INSTITUTO SISTEMAS COMPLEJOS DE INGENIERIA

CENTRE TECNOLÒGIC FORESTAL DE CATALUNYA

TALCA UNIVERSIDAD CHILE

A MIP Approach for Multi-Action Planning for Threat Management

José Salgado
Universidad de Talca, Chile

Jordi Garcia-Gonzalo
CTFC, Spain

Virgilio Hermoso
CTFC, Spain

Andrés Weintraub
Universidad de Chile, Chile

Eduardo Álvarez-Miranda
Universidad de Talca, Chile

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SuForRun

Outline

- **Introduction and Motivation**
  - Conservation Planning Relevance
  - Conservation Planning Tools
  - Existing MIP approaches
- **A MIP Approach for Multi-Action Planning for Threat Management**
  - Multi-Action Planning for Threat Management
  - MIP Model Definition
  - A MIP-based extension
- **Case Study: Mitchell River Catchment**
  - General information
  - Species and threats distribution
- **Computational Results**
  - Cost efficiency and degree of connectivity
  - Comparison with Marxan and Cattarino et al. 2015' results
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- **Conclusions**

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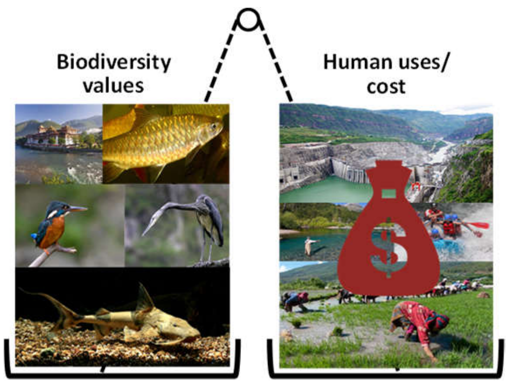
Introduction: Conservation Planning Relevance

The main planning challenge is represented by:



Challenge We need to be capable of reaching a envirotmentally sustainable balance between economic development and biodiversity conservation.

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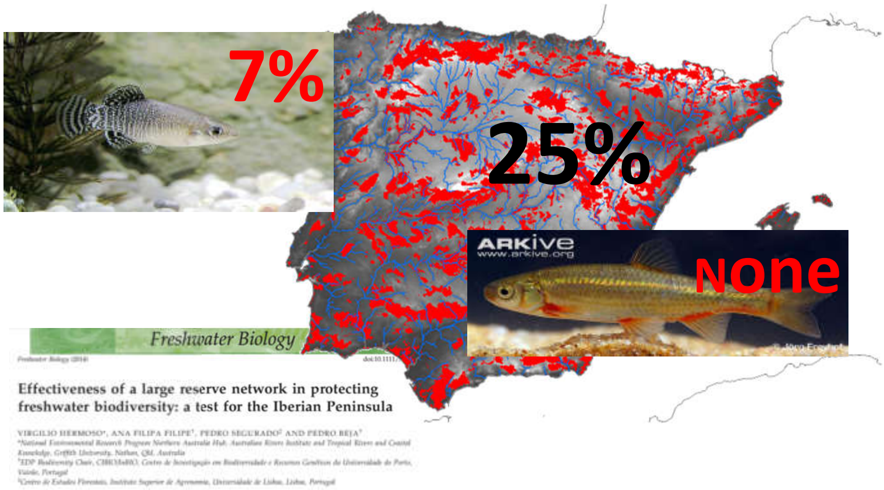
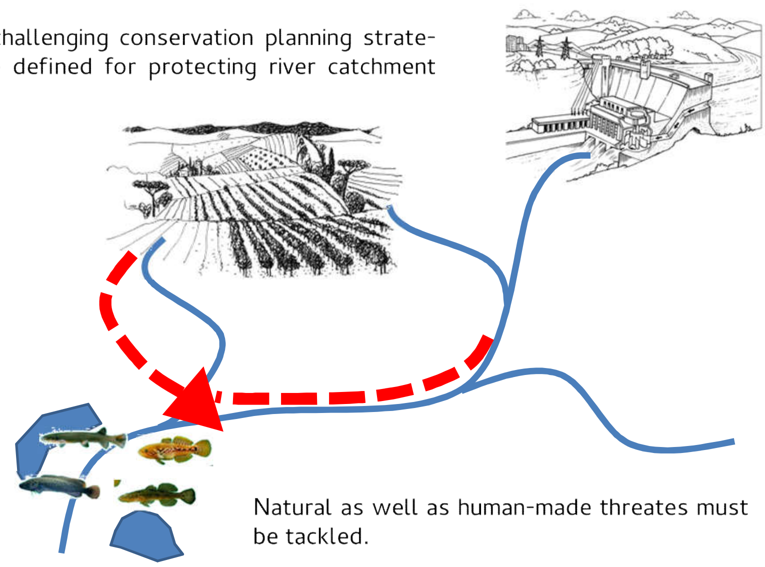
Introduction: Conservation Planning Relevance

