Chapter 15. Strengths and weaknesses of decision support tools

A didactic example on the archipelago of Fernando de Noronha

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Introduction

1 Marine environments are now often considered as the territories of tomorrow for "blue growth" (EUROPEAN COMMISSION, 2014, 2017; WWF, 2018). However, these spaces are already subject to multiple anthropogenic pressures (fishing, aquaculture, maritime routes, seabed exploitation, recreational activities, renewable energies, etc.). In this context, marine spatial planning (MSP) is positioned as a collective and rational decision-making process that aims to regulate the use of marine spaces and resources in order to reduce tensions between uses and conservation and between ocean stakeholders. MSP has spread widely, becoming the governance paradigm favoured by management institutions in search of sustainable development. MSP involves collective mobilisation, as its process is based on transversal, spatially explicit information (ecological, legal, social, economic, etc.). In this data analysis-based framework, decision support tools (DSTs) have proven to be indispensable for rationally informing the decision-making process. DSTs take the form of spatially explicit tools, involving interactive software with maps, models, communication modules and additional elements that can help solve multifaceted problems that are too complex to be solved by human intuition or conventional approaches alone (Box 1).

2 While the number and types of DSTs have continued to grow, those that focus on systematic conservation planning and selection of sites for nature reserves (e.g. Zonation, Marxan, prioritizR) have gained particular popularity. The United Nations (Aichi Target 11 in the Convention on Biological Diversity, Sustainable Development Goal 14) encourages the coverage of 10% of coastal and marine areas by marine protected areas (MPAs) by 2020. More recently, the International Union for

Conservation of Nature (IUCN, 2014 and 2016) has set an ambitious target of 30% protection for each marine ecoregion by 2030, up from less than 8% today. Therefore, systematic site selection tools are needed to delineate, with as little opacity as possible (PRESSEY, 1994; PRESSEY and TULLY, 1994), areas dedicated to conservation. DSTs for nature reserve design have rapidly become central to conservation research and have been used globally, particularly to address MSP challenges.

3 Early attempts to design nature reserves were based on intuitive rules: estimating a conservation value associated with a given area (HELLIWELL, 1967; TUBBS and BLACKWOOD, 1971; GOLDSMITH, 1975; WRIGHT, 1977), then classifying areas according to their values (TANS, 1974; GEHLBACH, 1975; RABE and SAVAGE, 1979), and finally enriching the process with iterative classification approaches to overcome the lack of complementarity between reserves (KIRKPATRICK, 1983; MARGULES *et al.*, 1988; PRESSEY and NICHOLLS, 1989). However, since COCKS and BAIRD (1989), the problem of conservation site selection has been mathematically understood, in a consensual manner, as a constrained optimisation problem. This mathematical framing of the problem has the advantage of bringing back to the forefront the need to preserve anthropic uses as much as possible, while protecting the biodiversity of natural areas. However, it involves more complex numerical procedures, such as the integer programming framework (POSSINGHAM *et al.*, 1993, 2000; MARGULES and PRESSEY, 2000; POSSINGHAM *et al.*, 2006), or more recently, exact optimisation solvers (CHURCH *et al.*, 1996; BEYER *et al.*, 2016). The increasing complexity of these procedures carries the risk of depriving some stakeholders of a critical view of the space and rights allocation process.

4 In this context, the objectives of this chapter are (1) to make the mathematical functioning of commonly used DSTs more accessible to users through graphical illustrations of a simplified case study and (2) to raise awareness of conservation site selection DSTs by deciphering the effects that data (or lack of data) and parameterisation options can have on the results. To do this, we consider a small-scale and deliberately simplified didactic example: the Fernando de Noronha archipelago in the tropical Atlantic, northeast of Brazil.

Box 1. Decision-making tools: the challenges and importance of regulation
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According to the joint "roadmap" published by the European Union and the Intergovernmental Oceanographic Commission of UNESCO, DSTs are technical means enabling the decision-maker to envisage MSP that takes into account all possible scenarios. This refers to the set of technical tools and systems that inform and facilitate decision-making in the planning process (TROUILLET, 2008). DSTs operate using algorithms, characterised by "the input of a mass of initial data [which is processed by mathematical formulae], to arrive at results by correlation" (BARRAUD, 2018). These computer programmes serve to formalise policy objectives through mathematical operations on the basis of scientific data.
A guide published in 2011 by the Center for Ocean Solutions (COS) lists the main DSTs used in MSP. The four functions of DSTs according to this guide are (1) combining data of various kinds (ecological, economic and social), (2) transparent assessment of different management scenarios, (3) stakeholder participation and (4) assessment of progress towards management objectives. The document

recognises that not all the selected tools perform equally well. Furthermore, depending on their function, DSTs can be used at different stages of the planning process (STELZENMUELLER *et al.,* 2013). They can be useful during the phase of defining objectives and analysing existing conditions, which consists of collecting scientific data, carrying out a baseline survey, mapping uses, identifying conflicts and compatibilities. They can also be used during the phase of analysing future conditions, which consists of establishing trends according to needs and different possible scenarios.

It is up to the public authority to determine the solution deemed most effective to achieve the planning objectives based on the expertise offered by the tool. The result is that MSP DSTs are developing within a rationale of performance, but in a poorly regulated context. Apart from the regulation of data, there are no standards or norms that make it possible to control the way in which this data is processed, the practices of professionals or the results of the tools. This opacity represents a risk that a public authority will use DSTs to provide the illusion of the consideration of environmental issues in public processes. To overcome these shortcomings, upstream regulation is essential. This would make it possible to define good practices that could potentially be accompanied by official certification (PAVEL and SERRIS, 2018); it would also make it possible to establish the different frameworks of responsibility of operators and practitioners. This would provide legal certainty both for the public authority and for users and professionals. In the absence of such measures, one of the legal bulwarks is to carry out both a priori and a posteriori controls on the basis of existing instruments of environmental law.

While the use of DSTs plays an essential role in the formulation of public policies, this does not imply transferring the responsibility for environmental decision-making to DST operators. The public authority remains the sole guarantor of administrative decisions, even if its actions are counterbalanced by the role of scientific expertise in decision-making (GONOD and FRYDMAN, 2014).

For more information

BARRAUD B., 2018

Les algorithmes au cœur du droit et de l'État postmoderne. *Revue internationale de droit des données et du numérique*, 4: 37-52.

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Decision guide: selecting decision support tools for marine spatial planning. Stanford, The Woods Institute for the Environment, Stanford University, 56 p.

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Le juge administratif et l'expertise. *Actualité juridique de droit administratif* (*AJDA*), 1361.

PAVEL I., SERRIS J., 2018

Faut-il réguler les algorithmes? *THIRD Digital*, 1: 42-45.

STELZENMUELLER V., LEE J., SOUTH A., FODEN J., ROGERS S. I., 2013
Practical tools to support marine spatial planning: a review and some prototype tools. *Marine Policy*, 38: 214-227. https://doi.org/10.1016/j.marpol.2012.05.038

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Les dynamiques du contentieux climatique. Usages et mobilisations du droit pour la cause climatique. Final research report, Paris, Law and Justice Research Mission, CNRS, Climalex, Institut des Sciences Juridiques et Philosophique de la Sorbonne, 244 p.

TROUILLET B., 2008
Les pêches dans la planification spatiale marine au crible des géotechnologies: perspectives critiques sur le 'spatial' et l'environnement. Accreditation to Direct Research (HDR), University of Nantes, 31 p.

Materials and methods

5 The methodology used was based on Marxan and prioritizR, two (free and open source) optimisation-based DSTs developed for conservation site selection purposes. The data processing scripts were written in the R language for reasons of sharing and simplicity[1]. Acoustic, bathymetric and fisheries data were used. These data were collected at a workshop of the "Planning in a liquid world with tropical stakes" (Paddle) project in November 2019 in Recife, Brazil. The data collection was carried out in situ during different scientific campaigns carried out in recent years.

Tools for the systematic selection of conservation sites

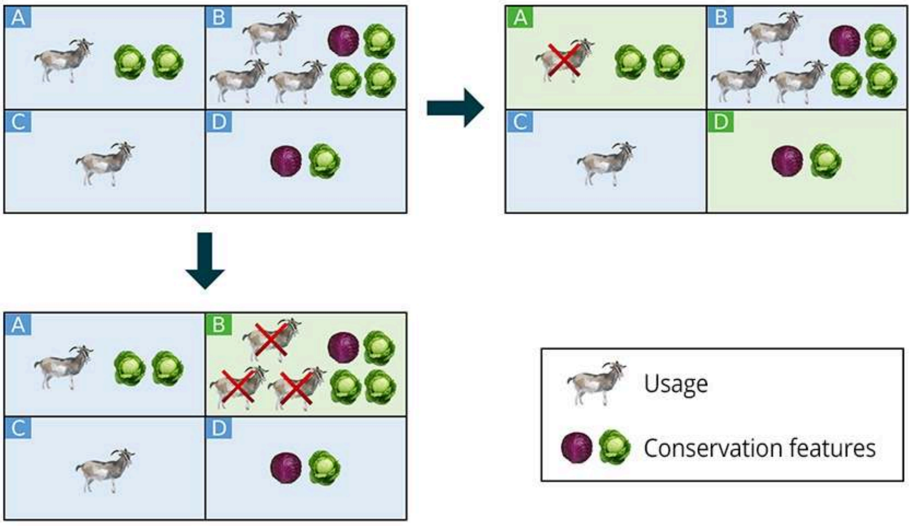
6 Protected areas are commonly considered an essential contribution to conservation efforts to ensure the sustainability of biodiversity. In this context, DSTs have been proposed to systematically determine which sites should be included in a nature reserve or an MPA. DSTs can help planners find the best trade-off between human activities and conservation objectives such as ecosystem health. Two main formulations of the problem have been proposed: maximising a nature reserve's coverage of conservation features[2] under an a priori budget constraint (maximum coverage problem) or minimising the cost of the reserve (cost being understood as a limitation on human activities) while ensuring the coverage of conservation features at a minimum level established a priori (minimum set problem). Here, we focus more on the latter, as this is dominant in the scientific literature and is addressed by Marxan and prioritizR.

Optimisation for maths dummies

7 We present here an illustration of an optimisation problem that is a relevant example of the spatially explicit problems solved by conservation site selection algorithms, such as those implemented in Marxan and prioritizR. Imagine that green and red cabbages are growing in goat pens. Naturally, if the goats are free to access their usual pens, they will eat all the cabbages. We need to establish a conservation plan to protect a predefined, ecologically relevant amount of cabbage. To do this, we need to determine which pens should be closed in order to protect enough cabbage while affecting as few

goats as possible. The data used in the problem is "spatially explicit", because we can count and locate the goats and cabbages. In practice, imagine four pens (labelled A, B, C, D) with goats and cabbages distributed as shown in figure 1, and a conservation target of at least three green and one red cabbage. Consequently, it seems better to close pens A and D rather than just B, as both meet the cabbage targets (three green, one red), but only one goat is affected instead of three. Pen C is not worth protecting, as it contains no cabbages and one goat uses it. In other words, systematic selection tools for conservation sites attempt to ensure the conservation of a given number of features (here, cabbages) while limiting the loss of benefits associated with a given use (here, goats).

