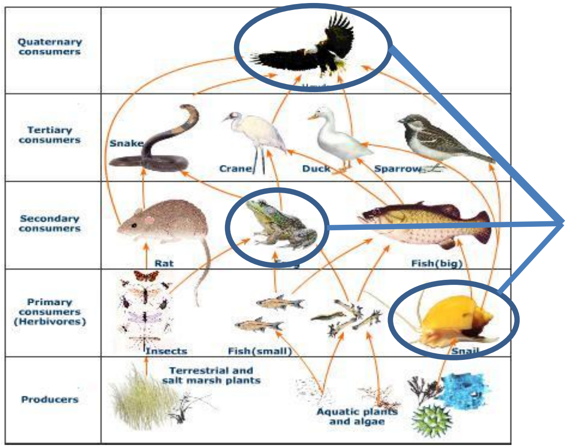
**Crop allocation to maximize ecosystem services**



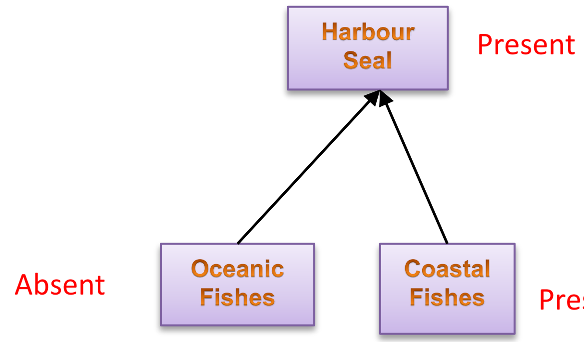
## Modelling/optimisation approaches

- « static node selection » to optimize expectation wrt a Bayesian Network
- « adaptive node observation » to optimize expected MAP in a Markov Random Field
- « policy selection » to maximize expectation wrt a Dynamic Bayesian Network

# Problem I : Conservation of multiple species in food webs




present/absent = 1/0

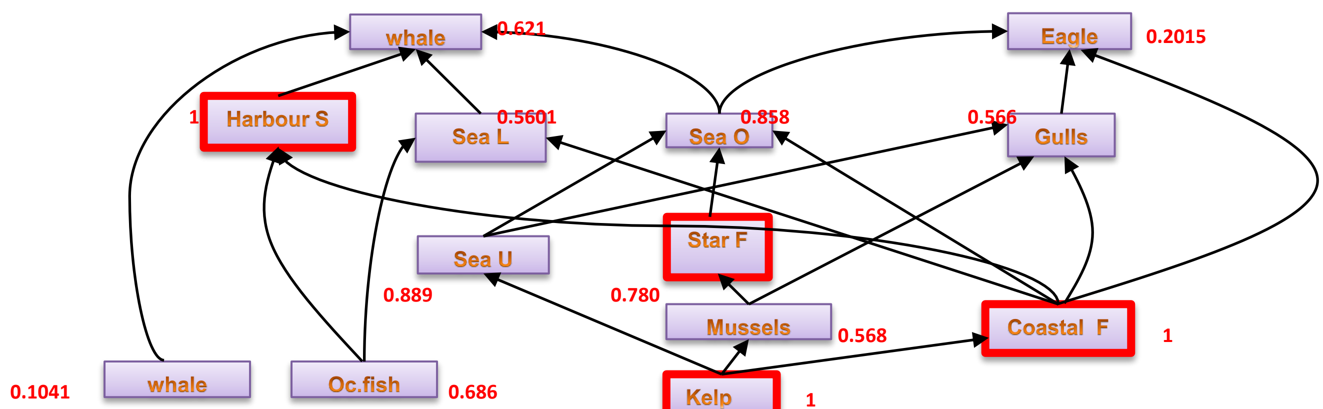



HS = « present/absent » (1/0)

P(HS=1|OF=0, CF=1, Protect)

$P(HS,OF,CF|P_{HS},P_{OF},P_{CF}) = P(HS|OF,CF,P_{HS})\ P(OF|,P_{OF})\ P(CF|,P_{CF})$

***« Which species to protect in a food web to optimize the expected number of present species? »***



# Problem I : Conservation of multiple species in food webs

Model: Bayesian Network = joint probability distribution over species occurrences.

