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Invited Review

Mathematical optimization ideas for biodiversity conservation

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ABSTRACT

Several major environmental issues like biodiversity loss and climate change currently concern the international community. These topics that are related to the development of human societies have become increasingly important since the United Nations Conference on Environment and Development (UNCED) or Earth Summit in Rio de Janeiro in 1992. In this article, we are interested in the first issue. We present here many examples of the help that using mathematical programming can provide to decision-makers in the protection of biodiversity. The examples we have chosen concern the selection of nature reserves, the control of adverse effects caused by landscape fragmentation, including the creation or restoration of biological corridors, the ecological exploitation of forests, the control of invasive species, and the maintenance of genetic diversity. Most of the presented models are – or can be approximated with – linear-, quadratic- or fractional-integer formulations and emphasize spatial aspects of conservation planning. Many of them represent decisions taken in a static context but temporal dimension is also considered. The problems presented are generally difficult combinatorial optimization problems, some are well solved and others less well. Research is still needed to progress in solving them in order to deal with real instances satisfactorily. Moreover, relations between researchers and practitioners have to be strengthened. Furthermore, many recent achievements in the field of robust optimization could probably be successfully used for biodiversity protection, a domain in which many data are uncertain.

1. Introduction

Biodiversity, short for biological diversity, represents the diversity of living organisms and ecosystems. It also incorporates the interactions between living organisms and the interactions between living organisms and their environments. It is now accepted that biodiversity – species, genetic and ecosystem – renders important services to human societies and that its preservation is essential. Thus the United Nations General Assembly has approved in late 2010, the creation of the Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services (IPBES). Biodiversity is undergoing significant erosion and that erosion has consequences for the planet as serious, although less known, than those related to climate change. This decline of biodiversity disturbs ecosystem functioning and thus affects the quality of services they provide to human populations concerned. These include, for example, agriculture, food, housing, health, tourism and economy. Biodiversity loss is a particularly serious problem because it is irreversible. According to the latest update of the Red List of threatened plant and animal species established by the International Union for Conservation of Nature (IUCN), about 17,000 species on the 48,000 listed are threatened with extinction (http://www.iucn.org/). The Convention on Biological Diversity (CBD) adopted at the Earth Summit in Rio de Janeiro in 1992, and ratified by about 190 countries had identified five main factors causing biodiversity loss: fragmentation of spaces, overexploitation of species, pollution, invasive species and climate change. In 2002, the signatory countries of the CBD had adopted at the World Summit on Sustainable Development in Johannesburg, a strategic plan to achieve by 2010 a significant reduction in the rate of biodiversity loss. In 2010 the commission found that no country had managed to achieve this goal. At the 10th meeting of the CBD, held in Nagoya in October 2010, a new plan for biodiversity conservation for 2020 was adopted. Available resources to protect biodiversity are obviously limited and it is important to use them effectively. For this, two types of approaches are possible: a direct approach based on the properties and algorithms for mathematical optimization, and simulation approach. They each have their advantages and disadvantages. The approach by simulation, generally simpler to implement, has been widely used to address complex problems in ecology and sustainable development. The approach by mathematical optimization, more difficult to implement, has been less used, but unlike the simulation approach, it allows us to evaluate a large number of options. We illustrate in this article the help that using operational research – mainly mathematical programming – can bring to decision-makers in the implementation of key strategies to protect biodiversity. Among the many optimization problems involved in this area, we chose a few representative

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issues: the selection of nature reserves, the control of adverse effects caused by landscape fragmentation, the rational exploitation of forests, the fight against invasive species, and the maintenance of genetic diversity. The literature is very abundant on these subjects and, in this paper, we mainly limited ourselves to problems that can be formulated, more or less directly, by linear or nonlinear programming with integer or mixed-integer variables. The integer programming approach presents many advantages compared to specific algorithms: simplicity of implementation if an integer programming software is available, reliability of the method, exact or guaranteed approximate solution of the problem, and finally, possibility of easily modifying the model. Many of the considered problems are derived directly or inspired from the literature. Others are generalizations and finally, some of them are new. For problems of the literature, we present the formulations published and sometimes more interesting formulations. Carefully implemented, mathematical programming – also known as mathematical optimization – is a powerful tool that can be used to solve many problems of operational research. There are indeed very efficient algorithms for these problems and many software based on these algorithms are available. This should enable operational research to play an important role in the field of biodiversity conservation, as important as it plays in the fields of transport, energy, telecommunications and manufacturing. Finally, note that mathematical models are one small part of conservation planning. The management context, although important, is little addressed in this review the aim of which is to present mathematical optimization ideas widely applicable to biodiversity protection. Describing the management context and also assessing the utility and applicability of the models would be another work in itself. Regarding these issues, the reader may consult, for example, the following references: (Margules and Pressey, 2000) where six different stages are identified in systematic conservation planning, (Prendergast et al., 1999) where the utility of reserve selection algorithms is examined and the comments on this article by Pressey and Cowling (2001), (Lindenmayer et al., 2006) for a checklist of measures that reflects the multi-scaled nature of conservation approaches on forested lands, (Halkos and Jones, 2012) for an investigation of the influence of social factors on the decision of individuals to contribute an amount for improving environmental protection of biodiversity, (Bergseng and Vatn, 2009) for a discussion about the reasons for conflict in protection of biodiversity in forests, and (Wallace, 2012) for a planning framework in which the planning components are linked through cause-effect relationships and driven by human values.

