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Risk-averse optimisation for the marine reserve site selection : chance constraint by sampling approximation approach

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Abstract

In response to marine habitats destruction and living population depletion, marine spatial planning (MSP) proposes to regulate uses of the marine environment. Practically, MSP seeks an ocean zoning to meet both ecological and socio-economic objectives eventually aiming at a sustainable development. In particular, an identified conservation answer to mitigate marine biodiversity erosion consists in the development of a comprehensive network of marine protected areas (MPAs) accompanied with global benefits [1]. The International Union for Conservation of Nature (IUCN) established a 30% protection target of each marine eco-regions by 2030 reaffirming United Nations (UN) commitment of Aichi Target 11. Similarly and more recently, the European Green Deal aims to protect 30% of European seas. Consequently, conservation science and especially reserve design knows a strong appeal among decision-makers and institutions. Systematic reserve site selection procedures and associated decision support tools (DSTs) are thus a strategic issue.

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 algorithms aim at finding the area which covers sufficient amount of biodiversity features with minimum impact on considered human activities.

Mathematically, it can be understood as a resource allocation optimisation problem and modeled as a binary programming problem thanks to a minimum set formulation as in P_0. The study area is divided into a set of J planning units within which a set of I conservation features are considered. The amount of conservation feature i in planning unit j is denoted a_{ij}. Each planning unit has a cost c_j. In the reserve site selection problem, we seek to find the collection of planning units covering sufficient levels of considered features at minimum cost. The covering of conservation feature i is sufficient if it exceeds the user-defined level t_i. The decision bears on whether or not to include the planning unit in the reserve. Thus, $x_j = 1$ if a planning unit j is selected in the reserve and $x_j = 0$ otherwise.

$$P_0 : \begin{cases} \min_x & \sum_{j \in J} c_j x_j \\ \text{s.t.} & \sum_{j \in J} a_{ij} x_j \geq t_i \quad \forall i \in I \\ & x_j \in \{0,1\} \qquad \forall j \in J \end{cases}$$

Conservation science research field extensively studied the deterministic reserve site selection problem. Yet, data uncertainty can lead to deprecated reserve solutions and potential irreversible damages towards marine ecosystems, and/or useless constraints on marine stakeholders. Nevertheless, most widely used DSTs (*e.g.* Marxan, Prioritizr) generally do not allow to explicitly account for uncertainties although being an identified research gap. Although a probabilistic approach was successfully proposed based on presence/absence data [4, 5], this hypothesis is too restrictive and we would like to account for uncertainty when abundance data is available. Therefore, we propose a risk-averse approach in P_α to incorporate the parametric uncertainty expressed through a chance constraint and the associated risk-level parameter :

$$P_\alpha : \begin{cases} \min\limits_{x} & \sum\limits_{j \in J} c_j x_j \\ \text{s.t.} & \mathbb{P}[\sum\limits_{j \in J} a_{ij}(\omega) x_j \geq t_i] \geq \alpha & \forall i \in I \\ & x_j \in \{0,1\} & \forall j \in J \end{cases}$$

Although abundance data cannot lead to analytic probability computation similarly as with presence/absence data, we propose to approach this chance constraint framework using a sampling approximation. Indeed, we benefit from geostatistics theory and especially conditional simulations to generate a user-defined number of scenarios $s \in S$ with an occurring probability of p^s. In addition, we introduce z^s the variable equal to 1 if the set I of constraints are simultaneously satisfied for scenario $s \in S$ and 0 otherwise. Using a big-M technique we can eventually express the problem approximation P_{sa} as :

$$P_{sa} : \begin{cases} \min\limits_{x,z} & \sum\limits_{j \in J} c_j x_j \\ \text{s.t.} & \sum\limits_{j \in J} a_{ij}^s x_j - t_i \geq M(z^s - 1) & \forall i \in I, \forall s \in S \\ & \sum\limits_{s \in S} z^s p^s \geq \alpha \\ & x_j \in \{0,1\} & \forall j \in J \\ & z^s \in \{0,1\} & \forall s \in S \end{cases}$$

Such model gives a simple and efficient procedure to incorporate parametric uncertainty in the reserve site selection problem with probabilistic abundance data. However, this integer linear programming model P_{sa}, although still deterministic, has a size proportional to the number of scenarios considered. An important size can involve computational difficulties thus preventing us from arbitrarily increase the number of scenarios to improve the approximation. Finally, a sensitivity analysis towards the risk-level parameter α provides great insights with respect to the robustness of the reserve solution. It gives a simple way to properly account and represent parametric uncertainty in the reserve site selection problem. Numerical application is illustrated on the real case of Fernando de Noronha Brazilian archipelago in Tropical Atlantic.

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