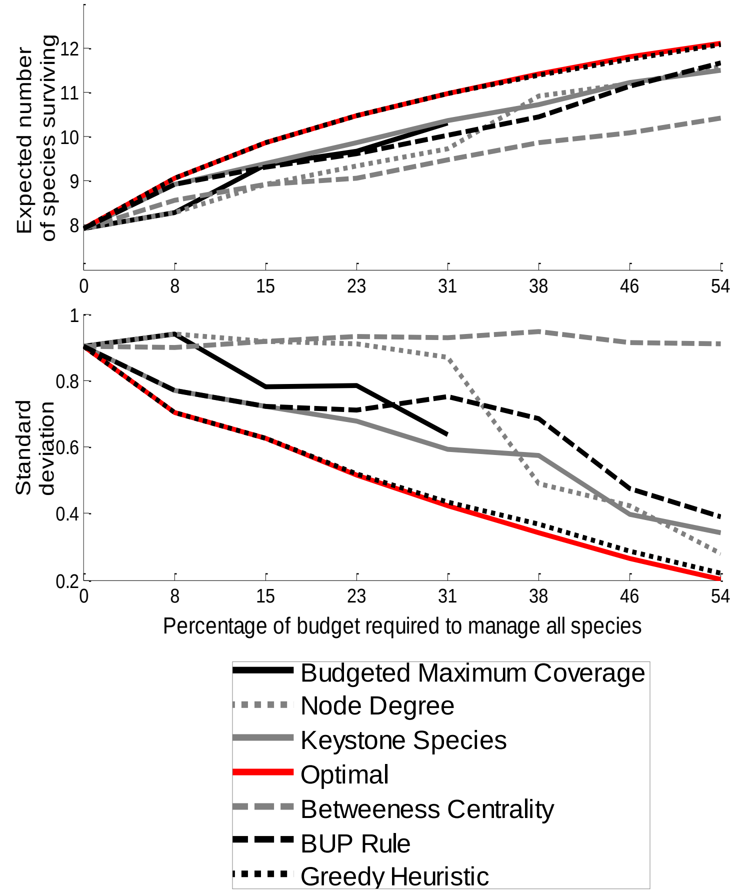
$$P(S_1,\dots,S_n) = \prod_{i=1..n} P_i(S_i \mid Preys(S_i), Pr_i)$$

Optimization problem:

$$\max_{\substack{\Delta \subseteq \{1..n\} \\ Cost(\Delta) \leq B}} \mathbf{E}\left[\sum_{i=1}^{n} S_i \mid \Delta\right]$$

Solution:

- Exact (naïve) for small problems
- Heuristics for large problems

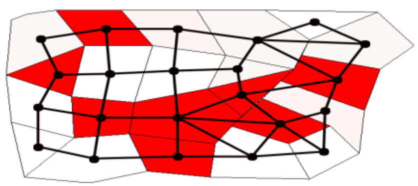



E McDonald-Madden, R Sabbadin, P.W.J. Baxter, I Chadès, E.T. Game and H.P. Possingham. Using food webs to manage ecosystems, Nature Communications (to appear).

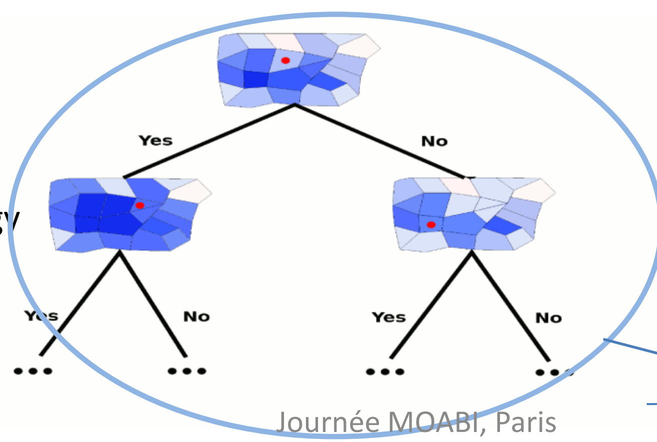
# Problem II: Optimal static/adaptive sampling for weeds map reconstruction