2. Selection of nature reserves

2.1. Interest of nature reserves

Many countries have pledged to halt biodiversity loss in the near future and have adopted different strategies for this including the protection of land and sea areas. These protected areas – or reserves – play a decisive role in maintaining biodiversity because they aim directly at the protection of elements which have the strongest risk of extinction. These elements relate to flora, fauna, rocks, minerals and fossils, or major geomorphological sites. The objective is to ensure each threatened species or site has a place where its future is guaranteed. Thus, many governmental and nongovernmental programs seek to restore and protect habitat in order to preserve the species. At the 10th meeting of the CBD, a plan for biodiversity conservation for 2020 was adopted. It contains 20 goals including the restoration of degraded habitats and the establishment of protected areas (terrestrial, marine and coastal). Commenting on the plan, the President of the environmental organization *Conservation International*, said that the problem is not only quantitative but also qualitative and that the most important areas in terms of biodiversity must be protected. The resources available for this protection being obviously limited, it is important to use them efficiently. Until the 1980s, the proposed methods mainly consisted to rank the potential sites in order of interest by using scoring methods. Smith and Theberge (1986) and Cocks and Baird (1989) were some of the first authors to propose the use of mathematical optimization techniques for solving the problem of selecting which sites should ideally be included in a reserve network. Subsequently, many optimization models have been proposed in the literature of operational research and conservation biology to help select sites for designing reserves. These publications are usually theoretical, they are modeling realistic problems and propose algorithms – often heuristics – to solve them. Some authors discuss the applicability of these models (see e.g., Cabeza and Moilanen, 2001). Many objectives can be considered in selecting nature reserves. For example, Juutinen and Mönkkönen (2007) compare the obtained results with two different objectives, the presence of species and species abundance, while varying the relative weights of different species. They carry out their study using actual data for the boreal forest in Finland. Some articles are based on multi-objective mathematical programming (see e.g., Memtsas, 2003). Although many publications present applications of their models to real data (see e.g., Poulin et al., 2006; Toth et al., 2009; Fiorella et al., 2010; Groeneveld, 2010), few of them concern the actual use of these models by an organization to make decisions. Some articles discuss the gap in this field between theory and practice (see e.g., Prendergast et al., 1999; Pressey and Cowling, 2001; Knight et al., 2008; Schindler et al., 2011; Braunisch et al., 2012; Jolibert and Wesselink, 2012). Several software for selecting nature reserves are currently available. *Marxan* (http://www.uq.edu.au/marxan/) finds good solutions to a mathematically well-specified problem. Different optimization techniques are used to drive the optimization phase of this software: integer linear programming to obtain exact optimal solutions and metaheuristics such as genetic algorithms and simulated annealing to obtain approximate solutions. The reader can refer to (Ball et al., 2009) for a comprehensive description of this software including an example of its application to a conservation prioritization for the entire Australian continent. Other valuable software are also available: *Zonation* (http://www.helsinki.fi/bioscience/consplan/software/Zonation/index.html) and *C-Plan*, (http://www.edg.org.au/free-tools/cplan.html).

With regard to *Zonation* and *C-Plan*, the reader may refer to Moilanen et al. (2009) and Pressey et al. (2009), respectively. The reader may also refer to Sarkar et al. (2006), a comprehensive survey on the biodiversity conservation planning tools presented in the conservation biology literature. Among other things this survey reviews the various software tools for conservation planning that have been developed over the past 20 years. Four other interesting references are (Pressey et al., 1996), (Rodrigues and Gaston, 2002b), (Fischer and Church, 2005) and (Vanderkam et al., 2007). In these articles the authors compare exact and heuristics approaches to solve some reserve selection problems.

We present below some selection reserve problems and their formulation by mathematical programming. We first consider the basic problem and some variants. This problem is to select a set of areas, of minimum cost, to protect a set of predefined species. A variant consists in determining, under a budget constraint, a set of areas to protect a maximum number of species. These problems can be modeled easily by 0–1 linear programs and can be solved efficiently by commercial solvers. We then illustrate consideration of spatial constraints. These constraints may affect the compactness of the reserve, its connectivity or its shape. They can also impose a specific role to different areas of the reserve (central zone and buffer zone, for example). Taking into account