But efforts must be properly planned:



Introduction: Conservation Planning Relevance

Particularly challenging conservation planning strategies must be defined for protecting river catchment zones:



Natural as well as human-made threates must be tackled.

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Introduction: Conservation Planning Tools

There are several modeling and algorithmic alternatives; see, e.g., the book of Millspaugh & Thompson 2008, and the review paper Billionnet 2013, EJOR.

Despite of the diversity of planning tools, one of the most widely used tools is **MARXAN** (see Watts et al. 2009, Environmental Modelling & Software)

MARXAN is a (Simulated Annealing) heuristic-based solver that seeks for a subset of units that optimize the function:

$$\sum_{Sites} \text{Cost} + BLM \sum_{Sites} \text{Boundary} + \sum_{ConValue} CFPF \times \text{Penalty} + \text{Cost Threshold Penalty}(t)$$

Cost: measure of the cost, area, or opportunity of the reserve system

BLM (Boundary Length Modifier): importance given to the boundary length relative to the cost of the reserve system

CFPF (Conservation Feature Penalty): penalty given for not adequately representing a conservation feature

Penalty: additional value associated with each underrepresented conservation feature

Cost Threshold Penalty: penalty applied to the objective function if the target cost is exceeded.

The computed reserves are:

- Reduced fragmentation
- Ecologically effective
- Reasonable quality/good trade-off

Introduction: Conservation Planning Tools

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The optimization model solved by MARXAN can be formulated as:

$$\text{minimize} \sum_{i=1}^{m} c_i x_i + b \sum_{i1=1}^{m} \sum_{i2=1}^{m} x_{i1}(1 - x_{i2}) cv_{i1,i2}$$

$$\text{subject to} \sum_{i=1}^{m} a_{ij} x_i \geq t_j \quad \forall j.$$

$x_i = 1$ if unit i is selected, $x_i = 0$ otherwise.
c_i cost for selecting unit i
b boundary penalty
$a_{ij}\{0,1\}$ parameter that models if species j is present in unit i
t_j conservation target for species j
$c_{i_1 i_2}$ distance between units i_1 and i_2

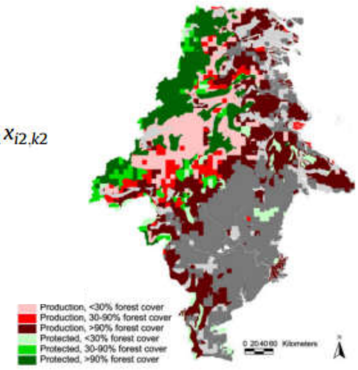
Introduction: Conservation Planning Tools

Although MARXAN is capable of dealing with the most common conservation planning tasks, more complex contexts require planning decisions involving several types of conservation/activity areas.