Figure 1. Example of an optimisation problem solved by systematic selection of a conservation site



The blue background means that the pen is open and the green background that it is closed (i.e. it is part of the reserve). From the initial situation (top left), which access to the pens should be prohibited in order to protect three green and one red cabbage while minimising the impact on the goats? If pen B is locked (bottom left), the conservation objective is achieved and three goats are affected, whereas if pens A and D are locked (top right), only one goat is affected and the objective is still achieved.
Source: A. Brunel, S. Lanco Bertrand

Underlying mathematics

8 Since conservation site selection problems are expressed in an optimisation framework, the field of conservation science largely overlaps with the scientific fields of decision theory and operations research. The Marxan and prioritizR software packages are "simply" optimisation solvers, more or less encapsulated in user-friendly features. Here, we give a general overview of optimisation in order to understand what exactly conservation site selection tools do. An example of a minimum set problem is also provided to allow a better understanding of the optimisation problem.

Overview

An optimisation problem can always be expressed by an objective function $f : \mathbb{R}^n \rightarrow \mathbb{R}$ and p inequality constraint functions

$c_i : \mathbb{R}^n \to \mathbb{R} c_i : R^n \to R$ .The inherent question is to derive,under the existence hypothesis,the decision variable $\mathrm{x} \in \mathbb{R}^n$ that minimises the objective function f while respecting all constraints c_i, with a negative value. Mathematically, this can be expressed as follows:

$$\begin{cases} \min\limits_{\mathrm{x} \in \mathbb{R}^n} f(x) \\ i \in [\![1, \mathrm{p}]\!], c_i(\mathrm{x}) \leq 0 \end{cases} \quad (1)$$

9 Optimisation problems are often divided into classes according to their nature. The most common is "continuous programming", which contains the subclasses "convex programming" and "linear programming", and in which the existence theorems and solution methods are well known and widely tested. However, our conservation site selection problem belongs to an intrinsically different class of optimisation, namely "integer programming", and more specifically, the sub-class of "binary non-linear programming". Indeed, our decision variable reflects a binary choice of whether to include a specific bounded area in the nature reserve. Therefore, $x \in \mathrm{D} = \{0,1\}^N$ where N is the number of units resulting from the division of the study area. Naively, one might think that this problem is simpler than the continuous programming problem because we "only" have to calculate all possibilities for the elements x, which is a finite number (equal to $|\mathrm{D}| = 2^N$),and take the smallest value from $f(D)$ (such a task is obviously impossible with a continuous decision variable).However, a finite set does not necessarily mean that today's computers can explore it in a reasonable time. For N>266 the number of evaluations of f is larger than the number of atoms in the universe ($\sim 10^{80}$).For example, in the very simple didactic case study we are considering, N=756, which corresponds to more than 10^{227} possibilities for x. Furthermore, solving the associated relaxed problem (i.e. allowing x to explore the smallest continuous set comprising D) and rounding the computed solution does not theoretically or practically guarantee finding a relevant solution. Unlike in continuous programming, the derivative of f, although it is the basis of most, if not all, continuous optimisation solvers, is meaningless.

Application to conservation site selection

10 In short, conservation site selection tools simply provide a method of solving the optimisation for binary programming. Why do we need a binary approach to frame the problem? First, the study area is divided into planning units (PUs), i.e. pixels of the grid used to discretise the study area. Each PU is associated with a socio-economic cost[3], but also with the quantity of each conservation feature (CF) considered. Keep in mind that the data is spatially explicit, i.e. quantitatively located in space, which makes it possible to associate a cost and a number of CFs (quantity such as biomass or abundance) to each PU (location by latitude and longitude). Secondly, overall conservation objectives, defined on the basis of available ecological knowledge (e.g. minimum population size to be viable, important connectivity patterns, etc.) are specified, representing the minimum total number of each CF that should be included in the final protected area.

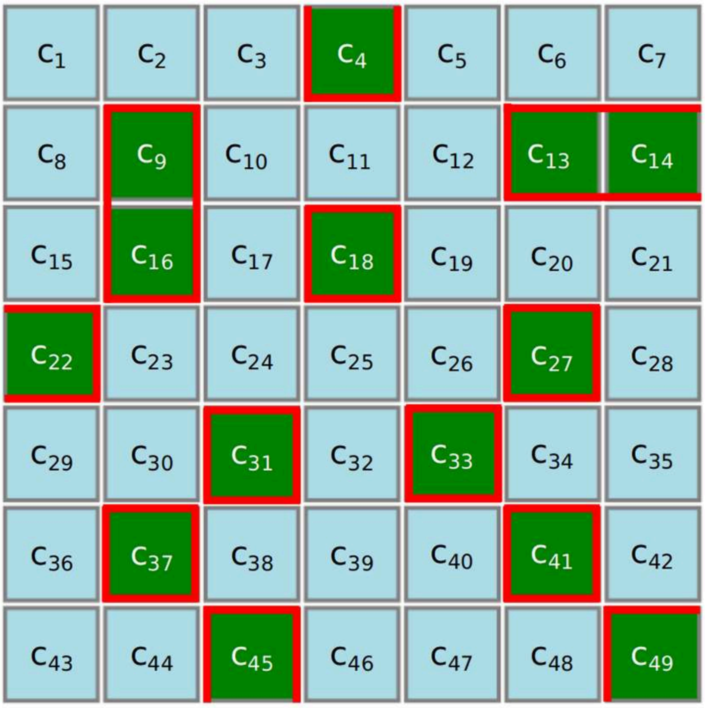
The objective of systematic site selection (in the minimum set problem) is to find which conservation area, represented by a list of PUs, achieves the predefined conservation objectives at minimum socio-economic cost. The decision is therefore about the activation (0 or 1) of a PU representing the inclusion of a site in the nature reserve. In a mathematical optimisation formula (see equation 1), the problem solved by the DST can be expressed as follows:

$$\begin{cases} \min_{x \in \{0,1\}^n} Cost(x) + BLM \times BoundaryLength(x) \\ i \in [\![1, p]\!], TargetedCF_i - ReservedCF_i(x) \leq 0 \end{cases} \quad (2)$$

11 A conservation site is mathematically represented by a vector $x \in \{0,1\}^N$ (the value of the row is 1 if the corresponding PU is selected,0 otherwise).The cost function *Cost* depends on the conservation site and gives the total cost of the selected PUs, i.e. the sum of the costs of all PUs selected as belonging to the protected area. The function $ReservedCF_i$ depends on the conservation site and gives the total amount of the i^{th} conservation feature in the protected area. The constant $TargetedCF_i$ is the user-defined target level of the i^{th} conservation feature. The function *BoundaryLength* depends on the conservation site and simply indicates its boundary. BLM (*boundary length modifier*) is a weight associated with the perimeter of the protected area leading to a greater or lesser penalty in the objective function and allows for a possible increase in the compactness of the site according to the stakeholders' point of view. The detail of the calculation of the value of the objective function is illustrated by a didactic example in figure 2.

12 Historically, debates about the geometry and general shape of protected areas originated in the scientific field of island biogeography (MACARTHUR and WILSON, 1967). This discipline crystallised around a debate over "single large or several small" (SLOSS) reserves, which questioned whether a single island could support more species than several small ones, assuming that both environments had the same total size. The relevance of this debate in conservation biology was illustrated by an analogy: an island and a reserve can both be considered as species-friendly places, separated by unfriendly areas of ocean or damaged habitats respectively. Consequently, interesting lessons were drawn from the literature on island biogeography (DIAMOND, 1975; MAY 1975), although they later demonstrated their practical failure for conservation (SIMBERLOFF, 1976; SIMBERLOFF and ABELE, 1976) and their inability to provide general answers (SOULÉ and SIMBERLOFF, 1986). A remnant of this debate in conservation science is the implementation in systematic site selection tools of a compactness control, i.e. the BLM parameter. A direct penalty is applied in the objective function, proportional to the length of the site boundaries, with the proportionality factor equal to the BLM (see equation 2). In this way, if the BLM parameter is on (i.e. strictly positive), it forces the optimisation solvers to prefer solutions with aggregated PUs rather than dispersed PUs. Selected PUs sharing a boundary imply the removal of the common boundary from the total perimeter calculation.

Figure 2. Example of a conservation site solution and the value of the objective function



The selected planning units are in green, the others in blue.
$Cost(x)=c_4+c_9+c_{13}+c_{14}+c_{16}+c_{18}+c_{22}+c_{27}+c_{31}+c_{33}+c_{37}+c_{41}+c_{45}+c_{49}$.
BoundaryLength(x)=46 is the sum of the red segments.
Source: A. Brunel, S. Lanco Bertrand

Marxan/prioritizR

13 Here we illustrate two widely used optimisation DSTs developed for conservation site selection purposes, namely Marxan and prioritizR:

- Marxan is free and open-source software (BALL and POSSINGHAM, 2000; GAME and GRANTHAM, 2008; BALL *et al.*, 2009; ARDRON *et al.*, 2010) that is the most widely used and successfully tested DST for marine protected area design (e.g. Great Barrier Reef, Channel Islands of California, Gulf of Mexico). In particular, The Nature Conservancy and the World Wildlife Fund (WWF) are well-known users and promoters. Marxan proposes a metaheuristic algorithm called "simulated annealing", which offers a good compromise between computational speed and optimality evaluation. Moreover, Marxan is able to handle all integer programming problems with non-linear optimisation. A priori, Marxan never provides the optimal solution, but many near-optimal solutions. The amount of near-optimal solutions is user-defined, a feature that planners can use to their advantage, as it yields various interesting backup solutions that can feed into the conservation discussion. Marxan's downside is that it may seem unintuitive to non-technical users, which can lead to clumsy use and misinterpretation of results. In particular, fine-tuning is required to achieve the conservation objectives through an infeasibility penalty weight directly included in the objective function. Formally speaking, the basic Marxan executable file is called in R scripts.
- prioritizR is an R package (HANSON *et al.*, 2020) that can formulate conservation site selection problems based on a free open-source integer linear programming (ILP) solver called

Symphony[4]. This recently developed R package provides an exact solution to the optimisation problem in a time-efficient manner. Although ILP solvers deal with linear problems, prioritizR takes into account the quadratic constraints of the BLM due to the binary nature of the problem. Unlike Marxan, no tuning is required to achieve solution feasibility. The prioritizR package has turned calls for ILP solution methods (CHURCH *et al.*, 1996) into a practical reality, opening up broader perspectives (Monte-Carlo approach, irreplaceability analysis, etc.).