***« Where to sample to optimize the expected quality of the returned map? »***

MRF model



Adaptive strategy

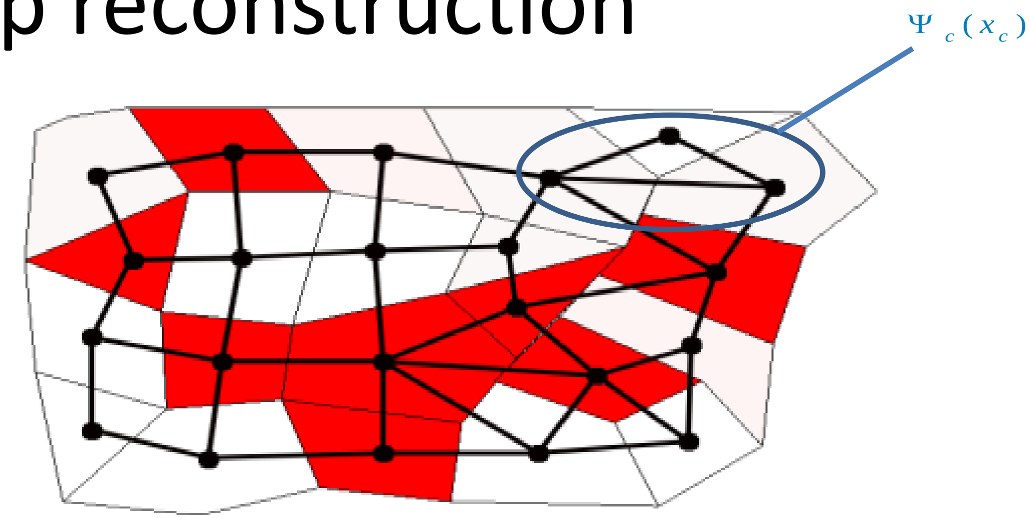



Reconstruction method

Optimization

Estimated weed map

# Problem II: Optimal static/adaptive sampling for weeds map reconstruction



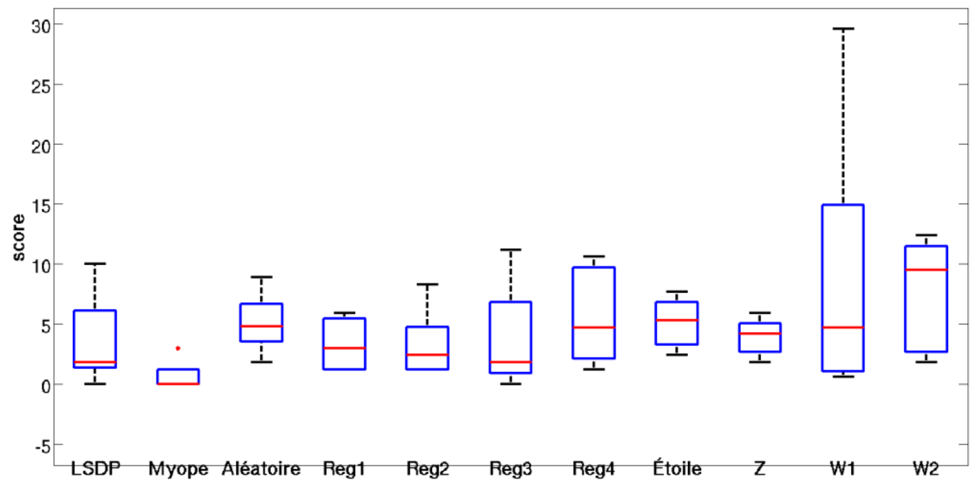

Model: Markov Random Field

$$P(x) \propto \prod_{c \in C} \Psi_c(x_c)$$

Optimization problem (static):

$$\max_{\substack{\Delta \subseteq \{1..n\} \\ Cost(\Delta) \leq B}} \mathrm{E}_{x_\Delta}\left[\sum_{i=1}^{n} \max_{x_i} P(x_i \mid x_\Delta)\right]$$

Solutions:
- Heuristics (static/adaptive)
- Reinforcement learning
- Planning under uncertainty




➢ M. Bonneau, S. Gaba, N. Peyrard and R. Sabbadin. Reinforcement learning-based design of sampling policies under cost constraints in Markov random fields: Application to weed map reconstruction, CSDA, 2014

➢A. Albore, N. Peyrard, R. Sabbadin and F. Teichteil. An Online Replanning Approach for Crop Fields Mapping with Autonomous UAVs, ICAPS, 2015.

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# Problem III: Optimal crop allocation to maximize ecosystem services provision

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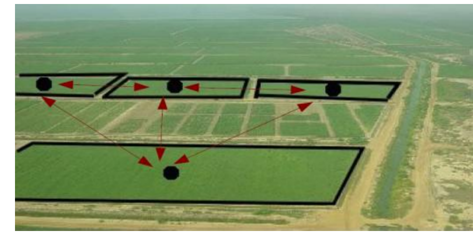
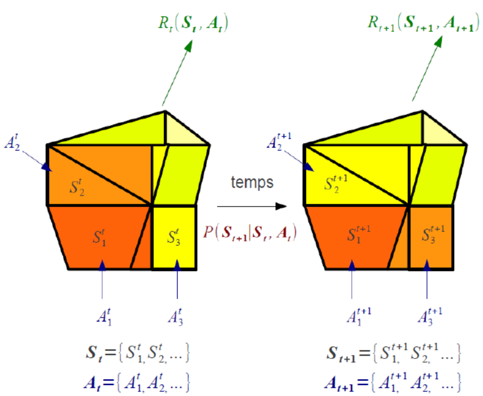
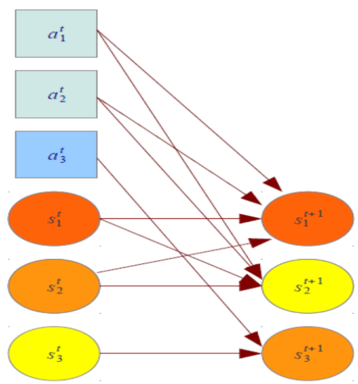





