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Value-based ecosystem service trade-offs in multi-objective management in European mountain forests

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ABSTRACT

Mountain forests provide a diverse range of ecosystem services (ES). In case of conflicting ES, trade-offs must be considered in forest resource planning. In this study, simulation-based scenario analysis and multi-criteria decision analysis is used to analyse expected utilities and value-based trade-offs in multi-objective forest management related to four key ES (timber production, carbon storage, biodiversity conservation, protection against gravitational hazards) in three European mountain regions. In each case study area a set of management alternatives including no-management were simulated over 100 years and ES quantified using ES indicators. Multifunctional goal scenarios are employed to aggregate partial ES utilities, accumulated RMSE between ES are used to quantify trade-offs. In two analysed case study areas no-management generated highest ES utilities for biodiversity conservation, carbon storage and protection against gravitational hazards. Alternatives based on small-scale silviculture combined timber production and biodiversity conservation very well. In all case study areas increasing goal preferences for timber production or biodiversity and nature conservation result in increasing overall trade-offs with rather decreasing overall utilities. In all case study areas the analysed managements support multiple ES and can thus be considered as multifunctional. Based on the presented analysis management alternatives could be further improved.

1. Introduction

Mountain forests have to provide a diverse range of ecosystem services (ES) such as timber, berries and mushrooms, carbon storage, water run-off regulation, protection against avalanches, rockfall, landslides and erosion, habitat for wildlife, and recreation. These services are essential for the ecological, economic and social functions of mountain regions themselves but benefit also regions further downstream (European Environment Agency, 2010; Schlaepfer et al., 2002; Millennium Ecosystem Assessment, 2005). Multifunctionality, meaning the simultaneous provision of a bundle of ecosystem services from relatively small parcels of forest land, has a long tradition in mountain forestry (Buttoud, 2002; Schlaepfer et al., 2002). However, according to Suda and Pukall (2014) and Hanewinkel (2011) there is a lack of explicit and transparent definition of management objectives and planning procedures for multiple ecosystem services, and consequently the evaluation of successful management activities in providing multiple ecosystem services is severely hampered (see also Rauscher, 1999).

In case of conflicting ES, trade-offs are inevitable and must be considered in forest resource planning. Trade-offs occur when the provision of one ES is reduced because of the increased use of another ES (Howe et al., 2014; Raudsepp-Hearne et al., 2010) or if external drivers such as management or climate change push the ecosystem into a state where one service is favoured at the cost of another (Bennett et al., 2009). The potential for trade-offs between objectives increases as the number and variety of management objectives grows (Bradford and D'Amato, 2012). A particular challenge in mountain forests is the demand for place-based services such as protection from gravitational hazards which can neither be substituted in space nor in time.

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While recently an increasing number of studies on ES provisioning by mountain forests became available, knowledge about ES trade-offs in European mountain forests in dependence of forest management regimes is still limited (Briner et al., 2012; Häyhä et al., 2015; Irauschek et al., 2015; Seidl and Lexer, 2013; Uhde et al., 2015).

According to Seppelt et al. (2013) there are two main approaches to analyse trade-offs among ES: (1) scenario-based approaches, and (2) multi-objective optimization. Scenario-based approaches require a priori definition of a discrete number of solutions (i.e. management alternatives) and the related decision matrix of (n) ES indicators for (m) alternatives. The decision matrix can be generated by simulation modelling, qualitative judgements or empirical data. Trade-off relationships among the ES indicators can be analysed visually with bivariate scatter plots or spider diagrams and correlation analysis (e.g. Häyhä et al., 2015). Bradford and D'Amato (2012) proposed the root mean squared error (RMSE) between pairs of ES to quantify trade-offs imposed by a specific alternative (see also Lu et al., 2014).

With optimization approaches, management alternatives are not specifically known prior to the analysis. The principal goal of multi-objective optimization methods is to identify the Pareto frontier. Solutions that are located on the Pareto frontier are called Pareto efficient and moving along the Pareto frontier necessitates a trade-off (Eskelinen and Miettinen, 2012; Seppelt et al., 2013). The Pareto frontier can also be approximated by scenario simulations; however, a huge number of simulations would be required. This in turn may be prohibitive for complex forest ecosystem models due to overly huge computing time.

