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Spatial zoning design for marine protected areas through multi-objective decision-making

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ABSTRACT

Systematic approaches to designing marine protected areas (MPA) have recently garnered more attention as an efficient planning tool. In particular, spatial zoning for various types of MPA designs could accommodate several demands for ecological conservation while minimizing socioeconomic impact. Most spatial zoning approaches are formulated as nonlinear Multi-Objective Decision-Making (MODM) models, which are solved using stochastic search algorithms, such as the popular Marxan with Zones. Due to the stochastic nature of these algorithms, the final MPA design is the composite result of several modeling experiments, and the solution is often suboptimal. For the current study, two MODM models were developed based on Multi-Objective Integer Linear Programming (MOILP) for MPA spatial zoning. The proposed models are referred to as a buffer cells model (BCM) and an external border cells model (EBCM). BCM allocates two types of cells to an MPA zone, covering core and buffer cells. The EBCM uses external border cells instead of buffer cells. Both models can minimize the cost incurred by MPA implementation while simultaneously satisfying different conservation targets. The solutions found are globally optimal. MPA designs from the BCM, EBCM, and Marxan with Zones are compared by displaying their spatial distributions. The results present the general characteristics of the BCM and EBCM and demonstrate how both models may have certain advantages over the Marxan with Zones method and can thus be considered as good alternatives for MPA spatial zoning.

1. Introduction

The marine environment is an essential component of the global life-support system and a positive asset that presents opportunities for sustainable development according to the Agenda 21 published by the United Nations Conference on Environment and Development. Since 1962, the concept of a Marine Protected Area (MPA), generated by The World Conference on National Parks, and protection of the marine environment has become increasingly important on a global scale. MPAs have often been recognized as efficient tools to preserve fishery resources and marine species' biodiversity because they satisfy ecosystem-based management, habitat conservation objectives and the precautionary principle with relatively simple means (CBD, 2004; Hoyt, 2012).

The International Union for Conservation of Nature (IUCN) published the guidelines for MPA in 1999 (Kelleher, 1999). According to these guidelines, a systematic approach is essential to the MPA design process. Using this type of integrated approach, we can synthesize the factors related to MPA site selection and find an efficient solution based on different aspects. However, most criteria in these guidelines are related to quality. If we want to objectively and explicitly select an area, we require certain quantifying tools. These tools can effectively aid decision makers in selecting between different areas that satisfy a certain level of biological conservation. A fair deal of recent research has used systematic approaches as decision-support tools for MPA planning (Adams et al., 2011; Crossman et al., 2007; Malcolm et al., 2012; Margules and Pressey, 2000; Williams et al., 2005).

1.1. The systematic approach

There are two main types of algorithms that have been used in systematic approaches for reserve selection: linear programming (LP) and heuristic algorithms (HA) (Önal, 2004; Vanderkam et al., 2007). The most commonly used LP method is Integer Linear Programming (ILP). Using ILP, the study area is rasterized, and each cell represents a decision variable. If the decision variable equals 1, the cell is selected as an MPA cell; in contrast, if the decision variable equals 0, the cell is not selected. Adding percentage area targets and/or biological protection goals as constraints, ILP can find an

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optimal solution (Vanderkam et al., 2007). ILP is typically used to solve two different types of problems: set covering problems (SCP) (Moore et al., 2003; ReVelle et al., 2002) and minimizing the MPA size/cost for a given biological conservation target. Maximum covering problems (MCP) (Arthur et al., 2004; Haight et al., 2000, 2005) seek to maximize biological conservation under an MPA size/cost constraint. The most important advantage of using ILP to design MPAs is that ILP can provide a globally optimal solution. On the other hand, an important disadvantage of ILP lies in the problem-solving computing time, which is very likely to increase with the data size and complexity (O'Hanley, 2009).

Heuristic algorithms have been used in reserve planning since the 1980s. The heuristic algorithm model framework is similar to ILP (SCP or MCP), but it has been a more popular tool for selecting conservation areas (Ball et al., 2009; Garson et al., 2002; Leslie et al., 2003; Possingham et al., 1993) because it is more computationally efficient than LP, and it can work with complex non-linear models. However, heuristic algorithms cannot ensure an global optimal solution nor inform the researcher on the level of sub-optimality of the solution (Vanderkam et al., 2007).

1.2. Spatial zoning

Zoning is a common MPA management method for satisfying different needs in different regions (Gubbay, 2005). Zoning plans can effectively address trade-offs between competing interests (Day, 2002). Even if the systematic approach has been used to solve many MPA selection problems, most studies (ILP or heuristic algorithm) have only considered one type of zone for their solution (e.g., the no-take zone). They could not simultaneously incorporate different types of zones to satisfy different stakeholder interests (Watts et al., 2009). Based on these one-zone tools, if we want to implement an MPA with zones, we must conduct several model experiments with different parameters and protection targets for each type of zone then overlap the results. This process is complicated, and the results are often suboptimal.