The alternative for that is **MARXAN with zones**, presented in Watts et al. 2009, Environmental Modelling & Software.

$$\text{minimize} \sum_{i=1}^{m} \sum_{k=1}^{p} c_{ik} x_{ik} + b \sum_{i1=1}^{m} \sum_{i2=1}^{m} \sum_{k1=1}^{p} \sum_{k2=1}^{p} cv_{i1,i2,k1,k2} x_{i1,k1} x_{i2,k2}$$

$$\text{subject to} \sum_{i=1}^{m} \sum_{k=1}^{p} a_{ij} ca_{jk} x_{ij} \geq t1_j \quad \forall j$$



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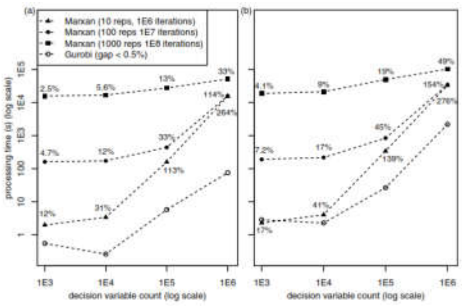
Introduction: Existing MIP Approaches

There are classical mixed integer programming approaches such as **Set Covering Problem** (Garey & Johnson, 1979), **Maximum Covering Problem** (Church & Revelle, 1974)

Current state-of-the-art MIP-based approaches allow to model spatial requirements; see, e.g., Williams et al. 2015, Billionet 2013, Beyer et al. 2016.

In Beyer et al. 2016 it is shown that a MIP-approach was capable of **outperforming** MARXAN: better solutions and much faster.

While MARXAN solves only one type of problem, a MIP-based approach is capable of incorporating additional side constraints.



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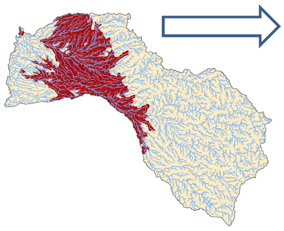
Multi-Action Planning for Threat Management: Preliminaries

The problem we are aiming to solve can be characterized as follows:



In each unit: There is a set of species
There is a set of threads

Besides, we must consider:

- Penalty associated to units fragmentation (β_1)
- Distances among units ($cv_{ii'}$)
- Cost for *buying* each unit (cf_i)
- Cost for treating each threat in each unit (c_{ik})

For formulating the problem:

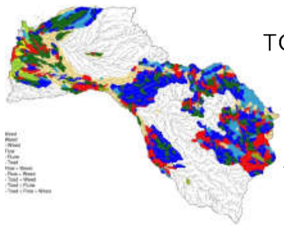
I is the set of all units → $J_i \subseteq J$ the set of species in unit i; $K_i \subseteq K$ the set of threats in unit i

J is the set of all species → $K_j \subseteq K$ the set of threats menacing species j

K is the set of all threats

Multi-Action Planning for Threat Management: Preliminaries

In Cattarino et al. 2015, the authors seek for a set S of units along with a set of actions against threats so that the function:



TC $= \boxed{\mathbf{c}(S)} + \boxed{\mathbf{p}(S)} + \boxed{\mathbf{f}(S)}$ must be **minimized**

buying + treating costs

penalty for insufficient conservation

penalty for units fragmentation

... so that a conservation target t_j is (almost) fulfilled for each species j

In Cattarino et al. 2015 the authors implemented an ad-hoc Simulated Annealing algorithm for solving the problem.

The authors also compared their approach with the solutions obtained using Marxan on a properly modified set of instances.

Outline

Multi-Action Planning for Threat Management: A MIP Model

Similar as done by Beyer et al. 2016, we can find Multi-Action Planning decisions using a MIP formulation.