14 The choice of Marxan or prioritizR illustrates one of the earliest debates in conservation science, namely whether to favour fast but sub-optimal solutions over slow but accurate ones. The improved performance of ILP algorithms (SCHUSTER *et al.*, 2020) has enabled the development of ILP algorithms and initiated a possible paradigm shift recognised by the creator of Marxan (BEYER *et al.*, 2016). While we compare the two DSTs in this case study, most of the results were obtained via exact resolution methods using prioritizR.

Input data

15 Marxan and prioritizR require only a few input files providing the essential information for the expression of the optimisation problem:

- pu.dat: a list of the reference indices of the PUs (column 1) and the corresponding socio-economic cost (column 2). It thus represents the grid of PUs in the study area on which the map of cost functions is appended
- spec.dat: a list of the CFs considered (column 1) with the corresponding total targeted amount in the final conservation site (column 2)
- puvsp.dat: a list giving the quantitative geographical distribution of each CF (column 1). It contains the amount of the CF (column 2) associated with the corresponding PU (column 3).
- bound.dat: a list giving the shared boundary length (column 3) between two PUs (columns 1 and 2)
- input.dat: a list of all the high-level setting parameters (algorithms, display, save options, etc.).

Output data

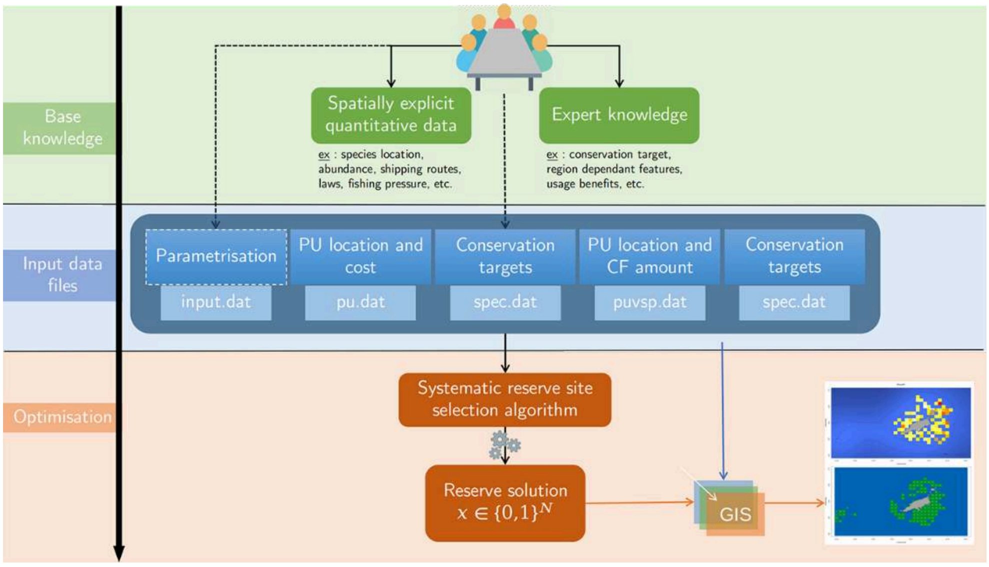
16 The output of the conservation site selection algorithms is the selected site in the form of a two-column text file that contains a list of PU references and the corresponding decision variable (0 or 1). Note that Marxan provides many more files, since three files (solution, feasibility information, summary) are generated for each run of the algorithm.

Graphical representation of the analysis flow

17 The different steps in selecting a conservation site are summarised in figure 3. The first step (green) consists of establishing ecological objectives and building consensus between stakeholders. The second step (blue) translates these discussions and the spatially explicit information available into quantitative input files for the DSTs. The last step (in orange) calculates the solutions through site selection algorithms. Their visualisation is provided by geographic information systems (GIS). The whole process

can be iterated to converge on a solution that is satisfactory to stakeholders and decision-makers.

Figure 3. Analysis flow for systematic selection of conservation sites



Source: A. Brunel, S. Lanco Bertrand

Data

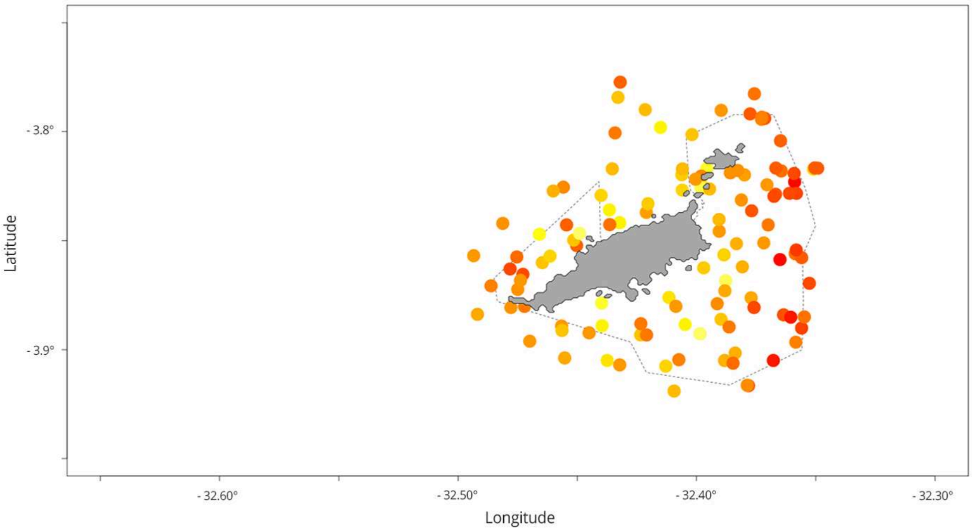
18 In this section, we present the data used for our case study, i.e. the Brazilian archipelago Fernando de Noronha in the tropical Atlantic. We explain how we discretised the input data to make it understandable to site selection software. The study area was defined as an extension grid in latitude and (which represents approximately 1.05 km at Fernando de Noronha's latitude), resulting in a 36 x 21 grid of 756 PUs (numbered from left to right and from bottom to top), in order to capture fisheries data in an exhaustive manner.

Acoustics

19 Recent at-sea campaigns around Fernando de Noronha collected raw in situ acoustic data (fig. 4) on fish abundance and distribution (Farofa3 campaign, April 2019, collaboration between the French National Research Institute for Sustainable Development, IRD, the Federal Rural University of Pernambuco, UFRPE, and the Federal University of Pernambuco, UFPE). Sampling was generally conducted in or around the existing Fernando de Noronha Marine Park. This means that no acoustic data was available outside this area. The existing marine park is shown in figure 4. The raw acoustic data consisted of a list of measurement points with latitude, longitude and S_A (an acoustic indicator of fish biomass). The acoustic data was considered here as a proxy for CF. To make the information understandable for site selection tools, we summed all S_A values located within a PU[5]. In this way, we were able to prepare the input file "puvsp.dat", visualised in figure 5. We can see the resolution and the boundaries of the chosen grid, and the colour gradient and displayed values describe

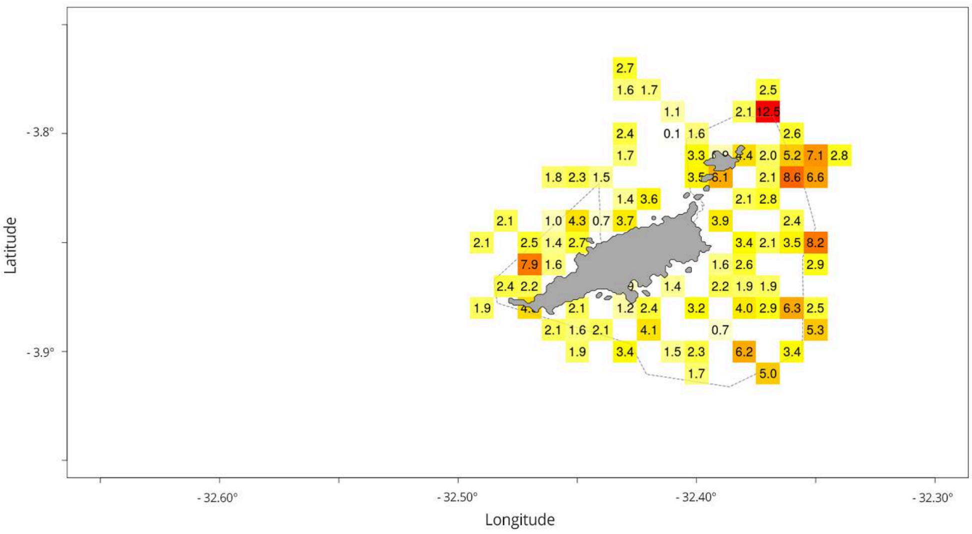
the process of converting the raw acoustic data for Marxan/prioritizR by summing up all the S_A values observed within a PU.

Figure 4. Raw acoustic data, collected around Fernando de Noronha, represented with a yellow to red colour gradient indexed on the values



The dotted line around the archipelago is the current marine park.
Source: A. Brunel, S. Lanco Bertrand

Figure 5. Acoustic data processed in a grid adapted to the DST, represented by a yellow to red colour gradient indexed on the S_A values



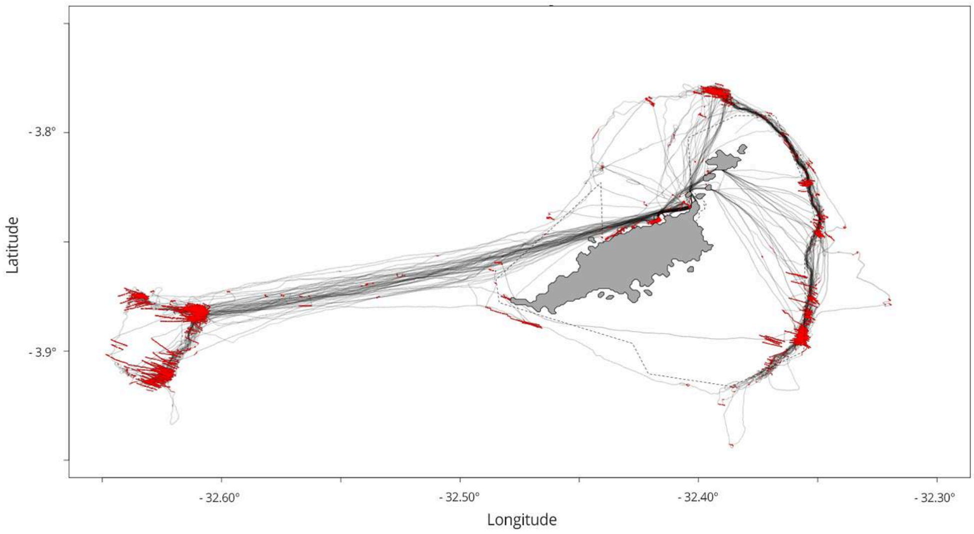
This information was used as the spatial distribution of CF no. 1.
Source: A. Brunel, S. Lanco Bertrand