Many state variables and action variables (here one for each plot)




Factored representation : dynamic bayesian network (DBN)

$$P(S^{t+1}|S^t, A^t) = \prod_{i=1}^{n} P(S_i^{t+1}|pa(S_i^{t+1}))$$

Approximate resolution

***« How to allocate crops in space/time to optimize the expected compromize between Ecosystem services through time? »***



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# Problem III: Optimal crop allocation to maximize ecosystem services provision

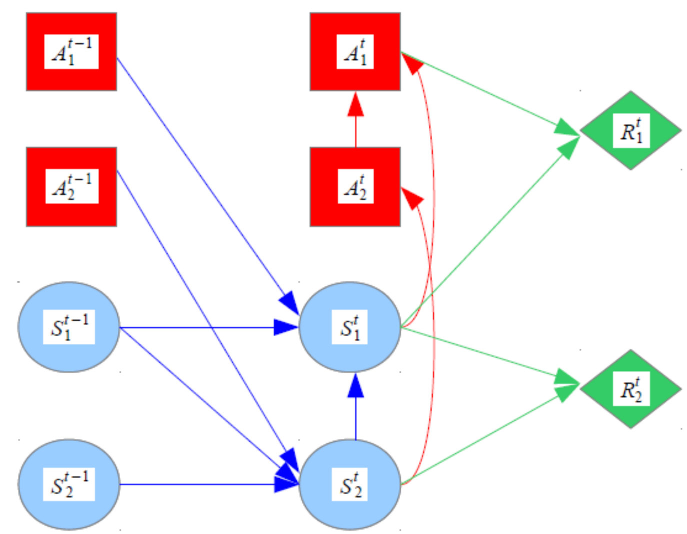
Model: “triply factored Markov Decision process”

- A Dynamic BN (t=0..T): $P(s^{t+1} \mid s^t, a^t) = \prod_{i=1}^{n} P_i(s_i^{t+1} \mid pa_P(s_i^{t+1}))$
- Local instant rewards: $R(s^t, a^t) = \sum_{\alpha=1}^{r} R_\alpha(pa_R(R_\alpha^t))$
- Local stochastic policies: $\delta(a^t \mid s^t) = \prod_{j=1}^{m} \delta_j(a_j^t \mid pa_\delta(a_j^t))$

Policy value and continuous optimization:

$$V_\delta^{R,T}(P^0) = \mathrm{E}_{P_\delta^T}\left[\sum_{t=0}^{T} R(S^t, A^t) \mid P^0, \delta\right]$$

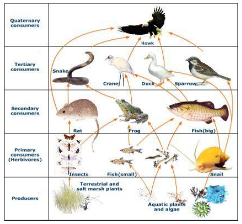
$$\max_\delta V_\delta^{R,T}(P^0)$$



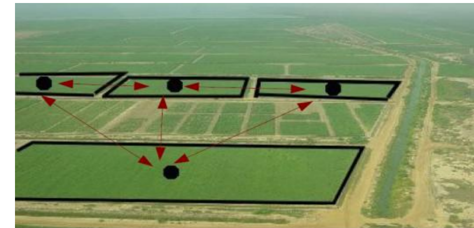

Solution: successive evaluation/improvement of policies

- Approximate evaluation of $\delta^t$ through marginal probs (ex. Loopy BP)
- Improvement of $\delta^t$ through Gradient Descent


J. Radoszycki, N. Peyrard and R. Sabbadin. Solving F3MDPs: Collaborative Multiagent Markov Decision Processes with Factored Transitions, Rewards and Stochastic Policies. PRIMA, 2015.




# General conclusions



- **Managing ecological networks**
  - **Networks can be**: spatial, causal, …
  - **Management can be**: control, conservation, sampling ..
  - **Ecosystems and agricultural systems** : management share similarities
- **Common tools for all these problems**
  - graphical models, simulation, optimization
  - **Computing exactly** the optimal strategy is out of reach (all problems are at least $NP^{PP}$-hard)

Current research focuses on approximate resolution

- **Still some challenges!**
  - Sampling **dynamic processes**
    - How to sample a system where the underlying process changes through time?
  - How to manage processes over an **ill-know network**?
    - Combine network learning and control/conservation actions optimization
  - …

# References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**GMDP, FA-FMDP, applications to agro-ecological processes management**

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- J. Radoszycki, N. Peyrard and R. Sabbadin. Solving F3MDPs: Collaborative Multiagent Markov Decision Processes with Factored Transitions, Rewards and Stochastic Policies. PRIMA, 2015.