Compared to multi-objective optimization approaches, scenario analysis based approaches have the advantage that a particular solution, i.e. a management alternative, is most likely feasible as it was designed prior to the analysis. However, as only a limited number of alternatives are investigated, these solutions might be sub-optimal. In contrast, multi-objective optimization identifies all – or at least a huge number of – optimal solutions. However, solutions might be not achievable in real life due to social, institutional, technical or economic limitations (Seppelt et al., 2013).

Furthermore, direct and value-based trade-offs must be distinguished (Eskelinen and Miettinen, 2012). The former measures the change in one ES indicator in relation to the change in another one, when moving from a feasible solution to another one. Value-based trade-offs consider subjective preferences and interests in determining the sacrifice of some objectives when one alternative is preferred over another (Eskelinen and Miettinen, 2012).

A useful set of tools for value-based analysis is provided by multi-criteria decision analysis (MCDA) which is often used for evaluating and choosing among alternatives by aggregating expected benefits from individual objectives (i.e. ES) to an overall benefit (e.g. Ananda and Herath, 2009; Diaz-Balteiro and Romero, 2008; Kangas and Kangas, 2005; Mendoza and Prabhu, 2000). Preferences of decision makers and stakeholders for specific ES are made explicit and used in the evaluation of alternatives. In most applications identifying the best alternative is the main objective while the aspect of trade-offs between ES has been rarely covered (Uhde et al., 2015).

This study sets out to analyse ES provisioning in three European mountain regions. Specifically, the study combines simulation-based scenario analysis and multi-criteria decision analysis (i) to explore the multifunctional benefits of alternative forest management options from different stakeholder perspectives, and (ii) to identify related value-based trade-offs between ES.

2. Material and methods

2.1. Case study areas

For the current analysis data from three case study areas (CSA) of the ARANGE project (''Advanced Multifunctional Forest Management in European Mountain Ranges''; www.arange-project.eu) were available: Valsain in the Sierra Guadarama in central Spain, Montafon in the Eastern Alps in Austria, and Shiroka laka in the Rhodope Mountains in Bulgaria. The three study regions represent distinct biophysical settings on a West-East gradient in Europe. The Spanish case study represents a sub-Mediterranean forest composed mainly of *Pinus sylvestris* and *Quercus pyrenaica* and serves as an important recreation area due to its proximity to the city of Madrid. The alpine case study area in Austria is dominated by *Picea abies* and is characterized by steep slopes (30–45°) requiring skyline-based logging techniques. The case study area in Bulgaria features various broadleafed, mixed broadleaf-conifer and conifer stand types along the altitudinal gradient (see also Table 1).

2.2. Forest scenario simulations

To assess ES provisioning under different management regimes representative stand types (RST) in all case study areas have been simulated with the forest ecosystem model PICUS v1.5 (Lexer and Hönninger, 1998; Seidl et al., 2005) for a 100-year assessment period (2010–2110).

PICUS generates stand and tree attributes at annual resolution which are used to calculate indicators for one provisioning service (timber production) and three regulating services (carbon storage, biodiversity and nature conservation, protection against gravitational hazards). A brief model introduction as well as an overview on climate data and management regimes are provided below.

2.2.1. PICUS

PICUS is a hybrid of classical gap model components (PICUS v1.2, Lexer and Hönninger, 2001), process-based stand-level NPP algorithms (3PG, Landsberg and Waring, 1997) and carbon and nitrogen cycling algorithms based on Currie et al. (1999). A detailed description of the model is provided in Seidl et al. (2005). Here, just a brief overview on the core model concept is given.

Table 1
Case study area overview.

Case study area	Mountain range	Altitudinal range [m a.s.l.]	Stand types
Valsain, Spain	Iberian Central Mountains	1180–2130	*Quercus pyrenaica;Quercus pyrenaica & Pinus sylvestris; Pinus sylvestris*
Montafon, Austria	Eastern Alps	1060–1800	*Picea abies & other species; Picea abies & Fagus sylvatica& other species; Picea abies & Fagus sylvatica & Abies alba & other species; Picea abies & Acer pseudoplatanus & other species; Picea abies & Abies alba & other species*
Shiroka laka, Bulgaria	Western Rhodopes	1000–2100	*Fagus sylvatica; Pinus nigra & Picea abies & Fagus sylvatica; Pinus sylvestris & Pinus nigra & Picea abies & Fagus sylvatica; Picea abies & Abies alba; Picea abies*