Consider the following set of variables:

$$w_i = \begin{cases} 1, & \text{if unit } i \text{ is selected as part of the reserve} \\ 0, & \text{otherwise} \end{cases}$$

$$x_{ik} = \begin{cases} 1, & \text{if an action is taken against threat } k \text{ in unit } i \\ 0, & \text{otherwise} \end{cases}$$

Besides, we consider the auxiliary variable:

$$z_{ij} = \begin{cases} 1, & \text{if unit } i \text{ contributes to the habitat conservation for species } j \\ 0, & \text{otherwise} \end{cases}$$

Multi-Action Planning for Threat Management: A MIP Model

The contribution of selecting unit i and applying actions in it, to the conservation of species j is given by:

$$B_{ij} = \left[\frac{\text{\# of treated threats in } i \text{ that affect } j}{\text{Total \# of threats in } i \text{ that affect } j}\right]^3 = \left(\frac{\sum_{k \in K_i \cap K_j} x_{ij}}{|K_i \cap K_j|}\right)^3$$

So the total conservation *effort* to species j of all selected units and all performed actions is given by:

$$TB_j = \sum_{i \in I : |K_i \cap K_j| \neq 0} B_{ij} + \boxed{\sum_{i \in I : |K_i \cap K_j| = 0} z_{ij}}$$

associated to units without threats

Multi-Action Planning for Threat Management: A MIP Model

Hence, the MIP model for Multi-action planning for threat management is given by

action costs buying costs fragmentation costs

$$\min \boxed{\sum_{i \in I} \sum_{k \in K_i} c_{ik} x_{ik}} + \boxed{\sum_{i \in I} cf_i w_i} + \boxed{\beta_1 \sum_{i_1 \in I} \sum_{i_2 \in I : i_1 \neq i_2} cv_{i_1 i_2} w_{i_1} (1 - w_{i_2})}$$

subject to

$$\sum_{i \in I : |K_i \cap K_j| \neq 0} B_{ij} + \sum_{i \in I : |K_i \cap K_j| = 0} z_{ij} \geq t_j, \ \forall j \in J$$

ensures conservation **targets**

$$\sum_{k \in K_i} x_{ik} \leq |K_i| \, w_i, \ \forall i \in I$$

$$\sum_{j \in J_i} z_{ij} \leq |J_i| \, w_i, \ \forall i \in I$$

$$x_{ik}, z_{ij}, w_i \in \{0, 1\}, \ \forall k \in K, i \in I, j \in J$$

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Multi-Action Planning for Threat Management: An extension

In order to improve the functional and ecological performance of the reserve, we are also interested in reducing the fragmentation of the units sharing actions against commont threats:

$$\text{Actions fragmentation cost } = \beta_2 \sum_{k \in K} \sum_{i_1 \in I} \sum_{i_2 \in I : i_1 \neq i_2} cv_{i_1 i_2} x_{i_1 k} (1 - x_{i_2 k})$$

So the objective function becomes:

$$\min \sum_{i \in I} \sum_{k \in K_i} c_{ik} x_{ik} + \sum_{i \in I} cf_i w_i + \boxed{\beta_2 \sum_{k \in K} \sum_{i_1 \in I} \sum_{i_2 \in I : i_1 \neq i_2} cv_{i_1 i_2} x_{i_1 k} (1 - x_{i_2 k})} + \beta_1 \sum_{i_1 \in I} \sum_{i_2 \in I : i_1 \neq i_2} cv_{i_1 i_2} w_{i_1} (1 - w_{i_2})$$

Although this is a small change in the problem definition, the algorithmic strategy developed in Cattarino et al. 2015 **cannot easily address it**, while in our **MIP strategy** this can be done **straighforwardly**.

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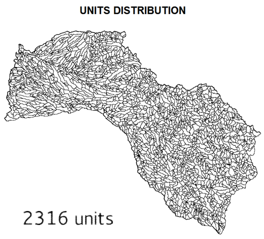
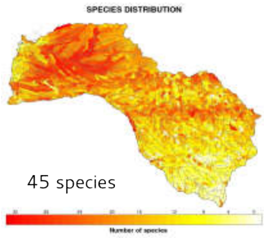
Mitchell River Catchment : General Information