Fishing

20 The raw fishing data (fig. 6) was composed of 69 GPS trajectories corresponding to the movements of fishing boats collected in situ over the last five years in Fernando de Noronha. A first statistical model (hidden Markov segmentation model) was applied (BELTRÃO, 2019) to classify each segment of these GPS trajectories into two behavioural

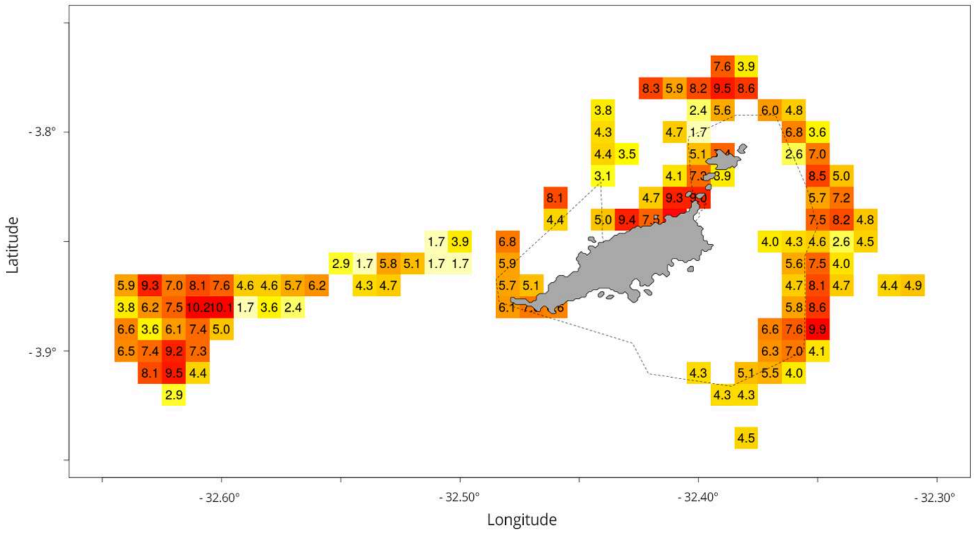
states: fishing and travel. Despite the inherent uncertainty in the modelling, we can consider the amount of "fishing" points as a quantitative index of fishing pressure. In order to calculate a fishing-based scalar value for each PU, we counted the number of fishing points in each PU and called this quantity "fishing count" (FC). This derived value for each PU contributes to the construction of the input file "pu.dat" if we want to represent the fishing pressure in a conservation scenario. FC values vary from a few hundred (moderate fishing activity) to over 10,000 (high fishing pressure), with some areas having no fishing at all (FC = 0). We then applied a logarithmic transformation, resulting in FC values ranging from about 0 to 10 (fig. 7). The FC values in this case study represent the socio-economic cost and are considered from the manager's perspective. Thus, selecting a PU with a high concentration of fishing points in the conservation site will represent a high cost to human communities while relieving pressure on biodiversity. Other socio-economic costs could also be tested (e.g. diving pressure, surface area of the PU).

Figure 6. Raw GPS fishing data (black) and segments estimated as fishing activity (red dots)



Source: A. Brunel, S. Lanco Bertrand

Figure 7. Fishing data processed in a grid adapted to the DST, represented by a yellow to red gradient indexed on the number of fishing points in each PU

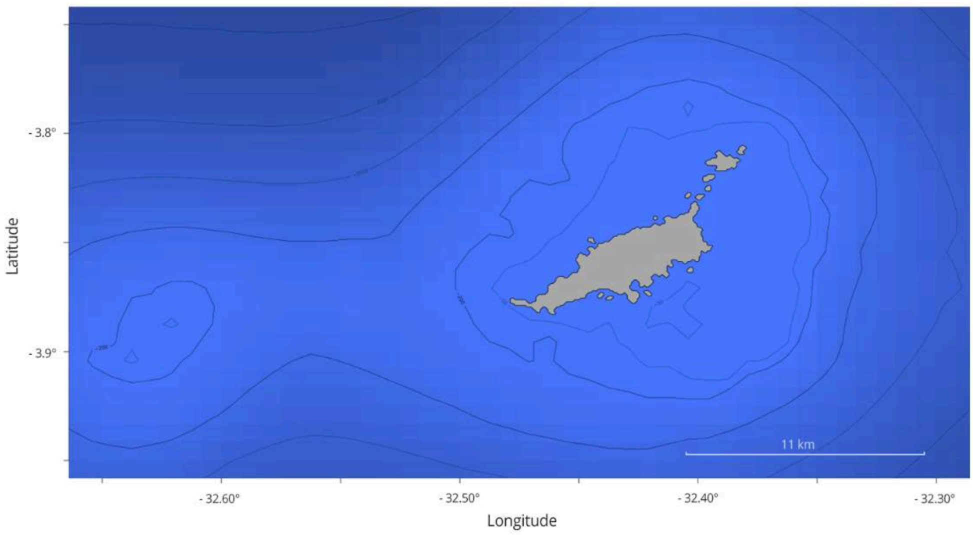


Source: A. Brunel, S. Lanco Bertrand

Bathymetry

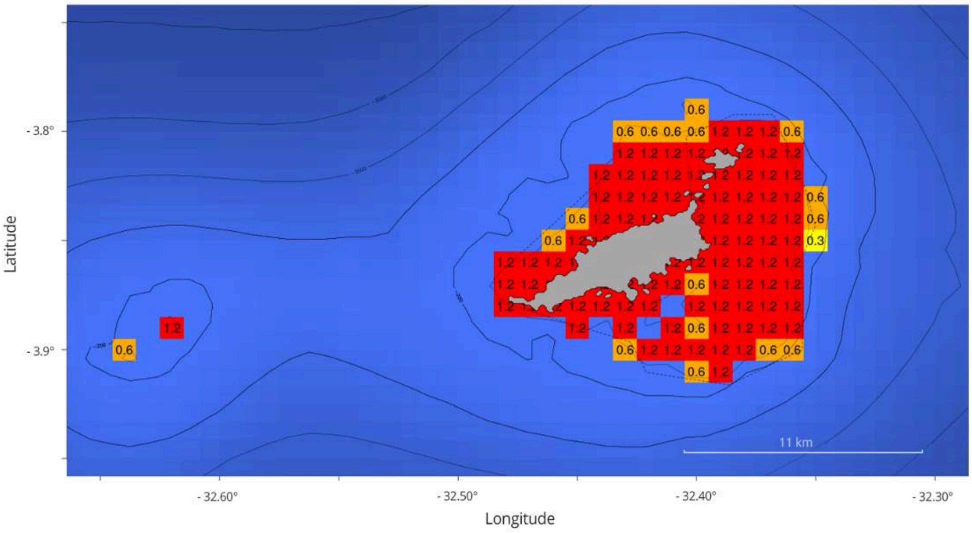
21 The bathymetric data (fig. 8) was obtained from GEBCO (General Bathymetric Chart of the Oceans, 2014 update) as a list of latitudes, longitudes and ocean depths. Since the continental shelf and the slope can be considered as two quite different and appropriate habitats that deserve protection and thus included in the reserve, the bathymetric data was used to derive two types of CF. We chose to define the continental shelf (CF no. 2, fig. 9) and the continental slope (CF no. 3, fig. 10) as corresponding to the depth intervals and . For each PU, the quantity of these two CFs was equal to the area occupied in the PU in km². The input file "puvsp.dat" was modified accordingly.

Figure 8. Raw bathymetric data (GEBCO 2014) represented by a blue gradient and isobath lines in black (50 m, 200 m, 1000 m, 2000 m, 3000 m, 4000 m)



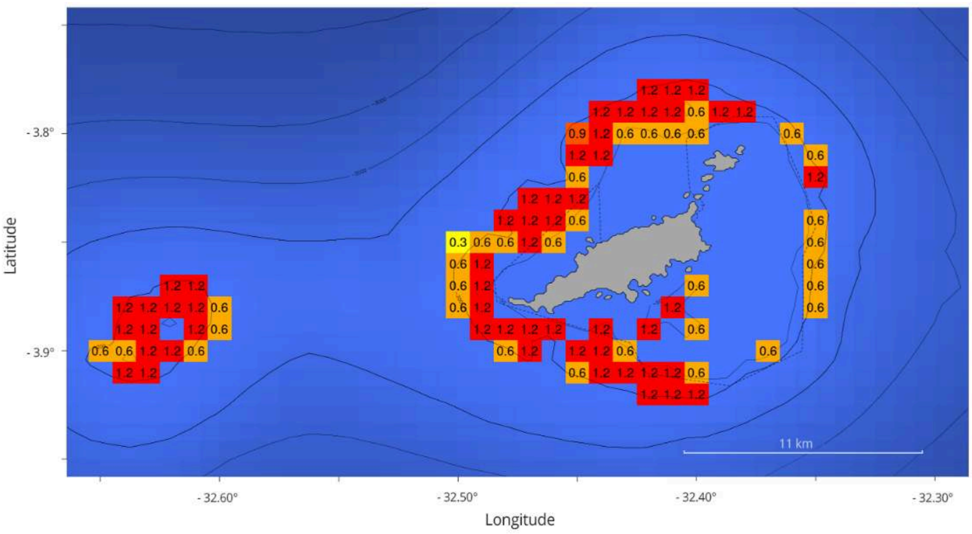
Source: A. Brunel, S. Lanco Bertrand

Figure 9. Continental shelf habitat included as CF no. 2, yellow to red colour gradient and % of PU occupied by this habitat type (in km²)



Source: A. Brunel, S. Lanco Bertrand

Figure 10. Continental slope habitat included as CF no. 3, yellow to red colour gradient and % of PU occupied by this habitat type (in km²)



Source: A. Brunel, S. Lanco Bertrand

Summary of scenarios

22 In this section, we present the summary of our simulation design. Tables 1, 2, 3, 4 and 5 show the parameterisation of the conservation site selection problem of the scenario studied and then presented in the results section. The experimental design consisted of numerous sensitivity analyses. Parameter sensitivity analysis is the preferred method to understand the influence of a given parameter on a simulation result. The main advantages of such an approach are to evaluate the relative importance of the different parameters included in the optimisation model by numerical trial and error. The basic

principle is to run simulations for different values of a given parameter while the others are fixed at a given value. In this way, the influence can be observed qualitatively and/or quantitatively through a simple comparison between the simulations.

23 First, we performed a sensitivity analysis of the BLM parameter in order to understand how the weight associated with the site perimeter influenced the final calculated site. To perform the BLM sensitivity analysis (values tested: 0, 0.5, 1, 2, 5 and 10), we arbitrarily chose a target of 50% for the three CFs and incorporated a constant cost function of 1, which led the optimisation solvers to minimise the number of PUs selected (and thus to choose the smallest site area since PUs had approximately the same size). A simple constant cost is often chosen as a first approximation; in our case, this allowed us to better illustrate the influence of the BLM compactness parameter.

