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A review of multi-criteria optimization techniques for agricultural land use allocation

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A B S T R A C T

Optimal land use allocation with the intention of ecosystem services provision and biodiversity conservation is one of the key challenges in agricultural management. Optimization techniques have been especially prevalent for solving land use problems; however, there is no guideline supporting the selection of an appropriate method. To enhance the applicability of optimization techniques for real-world case studies, this study provides an overview of optimization methods used for targeting land use decisions in agricultural areas. We explore their relative abilities for the integration of stakeholders and the identification of ecosystem service trade-offs since these are especially pertinent to land use planners. Finally, we provide recommendations for the use of the different optimization methods. For example, scalarization methods (e.g., reference point methods, tabu search) are particularly useful for a priori or interactive stakeholder integration; whereas Pareto-based approaches (e.g., evolutionary algorithms) are appropriate for trade-off analyses and a posteriori stakeholder involvement.

Contents

1. Introduction 80
2. Solving land use allocation problems with multi-criteria decision analysis (MCDA) 80
  2.1. An overview of MCDA 80
  2.2. Optimization methods 82
    2.2.1. Scalarization methods 82
    2.2.2. Pareto-based methods 83
    2.2.3. Hybrid methods 84
    2.2.4. Constraint handling 84
3. Stakeholder integration 84
4. Discussion & recommendations 85
  4.1. Using scalarization methods 85
  4.2. Using Pareto-based methods 87
  4.3. Recommendations for the method selection 87
5. Conclusion 88
Acknowledgement 88
Appendix 88
References 91

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1. Introduction

Humans have been changing landscapes for millennia by converting natural areas for agricultural production and settlement (Delcourt and Delcourt, 1988). As a result, "40–50% of the world's land surface had been visibly transformed" for these purposes by the 20th century (Western, 2001). Many of the different land uses are conflicting: for instance, there is agricultural and timber production on one side, competing with space for urban settlements or protected areas on the other side. All these anthropogenic usages impact the provision of ecosystem services (ESS) and therefore directly affect, for example, soil quality as well as water quantities and quality (Fontana et al., 2013). Meanwhile, natural areas provide habitats for wildlife and are especially important for the protection of endangered species (Behrman et al., 2015). Biodiversity loss has been directly linked to land use changes (Sala et al., 2000), and population growth as well as increases of agricultural land use have been labelled the biggest threat to biodiversity and ESS (Behrman et al., 2015).

One way to address biodiversity loss is to integrate ESS into systematic conservation planning (Faith, 2015) and re-allocate land uses in order to support the multifunctionality of landscapes. Sustainable land use allocation therefore seeks to take into account the current and future provision of ESS and biodiversity in order to determine so-called 'optimal' land use allocations. In general, land use allocation (also sometimes referred to as land use planning (Stewart et al., 2004)) is a type of resource allocation and can be defined as the process of allocating different activities or uses (e.g., agriculture, residential land, recreational activities, conservation) to particular areal units within a region (Cao et al., 2012). Agricultural land use allocation specifically deals with the allocation of species and activities to areas in agricultural landscapes (Memmah et al., 2015).

Decision support research within the field of natural resources management has relied heavily on multi-criteria decision analysis (MCDA) and its corresponding tools (Mendoza and Martins, 2006). In this paper, we provide a detailed review of MCDA and focus in particular on one branch of MCDA – optimization techniques – since land use allocation problems have been widely formulated as mathematical optimization problems. These problems typically consider multiple, mostly conflicting objectives and aim to minimize the trade-off between them (Liu et al., 2013; Porta et al., 2013). These can include trade-offs between various ESS such as provisioning and regulating services but also between ESS and biodiversity. A trade-off describes the amount that has to be given up of one ESS in order to increase the provision of another (Rodríguez et al., 2006). For example, the intensification of agricultural production may reduce water quality due to a greater use of fertilizers and pesticides and the resulting nonpoint emissions of pollutants from the agricultural fields. The main task is thus to find the right balance between the usage of different ESS.

Solving complex, real-world land use allocation problems remains a key research challenge (Fowler et al., 2015). Additionally, recent applications underline the need for methods that allow for increased stakeholder involvement (Eikelboom et al., 2015; Stewart et al., 2004; Uhde et al., 2015). This is particularly important since "agricultural land use allocation involves many competing actors such as farmers, farmers associations, environmental agencies, land planners and economists" (Memmah et al., 2015). Participatory approaches thus help to find solutions that achieve biophysical objectives but also consider the different perspectives and preferences of various stakeholders (Groot and Rossing, 2011).

Land use allocation problems can greatly differ in their mathematical formulation and therefore require different optimization techniques (see Section 2.2). However, the choice of a technique is often not guided by the characteristics of a problem but depends on the experience of the reseacher in charge or on historical usages (Memmah et al., 2015). While there exist some reviews about MCDA approaches and their applicability particularly in forest management (Mendoza and Martins, 2006; Uhde et al., 2015), current literature lacks guidelines for how to choose the best suitable optimization technique for a particular agricultural land use allocation problem. Therefore, this paper aims to fill this gap by providing a review of current MCDA optimization techniques and their applicability for land use allocation problems; we specifically focus on agricultural landscapes and on studies that aimed to achieve objectives related to ESS and biodiversity.

The following sections provide a review of optimization approaches that have been used in land use management. For an overview, we first classify multi-objective optimization within the broader field of decision support techniques giving an introduction to MCDA. Then, we evaluate different multi-criteria optimization methods in terms of their ability to integrate stakeholder opinions and identify trade-offs between ESS and biodiversity. Furthermore, we mention how constraints can be handled. The suitability of the optimization approaches for different types of land use allocation problems is discussed before we provide a short conclusion and give directions for further research.

2. Solving land use allocation problems with multi-criteria decision analysis (MCDA)

2.1. An overview of MCDA

MCDA has been widely used to perform mathematical optimization in order to analyze multi-objective decisions and incorporate the varying opinions of decision-makers (Collins et al., 2001). MCDA addresses land allocation problems in a more realistic way than single-objective approaches, since in practice, these problems consist of multiple, conflicting objectives (Antoine et al., 1997), especially when multiple ecosystem services are taken into account (Birkhofer et al., 2015). Furthermore, MCDA methods can combine ecological objectives with social and economic criteria and are able to consider non-market values of ESS. Therefore, they are very popular and frequently used in ecological economics (Fontana et al., 2013; Uhde et al., 2015; van Huylenbroeck, 1997).

Most of the literature classifies multi-criteria optimization either within the broader field of decision support systems (e.g., Myllyviita et al. (2011)) or within MCDA directly (e.g., Aerts et al. (2003)). Therefore, we first provide an overview of the linkage between the two fields and where multi-criteria optimization is set amongst these (see Fig. 1).

MCDA is one of many decision support techniques, which can be divided into qualitative, quantitative and hybrid methods. Qualitative methods (e.g., interviews, voting), focus on structuring a problem. They also help to define initial goals and to evaluate stakeholders' opinions (Myllyviita et al., 2011; Uhde et al., 2015). Cost-benefit analysis (CBA) and MCDA – including mathematical optimization techniques – belong to the group of quantitative methods that use numerical information in order to evaluate a number of decision alternatives. Finally, hybrid methods are composed by the combination of different approaches (see Uhde et al. (2015) for an overview of hybrid MCDA methods in forest management).