The Mitchell River catchment is located in northen region of Australia

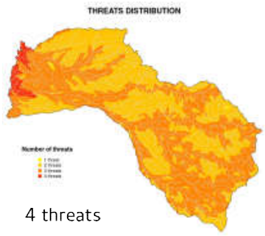


2316 units

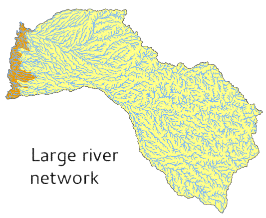


45 species

Total area: 71,630 km^2



4 threats



Large river network

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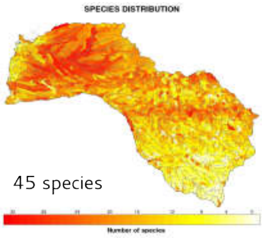
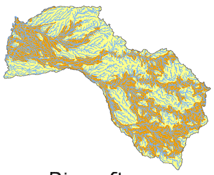
Mitchell River Catchment : Species and threats distribution

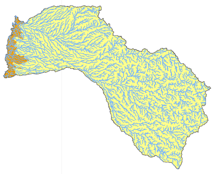


In total we consider 45 freshwater fish species which are unevenly distributed accross the whole catchment

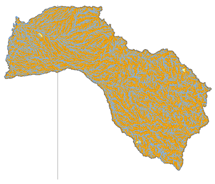
4 major threats to freshwater fish species: water buf-falo, cane toad, river flow alteration, and grazing land use.



River flow alteration.



Water buffalo.



Grazing land use

Cane toad

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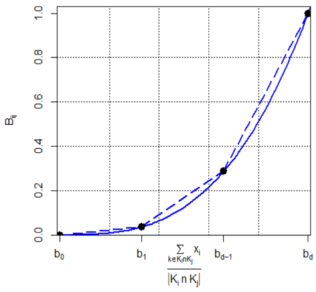
Computational Results

The resulting MIP models are linearized by standard techniques, and the expression B_{ij} is linearized using a piecewise function.

$$\hat{f}(x) = f(b_{m-1}) + \left(\frac{f(b_m) - f(b_{m-1})}{b_m - b_{m-1}}\right)(x - b_{m-1}),$$

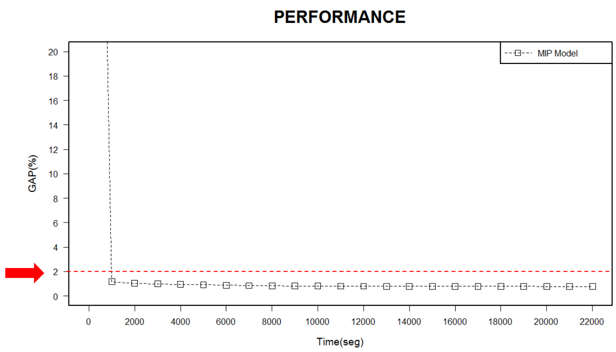
$$x \in [b_{m-1}, b_m], \forall\, m = 1, \dots, d$$



All resulting MIP models where solved using a INTEL i7-5820k 3.3 GHz 12 cores processor with 32 GB RAM machine. The time limit of each run was set to 6 hours (while in Cattarino et al. 2015, the Simulated Annealing was run for 16 hours).

Computational Results

In average, all solutions verified an optimality gap of less than 2%



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Computational Results: Cost efficiency and Connectivity

Given a certain multi-action plan represented by a particular solution $(\mathbf{w}, \mathbf{x}, \mathbf{z})$, the *cost-efficiency* is given by

$$E(\mathbf{w}, \mathbf{x}, \mathbf{z}) = 1 - \frac{C(\mathbf{w}, \mathbf{x}, \mathbf{z})}{C_T} = 1 - \frac{\sum_{i \in I} \sum_{k \in K_i} c_{ik} x_{ik} + \sum_{i \in I} cf_i w_i}{\sum_{i \in I} \sum_{k \in K_i} c_{ki} + \sum_{i \in I} cf_i}$$

Additionally, the *degree of connectivity* of the selected units is calculated by

$$CDU(\mathbf{w}, \mathbf{x}, \mathbf{z}) = 1 - \frac{FU(\mathbf{w}, \mathbf{x}, \mathbf{z})}{FU_{\max}} = 1 - \frac{\sum_{i_1 \in I} \sum_{i_2 \in I : i_1 \neq i_2} cv_{i_1 i_2} w_{i_1} (1 - w_{i_2})}{FU_{\max}}$$

where $FU_{\max}$ is the maximum fragmentation found by any of the used methods (MARXAN, Cattarino et al. 2015, or ours).