Recently, many studies have used zoning to implement multi-objective MPA planning. Villa, Tunesi et al. (2002) used multi-criteria decision analysis (MCDA) through an overlap analysis with geographic information systems (GIS) to generate a map with fitness indices. Geneletti and van Duren (2008) also used MCDA to optimize the MPA zoning problem. Although the MCDA can provide a suitability map for an MPA zoning plan, it misses certain important MPA design principles. For instance, it cannot confirm whether conservation features are economically optimal (Klein et al., 2009).

The systematic approach can provide results that meet the biological conservation objective while minimizing the area selection cost. The most famous decision support tool using the systematic approach for MPA selection is Marxan (Ball et al., 2009). In the same way as former studies, the original Marxan was not an MPA zoning tool. It wasn't designed to use with zones. Later, the Marxan team produced Marxan with Zones, which expands the basic reserve design problem to allow the selection of zones (Watts et al., 2009). The Marxan with Zones algorithm is heuristic; thus, the user still cannot acquire an optimal solution.

In the past few years, computers have become more and more powerful, and the computing time of ILP has been largely reduced. Therefore, ILP might solve MPA design problems as effectively as heuristic algorithms but with optimal solutions (Crossman et al., 2007). In this paper, we present a Multi-Objective Integer Linear Program (MOILP) with zones. This model can manage different zoning strategies while using LP to generate an optimal solution.

Two types of spatial zoning models are introduced: a buffer cells model (BCM) and an external border cells model (EBCM). The BCM provides a more complete MPA zoning result because it includes buffer cells and core cells. Core cells are the main functional areas in each zone (e.g., conservation or recreation), and the buffer cells that surround the core cells can be used to improve the MPA contiguity and compactness while mitigating the impact from outside cells (Williams and ReVelle, 1998). The EBCM treats the buffer cells in the BCM as external border cells that surround core cells, and both the external border cells and core cells compose an MPA. Through the number of external border cells, we can control the shape of each zone. Using these two models, we show that the cost of MPA zoning can be minimized while ensuring that the different targets of each zone are met. The results are guaranteed to be globally optimal.

2. Method

2.1. Multi-Objective Integer Linear Program

The systematic approach has been used for reserve site selection for 20 years. Initially, it was mainly used for terrestrial protected areas. Researchers tried to find optimal solutions with imposed constraints on a finite resource, such as biodiversity or economic resources (Williams et al., 2005). Because the computing ability of computers has increased, more and more studies have used ILP as a decision-making tool to solve the reserve site planning minimum-cost problem (Church et al., 1996; Önal and Briers, 2003; Rodrigues and Gaston, 2002; Vanderkam et al., 2007).

MOILP is a method that can integrate multiple objectives in one decision framework, which can be solved through a single solution process. The aim of the MOILP is to aid decision makers in finding a preferred solution with limited resources and conflicts of interests (El-Amine Chergui et al., 2008). The MOILP concept has been adopted in management science, economics, market research and decision theory. In the past few years, MOILP has also been widely employed in environment planning, urban planning, production planning, resource allocation and supply chains management. MOILP is a suitable method for solving multi-objective MPAs site selection problems. Using MOILP, we can meet different functional demands or different levels of biological conservation while reaching the minimum cost of the spatial zoning of MPA cells.

In this study, we developed two spatial zoning models for multi-objective MPA planning based on MOILP. The proposed model formulations were inspired by the multi-site land use allocation study presented by Walters Aerts et al. (2003). The objective of their model was to minimize the cost of acquisition and satisfy the constraints imposed on each land use resource. Modeling for MPA designs and land use planning is similar; both problems require finding the best solution with a limited resource. While our MPA zoning models are based on the multi-site land use allocation model, biological conservation constraints are incorporated into our models. Ultimately, the aim of our models is to provide the best MPA zoning plan (i.e., the plan that satisfies different functional demands, specifically the levels of biological conservation) in each zone with a minimum implementation cost.

2.1.1. Buffer cells model

Using the BCM, we can design the study area with K functional zones depending on various levels of biological conservation or marine zoning needs. Each zone is composed of core cells and buffer cells, with buffer cells surrounding the core cells. The core cells represent the main functional zones, such as the no-take zone, recreational zone or any special MPA zoning plan requirement. Buffer cells are not intended to conserve features as core cells. Their function is to isolate each functional zone from the area outside of the MPA to mitigate the direct impact to core cells. We can control the MPA spatial distribution by adjusting the total number of buffer