Table 1. Summary of scenarios considered for the BLM sensitivity analysis

Scenario	CF	Targets	Cost	BLM
1.1	3	50%, 50%, 50%	1	0
1.2	3	50%, 50%, 50%	1	0.5
1.3	3	50%, 50%, 50%	1	1
1.4	3	50%, 50%, 50%	1	2
1.5	3	50%, 50%, 50%	1	5
1.6	3	50%, 50%, 50%	1	10

24 We examined various spatial distributions of costs to clarify their implications. As the cost directly influences the expression of the optimisation objective function, we performed a sensitivity analysis on the cost function. In addition to the logarithmic transformation already mentioned (see above), we evaluated other cost options (table 2):

- Scenario 2.1: cost = 1, simple and constant cost, adapted to consider all PUs equally, a relevant approach as a first approximation.
- Scenario 2.2: cost = 1 + FC, using our raw count of fishing points. We added 1 to avoid PUs of 0, as these can contaminate the solution search.
- Scenario 2.3: cost = 1 + ln (1+FC), a natural logarithm was applied to FC (where we added 1 for consistency of the logarithm definition domain). We added 1 to the expression to avoid PUs with a cost of 0 for the same reasons as above.
- Scenario 2.4: Cost = FC scale of 1 to 10; we transformed the FC value into a score from 1 to 10. This type of transformation has the advantage of being calculable, regardless of the format of the input cost data.
- Scenario 2.5: Cost = FC scale of 1 to 100; as above, but with a scale of 1 to 100 to better capture the influence of scale resolution.

25 With these sensitivity analyses, we addressed different questions:

- What are the implications of these differences in cost allocation in the calculated optimal site?
- Do correlated cost distributions imply a correlated solution?

26 In order to conduct our sensitivity analysis on the cost expression, we considered three CFs each with a target of 50% and a fixed BLM = 0, because a given BLM would imply a different quantitative share of the BLM term in the target function, since the range of the cost term changes considerably with the way it is derived (e.g. more than 10,000 in scenario 2.2, less than 10 in scenario 2.4).

Table 2. Summary of the parameters of the scenarios considered for the sensitivity analysis of the cost function

Scenario	CF	Targets	Cost	BLM
2.1	3	50%, 50%, 50%	1	0
2.2	3	50%, 50%, 50%	1+FC	0
2.3	3	50%, 50%, 50%	1+ln (1+FC)	0
2.4	3	50%, 50%, 50%	FC 1 to 10 scale	0
2.5	3	50%, 50%, 50%	FC 1 to 100 scale	0

* FC function projected on a scale of 1 to 10

27 We then compared the results of Marxan and prioritizR when fed with the same data. We compared the optimisation performance between the metaheuristics and the exact algorithms by applying the Marxan and prioritizR DSTs to our case study. In practice, we selected certain scenarios:

- one or three CFs with a 50% target each
- a constant cost of 1 or 1+ln (1+FC)
- a fixed BLM of 0 or 1.

28 This allowed us to explore extensively the performance of Marxan and prioritizR and their behaviour in various situations. To compare the results of the two software packages, we calculated two metrics, the optimality gap and the average correlation (table 3). The optimality gap quantifies the extent to which Marxan's solutions are sub-optimal compared to prioritizR. As Marxan provides a user-defined number of suboptimal solutions (100 in our case), the output of the Marxan "score" consists of a distribution of scores. To compare the outputs of Marxan and prioritizR, we averaged the Marxan scores and then calculated the optimal deviation according to the following formula:

Average Marxan score = (1 + optimal deviation) x prioritzR score.

29 As for the average correlation, the statistical correlation between each Marxan run and the prioritizR solution was calculated and then averaged.

Table 3. Summary of the parameters of the scenarios considered for the comparative performance analysis of Marxan/prioritizR

Scenario	CF	Targets	Cost	BLM
3.1	1	50%	1	0
3.2	1	50%	1	1
3.3	3	50%, 50%, 50%	1	0
3.4	3	50%, 50%, 50%	1	1
3.5	3	50%, 50%, 50%	1+ln (1+FC)	0
3.6	3	50%, 50%, 50%	1+ln (1+FC)	1

30 Then we carried out scenario simulations with different target values. The target values can be used as adjustment parameters if they are not ecologically driven. We performed a sensitivity analysis of the target values, while keeping the cost and BLM parameters constant (table 4). For simplicity, we increased each of the three CF targets simultaneously. Two scenarios with a single CF were considered.

Table 4. Summary of the parameters of the scenarios considered for the sensitivity analysis of the target values

Scenario	CF	Targets	Cost	BLM
4.1	3	10%, 10%, 10%	1	1
4.2	3	20%, 20%, 20%	1	1
4.3	3	30%, 30%, 30%	1	1
4.4	3	40%, 40%, 40%	1	1
4.5=1.3	3	50%, 50%, 50%	1	1
4.6	3	60%, 60%, 60%	1	1
4.7	3	70%, 70%, 70%	1	1
4.8	3	80%, 80%, 80%	1	1
4.9	3	90%, 90%, 90%	1	1
4.10	3	95%, 95%, 95%	1	1

31 A change in resolution was then applied to assess its effect on the delineation of the site area. The choice of grid resolution is important and depends on the trade-off between the level of detail aimed for (sufficient number of PUs) and the computational time

required for the analyses. It will also be partly determined by the quality of the raw data when provided as grid (raster file) or vector data (points or lines) recorded with a given accuracy. Here, we investigated the effect of increasing the resolution in latitude and longitude, by comparing the results obtained with the initial resolution of 0.01° for each axis (21 x 36 grid cells = 756 PUs), with those obtained with a resolution of 0.005° (41 x 71 grid cells = 2911 PUs). The resolution comparison was made for scenarios with constant cost (equal to 1), with a BLM set to 1 and for a CF equal to 1 or 3 (table 5).

Table 5. Summary of scenario parameters for the analysis of the influence of resolution

Scenario	CF	Targets	Cost	BLM	Resolution
5.1	1	50%	1	1	21x36
5.2	1	50%	1	1	41x71
5.3	3	50%, 50%, 50%	1	1	41x71

32 Lastly, the concept and calculation of irreplaceability can be useful for mapping and prioritising conservation actions. Irreplaceability distribution maps can be provided by prioritizR (CABEZA and MOILANEN, 2006); the Marxan selection frequency cannot be used as a measure of irreplaceability (it is only a numerical artefact, ARDRON *et al.*, 2010). Irreplaceability is indicated with values between 0 and 1, which indicate the extent to which a PU cannot be replaced by another (1 = irreplaceable, 0 = replaceable). For example, a PU that is unique in containing a rare species will be irreplaceable (value 1) in the sense that the protection of this species cannot be achieved otherwise, whereas a PU with an irreplaceability of 0 can be exchanged elsewhere in the study area, because other PUs contain similar species. The calculation of irreplaceability is relevant, as it provides a richer picture and potentially allows targeted priority conservation actions.

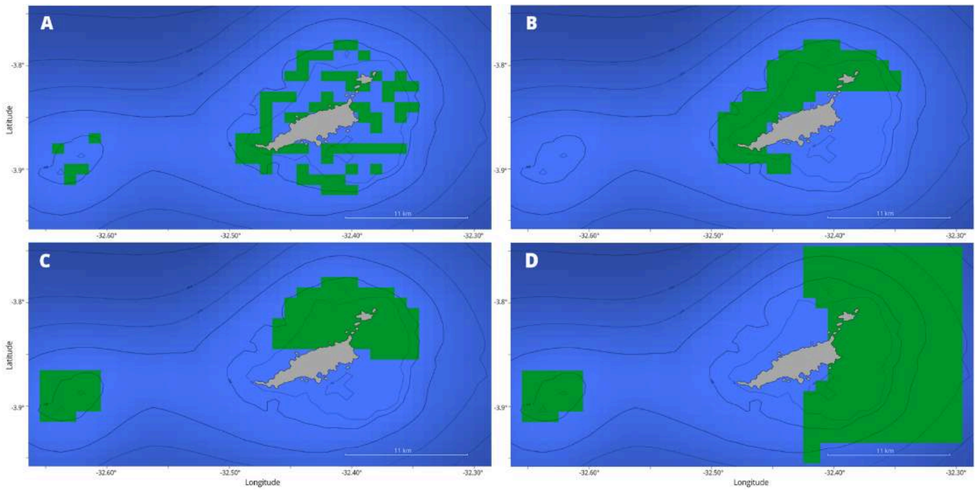
Results

Reserve compactness

33 The scenario in which the perimeter penalty was not activated (BLM 0, see fig. 11, panel A) naturally shows a dispersed conservation site solution, with most of the selected PUs around the Fernando de Noronha Marine Park, which can be explained by the fact that the fish biomass (CF no. 1, identified with acoustic data) is only found in the marine park. The aggregation effect of a non-zero BLM, i.e. with the compactness penalty activated, is immediate and visually striking (see e.g. figure 11, panel B where BLM = 1). As the BLM increases (e.g. with BLM = 5 in figure 11, panel C), the calculated solution seems to change, as the algorithm then favours the PUs of the continental shelf west of Fernando de Noronha, despite the absence of fish biomass in this area according to the acoustic data. Finally, with a BLM equal to 10 (fig. 11, panel D), i.e. forcing the prevalence of the boundary length penalty on the cost of the PU in the objective function, the conservation site solution degenerates. A numerical but unavoidable “boundary effect” occurs, which can be explained by the absence of a boundary cost for PUs at the boundary of the study area, as these PUs simply do not have neighbours. The

boundary effect is unavoidable, as a BLM that tends to infinity theoretically implies total coverage of the study area, as such a configuration would cancel out the cost term of the PUs in the optimisation objective and eventually produce an objective function equalling the total area perimeter. Note that the boundary effect can also occur for smaller BLM values if an area of interest is close to the edge of the study area. One idea to slow down and mitigate this purely numerical effect would be to create a ring of empty PUs with a "locked" status, i.e. a PU that cannot be selected.