Computational Results: Cost efficiency and Connectivity

Likewise, the *degree of connectivity* of an action plan against threat k is given by

$$CDA_k(\mathbf{w},\mathbf{x},\mathbf{z}) = 1 - \frac{FA_k(\mathbf{w},\mathbf{x},\mathbf{z})}{FA_{k,\max}} = 1 - \frac{\sum_{i_1 \in I} \sum_{i_2 \in I : i_1 \neq i_2} cv_{i_1 i_2} x_{i_1 k}(1 - x_{i_2 k})}{FA_{k,\max}}$$

where $FA_{k,\max}$ is the maximum fragmentation of associated to the units where a plan against threat k is applied found by any of the used methods (MARXAN, Cattarino et al. 2015, or ours).

Finally, the *degree of connectivity* of the while action plan is given by

$$CDA(\mathbf{w},\mathbf{x},\mathbf{z}) = \frac{\sum_{k \in K} FA_k(\mathbf{w},\mathbf{x},\mathbf{z})}{|K|}$$

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Computational Results: Comparison with state-of-the-art

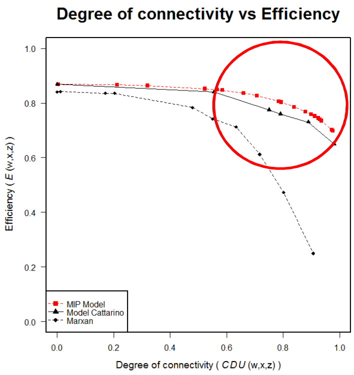
Following Cattarino et al. 2015, we computed solutions for different penalties

$$\beta_1 \in \{0, 0.2, 0.4, 0.6, 0.8, 1, 2, 3, \ldots, 9, 10\},$$

and we plotted the curve $E(\mathbf{w}, \mathbf{x}, \mathbf{z})v/sCDU(\mathbf{w}, \mathbf{x}, \mathbf{z})$

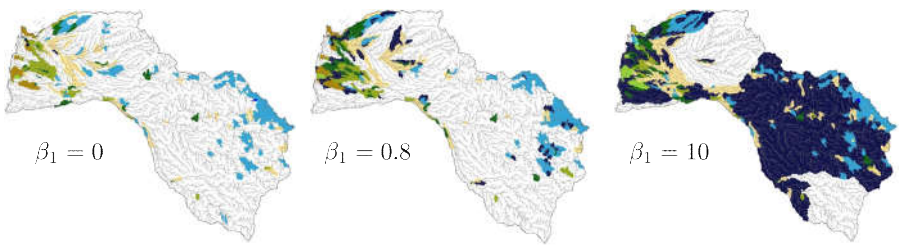
As can be seen in the plot, our approach provides a good efficiency/connectivity trade-off

The MIP approach **outperforms** MARXAN and the approach proposed by Cattarino et al. 2015



Computational Results: Results for different penalties

Spatial impact of having different fragmentation penalty:



Very reasonable solution from an ecological point of view.

