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Uncertainty in reserve site selection : provide a robust solution through risk-averse optimisation

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Abstract

Marine environment is nowadays frequently seen as tomorrow's «blue growth» areas . Yet these spaces are already being at the heart of multiple anthropogenic pressures (fishing, aquaculture, shipping routes, recreational activities, renewable energies, etc.). Marine Spatial Planning (MSP) positions itself as a rational decision-making process regulating use of marine spaces and resources in order to reduce tensions between exploitation and ecosystems. Besides, conservation institutions identified Marine Protected Areas (MPAs) as an essential part of the solution to ensure biodiversity resilience and eventually ecosystem services provision. Indeed, conservation dedicated area are proved to provide biotic communities global benefits [1]. Therefore, in the continuation of United Nations (UN) 10% target for global ocean protection of the coastal and marine areas in MPAs by 2020, International Union for Conservation of Nature (IUCN) members (governments, non-governmental organisations, agencies) agreed on an even more ambitious protection target of 30% for each marine eco-region by 2030 against less than 8% today [1]. That is why systematic conservation-based approach such as reserve selection Decision Support Tools (DSTs) (*e.g.* Marxan) knew a strong appeal among decision makers.

Indeed, to avoid ad-hoc and opaque conservation choices, systematic reserve selection procedure quickly became a worldwide research and operational stake. Although early attempts were based on simple ranking approach of areas based on a computed conservation value [2], reserve site selection problem is now assessed as an optimisation problem involving an integer programming framework [3]. Practically, conservation-based planning tools aim at finding where to locate areas dedicated to conservation, *i.e.* nature reserve, which can be intended as a resource allocation optimisation problem. The purpose is to find the resource layout which minimize a given objective subject to a set of constraints. Mathematically, it can be modeled as deterministic binary programming problem thanks to a minimum set formulation as a reserve is mathematically represented with a vector $x \in \{0,1\}^N$ (row value is worth 1 if the planning unit is included within the reserve, 0 otherwise). Each planning unit is associated with a socio-economic cost $c \in \mathbb{R}^N$ but also the abundance of each considered conservation feature $A \in \mathbb{R}^{P\times N}$.

$$\begin{cases} \min\limits_{x} & \sum\limits_{j\in J} c_j x_j \\ \text{s.t.} & \sum\limits_{j\in J} a_{ij} x_j \geq t_i \quad \forall i \in I \\ & x_j \in \{0,1\} \qquad \forall j \in J \end{cases} \tag{1}$$

1. https://www.protectedplanet.net/marine

Uncertainty within marine spatial planning was identified as an important research gap [4] as it can lead to inefficient protected areas and irreversible damages towards ecosystems. First major methodological advance a priori incorporating uncertainty into reserve selection associated conservation feature presence within a planning unit with a given probability [5, 6]. Thanks to this simple presence/absence probability distribution, the global probability of presence of a conservation feature within the reserve solution can be explicitly computed. It eventually results in a chance constraint optimisation framework.

However, these developments are based on probabilistic input data which cannot always be available or lead to analytic probability computation. For instance, in our case, measured abundance is considered instead of presence/absence data. Thus, we here consider a non-probabilistic uncertainty towards abundance parameters : a_{ij} takes values within a given uncertainty set. Consequently, we naturally propose a robust optimisation framework to deal with such parametric uncertainty. Note our work deals with epistemic uncertainty whether it is variability (natural source such as climate change) or incertitude (model or measure imprecision). In other words, we aim at finding the best feasible solution whatever the uncertainty realization within each parameter uncertain set. But, in order to avoid the too preservative worst-case solution, we introduce a budgeted uncertainty set [7]. For each conservation feature i, the parameter Γ_i represents the number of a_{ij} authorized to deviate within associated uncertainty set. Then, using a classical dualization approach of the robust constraints, we obtain the following deterministic model for the robust problem :

$$\begin{cases} \min\limits_{x,u,v} & \sum\limits_{j \in J} c_j x_j & \\ \text{s.t.} & \sum\limits_{j \in J} \bar{a}_{ij} x_j - (\Gamma_i v_i + \sum\limits_{j \in J} u_{ij}) \geq t_i & \forall i \in I \\ & v_i + u_{ij} \geq x_j \sigma_{ij} & \forall i \in I, \forall j \in J \\ & x_j \in \{0,1\} & \forall j \in J \\ & u_{ij} \in \mathbb{R}_+ & \forall i \in I, \forall j \in J \\ & v_i \in \mathbb{R}_+ & \forall i \in I \end{cases} \quad (2)$$

Such model gives a simple and efficient procedure to incorporate parametric uncertainty in the reserve site selection problem without probabilistic input data. However, this mixed-integer linear programming model (2), although still deterministic, has a greater size with respect to the initial problem (1). Finally, a sensitivity analysis towards Γ_i provides an efficient and low effort approach to illustrate reserve solution robustness level from nominal solution to worst-case scenario. Our robust modeling of the reserve site selection problem is illustrated through Fernando de Noronha archipelago application case.

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