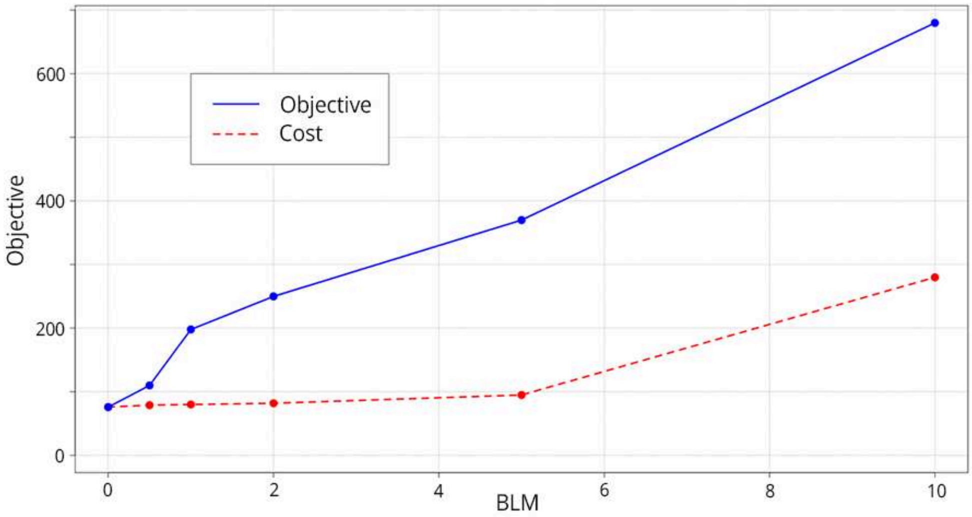
Figure 11. Three CFs each with a protection target of 50%, cost =1 and BLM in {0, 1, 5, 10} (shown in panel A, B, C, D respectively)



The selected PUs in the optimal conservation site solution are coloured green.
Optimisation performed with prioritizR.
Source: A. Brunel, S. Lanco Bertrand

34 The quantitative influence of the BLM parameter on the optimisation results is illustrated in figure 12. We first observe the continuous growth of the objective function with increasing BLM, which is a logical phenomenon since BLM directly increases the share of the boundary length in the objective function. Two trends can be identified in the curve in figure 12: the cost of the conservation site (number of selected PUs) remains stable, but then increases for BLMs above 5. The share of the BLM in the objective function (difference between the solid blue and dashed red lines) continues to increase with BLM although it stabilises at around 60–70% for a BLM above 1. In conclusion, the BLM parameter is necessary to force the optimisation solver to seek compactness, which makes sense for management objectives and is also ecologically desirable as indicated in the SLOSS discussion. Thus, it is relevant to activate the BLM compactness parameter, but it should remain reasonably small to avoid a numerical boundary effect. For all other analyses, we considered a default BLM of 1, to account for the compactness of the site.

Figure 12. **The number of selected PUs (i.e. the cost of the conservation site) and the value of the associated objective function are represented by a dotted red line and a solid blue line respectively. The BLM's share of the objective function is the difference between the red line and the blue line.**



Source: A. Brunel, S. Lanco Bertrand

Influence of cost allocation

35 Figure 13 illustrates how the way cost is expressed affects the cost distribution map. A more quantitative comparison is provided by the correlation matrix[6] (symmetric) between the cost distributions where the row/column number corresponds to the scenario number:

$$R_{cost} = \begin{bmatrix} 1 & - & - & - & - \\ & 1 & 0.62 & 0.99 & 1 \\ & & 1 & 0.54 & 0.61 \\ & * & & 1 & 0.99 \\ & & & & 1 \end{bmatrix}$$

36 For example, the cost correlation matrix R_{cost} indicates that scenarios 2.4 and 2.5 are almost identical to scenario 2.2. This is to be expected since these scenarios are simply a projection to a new scale of the distribution of the CF, which can also be understood as a (linear) change of unit. Conversely, the use of a natural logarithm implies a much lower correlation coefficient compared to scenario 2.2 (and thus to scenarios 2.4 and 2.5 due to the transitive nature of the correlation equivalence relationship). Note that the first dotted line of the correlation matrix, corresponding to scenario 2.1, is not defined, as the standard deviation of a constant distribution is 0 and is used in the denominator of the correlation formula[7].

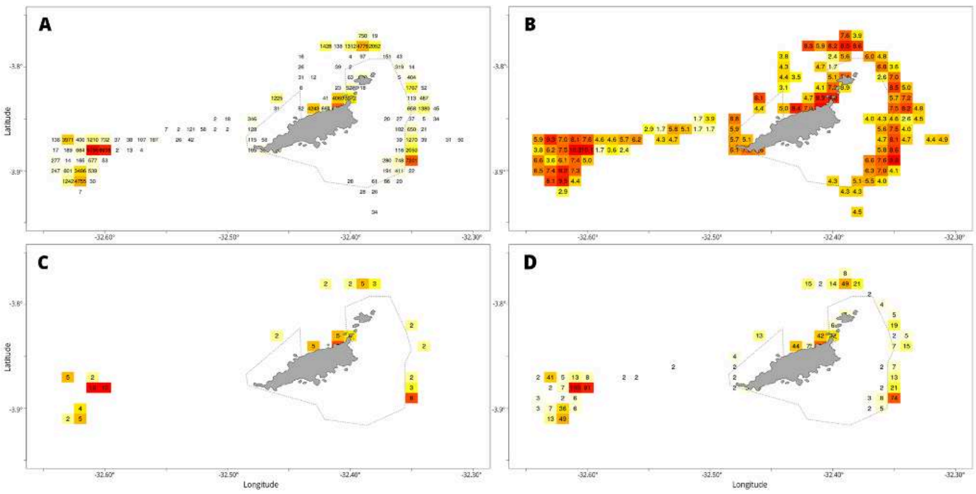
37 As we used BLM = 0, the PUs belonging to the conservation site were scattered (fig. 14) and visual comparison was difficult. We therefore opted for a quantitative comparison based on the correlation matrix between all solutions for the site:

$$R_{sol} = \begin{bmatrix} 1 & 0.44 & 0.42 & 0.71 & 0.62 \\ & 1 & 0.93 & 0.52 & 0.68 \\ & & 1 & 0.52 & 0.67 \\ & * & & 1 & 0.69 \\ & & & & 1 \end{bmatrix}$$

38 The first row of the matrix R_{sol} shows the correlation between any scenario and scenario 2.1 (i.e. with constant cost). The correlation is not zero, because the scenarios have common characteristics (same distribution of conservation characteristics). The correlation is weak, because the cost function definitely influences the solution. The correlation matrix shows that scenario 2.4 (FC scale 1–10) is closer to scenario 2.1 (cost = 1), while scenario 2.5 (FC scale 1–100) is closer to the other scenarios. This highlights the fact that the scale projection reflects its quality: it smooths out sparse data, but may fail to capture variations.

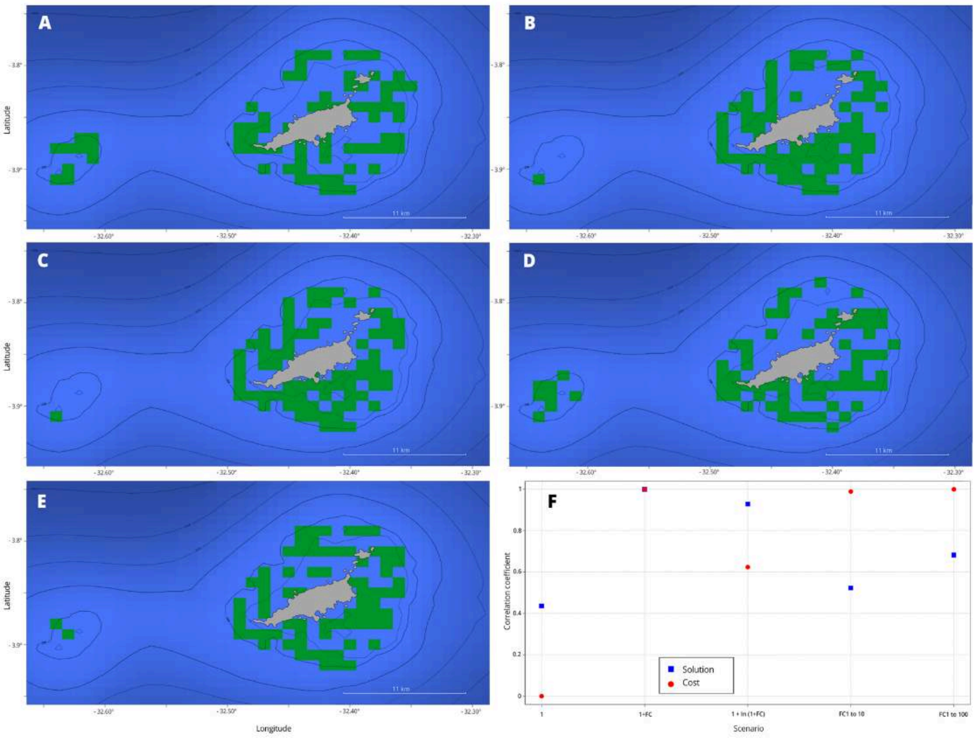
39 Despite the logarithmic transformation, the conservation site solutions of scenarios 2.2 and 2.3 are very similar (correlation of 0.93).

Figure 13. The spatial distribution of costs is represented by a colour gradient from yellow to red



White pixels have a cost of 1, which is not displayed.
The costs {1+FC, 1+ln (1+FC), FC1to10, FC1to100} are shown in panels A, B, C, D respectively.
Source: A. Brunel, S. Lanco Bertrand

Figure 14. Three CFs each with a protection target of 50%, a cost in {1, 1+FC, 1+ln (1+FC), FC 1to10, FC1to100} and BLM = 0 (shown in panels A, B, C, D, E respectively)



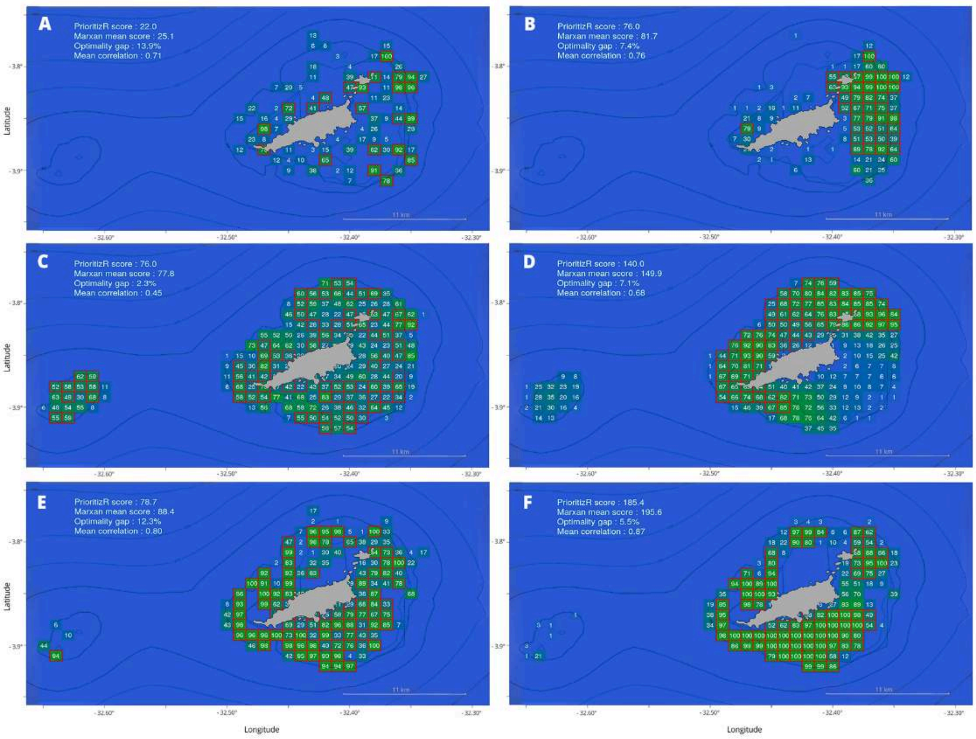
The PUs selected in the optimal conservation site solution are coloured in green. The optimisation was performed with prioritizR. Panel F shows the correlation coefficient between the spatial distributions of costs (red circle) and solutions (blue square) across scenarios. Scenario 2.2 (cost = 1+FC) is chosen as a reference. The correlation coefficient for scenario 2.1 does not exist (because the cost distribution is constant) and is arbitrarily set to 0.
Source: A. Brunel, S. Lanco Bertrand

40 Looking at the relationship between the cost distribution (red circles) and the correlation of the associated conservation site solutions (blue squares), taking the arbitrary scenario 2.2 as a reference (2nd coefficient row of the above-mentioned correlation matrices), it can be seen that a similar cost distribution can lead to a different site solution (see costs “FC1 to 10” and “FC1 to 100”), while a different cost can lead to a similar site solution (see cost “1+ln (1+FC)”) (fig. 14, panel F).