Impractical solution

- Bufalo + Flow + Weed
- Bufalo + Toad + Weed
- Bufalo + Toad + FLow
- Bufalo + Toad + Flow + Weed

- Toad + Weed
- Bufalo + Weed
- Toad + Flow
- Bufalo + FLow
- Bufalo + Toad
- Toad + Flow + Weed

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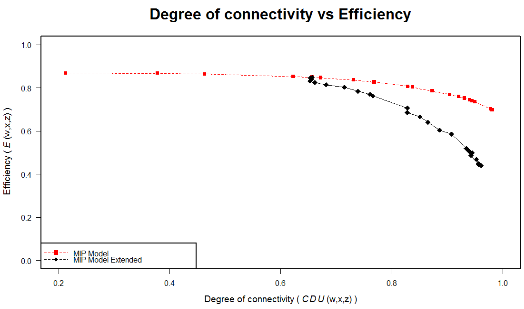
Computational Results: Results of the extended model

For the extended model (penalty to actions fragmentation), we considered penalties

$$\beta_2 \in \{0, 0.2, 0.4, 0.6, 0.8, 1, 2, 3, \ldots, 9, 10\},$$

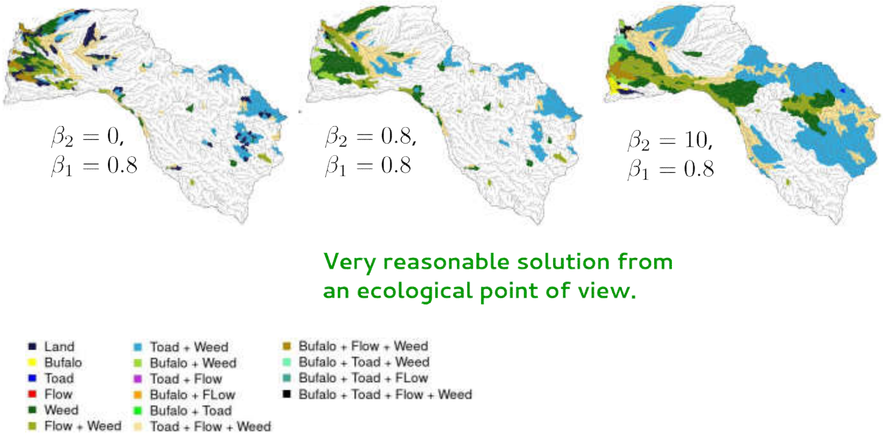
and computed the Efficiency v/s Connectivity plot (fixing $\beta_1 = 0.8$)

Penalizing the fragmentation of spatial distribution of actions yields less efficient solutions



Computational Results: Results of the extended model

Spatial impact of having different fragmentation penalty:



Very reasonable solution from
an ecological point of view.

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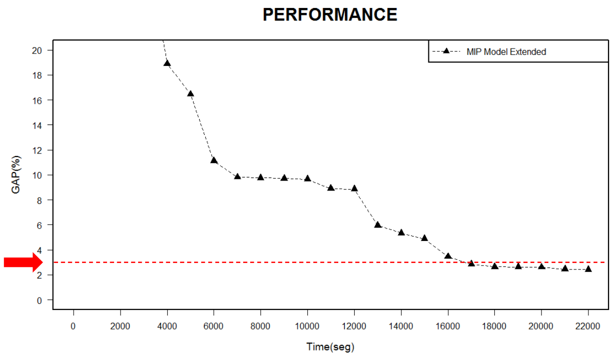
Computational Results: Results of the extended model

In average, all solutions verified an optimality gap of less than 3%



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Outline

- Introduction and Motivation
  - Conservation Planning Relevance
  - Conservation Planning Tools
  - Existing MIP approaches
- A MIP Approach for Multi-Action Planning for Threat Management
  - Multi-Action Planning for Threat Management
  - MIP Model Definition
  - A MIP-based extension
- Case Study: Mitchell River Catchment
  - General information
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- Computational Results
  - Cost efficiency and degree of connectivity
  - Comparison with Marxan and Cattarino et al. 2015' results
  - Results of the extended model
- **Conclusions**

Conclusions

A relevant conservation planning problem was addressed.

A Mixed Integer Programming formulation was used to model the corresponding conservation problem.

The obtained solutions outperform those obtained by Cattarino et al. 2016

The extended model allows to compute more effective solutions from a functional point of view

From computational point of view, the proposed approach seems to be more effective than heuristic strategies.

Thank you!!!

Questions??