Metaheuristic (Marxan) and exact (prioritzR) algorithms

41 By nature, Marxan gives a user-defined number (set to 100 in this example) of sub-optimal solutions, unlike prioritizR, which provides a single optimal solution. The average Marxan score ranges from 2% (fig. 15, panel C) to 14% (fig. 15, panel A) of the optimal solution depending on the scenario considered. The average correlation between the optimal solution of prioritizR and the Marxan iterations varies from 0.45 (panel C) to 0.87 (panel F). We observed a similar order of magnitude for the computation time for Marxan and prioritizR.

Figure 15

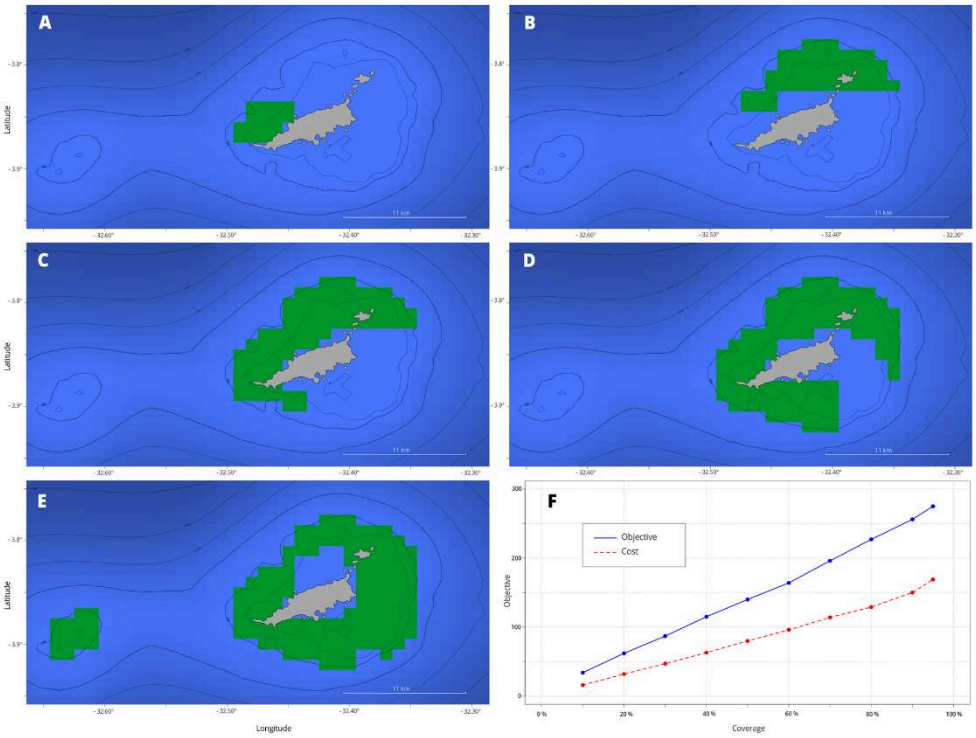


(A) A CF with a protection target of 50%, cost=1 and BLM=0.
(B) A CF with a protection target of 50%, cost=1 and BLM=1.
(C) Three CFs each with a protection target of 50%, cost=1 and BLM=0.
(D) Three CFs each with a protection target of 50%, cost=1 and BLM=1.
(E) Three CFs each with a protection target of 50%, cost=1+ln (1+FC) and BLM=0.
(F) Three CFs each with a protection target of 50%, cost=1+ln (1+FC) and BLM=1.
The PUs selected in the optimal conservation site solution by Marxan are represented by a gradient from blue to green according to the frequency of selection among 100 Marxan iterations (white number inside the PU). The red border around the PU indicates the selection by prioritization.
Source: A. Brunel, S. Lanco Bertrand

Target sensitivity analysis

42 The most obvious effect of increasing the conservation target value was the increase in the area of the conservation site solution (fig. 16). Moreover, the reserve seemed to be concentrated in the Fernando de Noronha Marine Park, and in the case of a 90% conservation target value, covered the park (fig. 16, panel E). This result should be taken with caution, as it is due to the distribution of CF1, as acoustic data was only available in the marine park. The fact that the conservation site solution gradually surrounds Fernando de Noronha is caused by the activation of the BLM, as the optimisation solver favours a compact site (and in one piece) if possible. By plotting both the objective function and the cost values for the different target values (fig. 16, panel F), we can inform/support decision-making, as planners can quantitatively choose a level of protection (target value).

Figure 16. **Three CFs each with a protection target in {10%, 30%, 50%, 70%, 90%}, cost=1 and BLM=1 (in panels A, B, C, D, E respectively)**

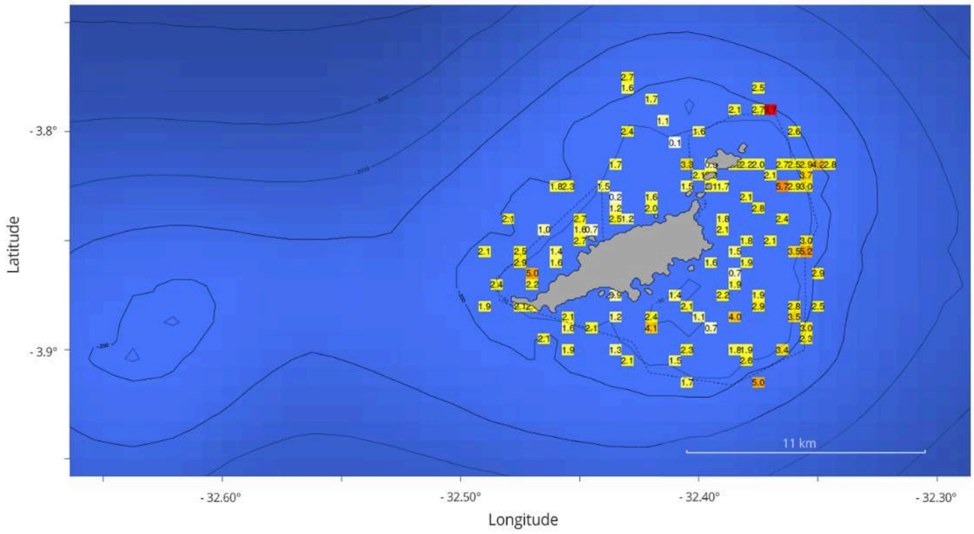


The selected PUs in the optimal conservation site solution are coloured green. The optimisation was performed with prioritizR. Panel F shows the respective changes in the objective function (in blue) and the cost (i.e. the number of selected PUs, in red) as a function of the chosen conservation objective.
Source: A. Brunel, S. Lanco Bertrand

Influence of the resolution

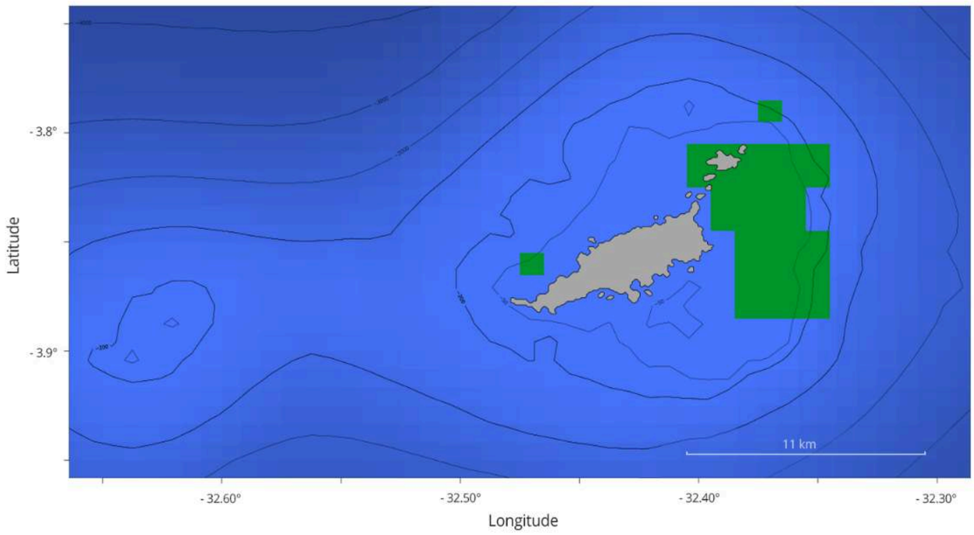
43 Figure 17 illustrates what happened to the acoustic data when the resolution of the grid was four times finer than that of the data. The increase in resolution resulted in a more precise delineation of the conservation site, with more scattered PUs (comparison between figures 18 and 19), and a total site area that was four times smaller (38 PUs of 0.01° resolution versus 41 PUs of 0.005° resolution). On the basis of this observation, it seems wise to collect data that is as detailed as possible in order to obtain a fine resolution.

Figure 17. CF1 based on acoustic data processed with a resolution of 0.005 °, i.e. a grid of 41 x 71 cells



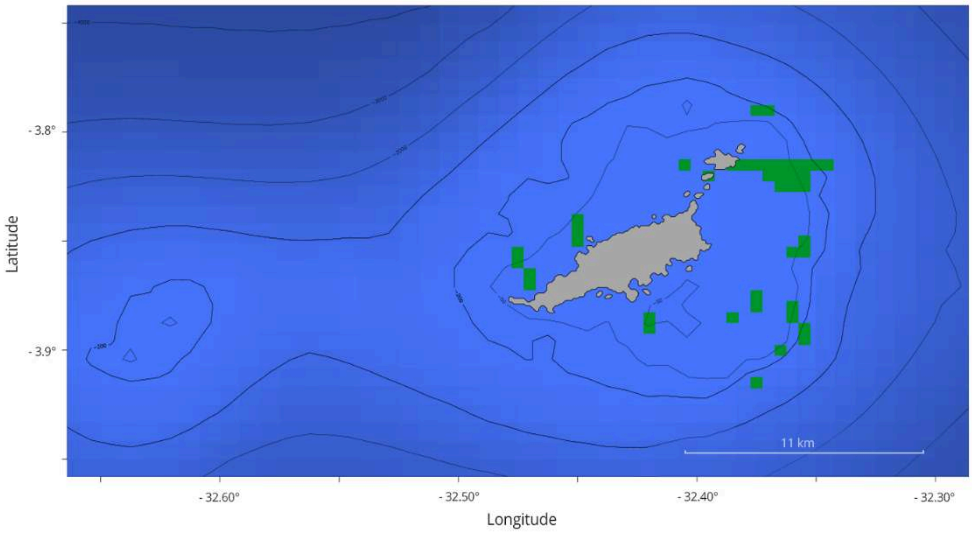
Source: A. Brunel, S. Lanco Bertrand

Figure 18. A CF with a protection target of 50%, a cost of 1 and a BLM of 1 (scenario 5.1)



The PUs selected in the optimal conservation site solution are coloured in green. Optimisation performed with prioritizR with a grid resolution of 21 x 36.
Source: A. Brunel, S. Lanco Bertrand

Figure 19. **A CF with a protection target of 50%, a cost of 1 and a BLM of 1 (scenario 5.2)**

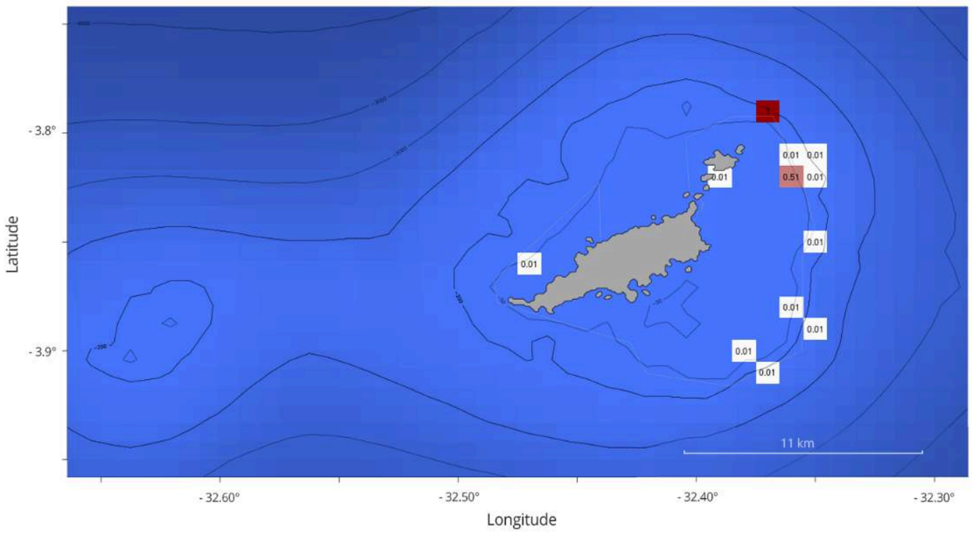


The PUs selected in the optimal conservation site solution are coloured in green. Optimisation performed with prioritizR with a grid resolution of 41 x 71.
Source: A. Brunel, S. Lanco Bertrand

Irreplaceability

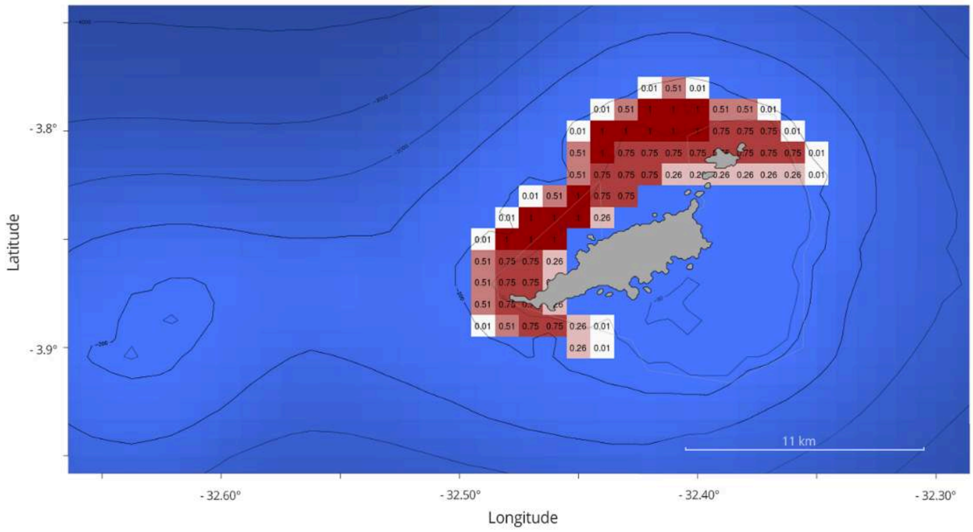
44 We can see from the maps calculated for scenarios 3.1 (fig. 20) and 1.3 (fig. 21) that irreplaceability showed different spatial patterns depending on the scenario, with most of the PUs not irreplaceable (except for the northeastern PU, which had a value of 1) for scenario 3.1, while there was a gradient of irreplaceability from the core to the periphery for scenario 1.3, probably due to a BLM effect.

Figure 20. **Distribution map of irreplaceability for scenario 3.1**



Source: A. Brunel, S. Lanco Bertrand

Figure 21. Distribution map of irreplaceability for scenario 1.3



Source: A. Brunel, S. Lanco Bertrand

Discussion

Limitations of DST approaches

45 The choice of raw data inputs, which represent one particular viewpoint among others, will strongly influence the outcome of DSTs. Therefore, depending on the purpose of the conservation actions, and to integrate the interests of a wide range of stakeholders, all necessary datasets should be included to ensure that all needs are properly taken into account in the site selection process. For example, our didactic example only represented the activity of a few fishermen, which eliminated from our scope the needs of unaccounted for fishermen and those of other stakeholders from completely different sectors (tourism, energy, marine transit, etc.). In the case of different stakeholder views, it is advisable to construct several single view cost functions rather than a complex multiple view for reasons of clarity.

46 Secondly, an inherent drawback of any MSP approach is the influence of the process of transforming the initial raw data into an input that is compatible and understandable by the DST. Indeed, there are many ways to transform spatially explicit data into a geographic scalar value and thus build an input file, and we have demonstrated the major influence of the generation of the cost function (constant, 1+FC, 1+ln (1+FC)) derived from the same initial information (raw data). This underlines the importance of the transparency of the approach in order to critically interpret the results of the DST. In this context, sensitivity analyses are extremely valuable and informative.

47 Another issue is that, as we repeatedly observed with our use of acoustic data, Marxan understands a zero abundance index as a definite absence when in fact it may be due to a lack of data (the boat transects simply did not cover this area). It is clear that fishermen would not go west of Fernando de Noronha if there are no fish. The conservation site result is a reflection of the quality and quantity of the input data, which is a key issue if there are gaps in the data or if it is heterogeneous. This highlights the complex need for a data surrogate or processing to achieve the same

data resolution and representativeness without distorting the information. Nonetheless, even if the acoustic data were perfect, this does not mean that the observed level at the observed location is certain. The optimisation framework as formulated by the tools implemented here prevented the consideration of data uncertainty, which is a major weakness of this approach; this has been identified as a gap to be addressed in the PINARBAȘI *et al.* (2017) meta-analysis on DSTs.

48 From a more philosophical point of view, we could suggest that DSTs should at least include the MinSet and MaxCov formulations, as both are equally subjective, but the latter may in some cases be more satisfactory, as the conservation objective is explicitly stated in the optimisation problem: maximising biodiversity conservation under a predetermined constraint of human use of space and resources. While this paradigm was initially dominant, the development and use of Marxan has imposed the "minimum set" formulation as standard to date.

49 Finally, DSTs are spatially explicit and static (data is not time dependent) and focus on the loss of benefits from human use of space and resources. It is therefore rather difficult to demonstrate the benefit obtained from a marine protected area using such tools.

Key points to keep in mind

50 Here we aim to provide key messages for stakeholders involved in MSP using DSTs in the process, regardless of their technical level and role:

- Conservation site selection DSTs calculate a solution that covers conservation characteristics in relation to preestablished protection objectives while minimising a cost in terms of impact on human activities.
- The site selection process is inherently subjective and therefore requires a high degree of transparency regarding the data and parameters used in the DST in order to encourage constructive criticism and improvements.
- Exact algorithms should be favoured, as they facilitate the interpretation of processing and solutions (a single optimal solution to be interpreted versus a multitude of sub-optimal solutions for Marxan), as well as opening up perspectives on protected area design in general (simulation of multiple scenarios).
- As the results can be highly dependent on the data used and its processing, they should be considered with great caution; sensitivity analyses are strongly recommended.
- Any "NA" value (which potentially means a lack of sampling) in the input data is in practical terms treated as a zero value, thus interpreted as a definite absence.
- Data processing is inherently subjective and must always be open to criticism and improvement.
- Although based on the same observations, the processing of the data can potentially lead to different conservation site solutions.
- The better the resolution of the data, the smaller the conservation site size.
- The higher the coverage targets, the larger the site size. Targets are not setup parameters and should be guided by ecological considerations.
- The BLM parameter, which regulates the compactness of the site, should be activated and its exact value should be motivated by the results of a sensitivity analysis. Too high a BLM value can lead to undesirable digital artefacts such as the "boundary effect".

- Although computationally expensive, irreplaceability maps shed a different light on the conservation issues at stake, as they allow the mapping and prioritisation of conservation actions and planning units.
- Sensitivity analyses (on conservation targets, BLMs, data selection and processing) should be carried out to provide a critical understanding of the problem formulation and the calculated conservation site solutions.
- The multiplication of scenario simulations allows for a better understanding of conservation issues and potential conflicts. They allow an assessment of whether the results are robust or not, i.e. whether they are highly dependent on the data used or whether they are generalisable. Simulating multiple scenarios from a single point of view (i.e. at a single cost) makes it possible to represent the interests of all stakeholders and thus to better resolve conflicts and avoid the risks of ocean grabbing.

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NOTES

1. These Marxan and prioritizR scripts are available at: https://github.com/AdrienBrunel/reserve-site-selection

2. A “conservation feature” is a given biotic or abiotic entity that deserves conservation consideration (species, habitat, etc.).

3. Assessed from the manager’s perspective.

4. It is possible to use the commercial Gurobi solver instead to improve computational performance.

5. We avoided data kriging for the sake of simplicity.

6. Two spatial distributions (cost or solution) were considered as independent random variables X and Y. The statistical correlation between X and Y was then given by: rXY=cov (X, Y) XY. A correlation of 1 means that the maps are equivalent.

7. Two spatial distributions (cost or solution) were considered as independent random variables X and Y. The statistical correlation between X and Y was a metric of interest and was given by : . A correlation of 1 means that the maps are identical.

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