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METHODS

Modelling of forest conversion planning with an adaptive simulation-optimization approach and simultaneous consideration of the values of timber, carbon and biodiversity

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ABSTRACT

The paper presents a combined simulation–optimization approach to model forest conversion planning taking the values of timber, carbon and biodiversity into account. The development of a virtual age-class forest was predicted by adopting a single tree forest growth tool, "TreeGrOSS". The effects of different conversion regimes with continuous variables describing silvicultural prescriptions were monitored for a finite conversion period of forty years in stand level. Dynamic linear programming was employed to adaptively solve the multi-period large-scale optimization problem of a forest enterprise encompassing five different age-classes of pure Norway spruce (*Picea abies*, L. Karst) stands. The global net present values of biodiversity, carbon sequestration and timber production along with the wood even flow constraint, were considered simultaneously. The obtained optimal sylvicultural pathway differed not only among different stands but also sometimes within a given stand. The integration of the utility of biodiversity into the optimization procedure favoured conversion strategies that foresee the establishment of beech regeneration in all forest stands. The simultaneous consideration of all mentioned utilities resulted in a global utility of 27451 €/ha consisting of 14499 (53%), 3412 (12%), 764 (3%), and 8777 (32%) €/ha for the value of timber, carbon, biodiversity, and standing volume respectively. The sensitivity analysis showed that the threshold from which no major changes in the relevant silvicultural parameters occurred was observed at 30 €/t carbon price with an interest rate of 2%.

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1. Introduction

1.1. *Forest conversion as an ecological and economic need*

The forests of the south-western Germany in the Black Forest are largely dominated by pure even-aged stands, with the coniferous forests mainly composed of Norway spruce (*Picea abies* L. Karst), which are very vulnerable to natural hazards and changing environmental conditions (Hanewinkel and Pretzsch, 2000; Rojo and Orois, 2005; Knoke et al., 2008). As a reaction to the unsatisfactory economic and ecological situation of the management of pure even-aged stands, species enrichment and other ecological benefits through the conversion of even-aged pure stands into multi-layered uneven-aged mixed forest stands is presently a major concern of forest management in Central Europe (Knoke et al., 2008), as

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well as in Germany (Hanewinkel and Pretzsch, 2000). However, only little is known about the ecological economics of such a conversion to state of the art planning of such a complex forest management.

1.2. Modelling of forest growth using simulators

Forest management planning needs to identify the most desirable silvicultural pathways regarding the global objectives and constraints of the whole forest enterprise (Buongiorno and Gilless, 2003; Yoshimoto and Marusak, 2007). Therefore, there is an obvious need for the modelling of the evolution of forests over time and choose the optimal management alternative. The simulation-optimization approach is a suitable management tool widely used in the literature to solve forest modelling problems (Haight et al., 1985; Gong, 1992; Buongiorno, 2001; Diaz-Balteiro and Rodriguez, 2006; Baskent et al., 2008a,b). In this approach, the prediction of the effects of different silvicultural treatments on forest stands is a primary modelling step towards forest management planning (Pretzsch et al., 2008).

In the last decades, many forest growth simulators have been developed to help modelling of forest evolution and predict the effects of different silvicultural interventions on forest parameters (e.g. Baskent and Sedat, 2005). However, many of these simulators are only able to deal with traditional timber production and may not be adaptable to a wide range of forest management issues like forest conversion, forest protection and many of the criteria of sustainable forest management. In order to investigate a complex forest management problem such as forest conversion, taking into account a multitude of objectives, a new simulation tool has to be developed or existing forest modelling tools must be adjusted to the problem in question using newly developed forest growth models (Hasenauer, 2006). In the present study, a single tree forest growth modelling tool, "TreeGrOSS", recently developed in a Java-Netbeans environment (TreeGrOSS, 2006) was modified to simulate forest growth and predict the effects of alternative conversion regimes on a wide range of forest parameters.

1.3. Dynamic linear programming (DLP)

The second modelling step in the simulation–optimization approach was to develop a suitable optimization program to discover the most desirable conversion pathway (Buongiorno and Gilless, 2003). The classical optimization algorithms such as Linear Programming (LP), Non-Linear Programming (NLP) and Dynamic Programming (DP) have proven to provide powerful search models to deal with forest management problems under a multitude of objectives (Haight et al., 1985; Teeter and Somers, 1993; Tarp et al., 1999; Buongiorno and Gilless, 2003; Diaz-Balteiro and Rodriguez, 2006; Lohmander, 2007; Baskent et al., 2008a,b). Among these methods, having a sequence of interrelated decisions, DP provides the most efficient procedure to solve a forest optimization problem with an adaptive decision (Haight et al., 1985; Tarp et al., 1999; Diaz-Balteiro and Rodriguez, 2006; Lohmander, 2007). LP is a method that can solve large-scale problems, is able to find optimal solutions and offers the opportunity of a post-optimality analysis (Buongiorno and Gilless, 2003; Baskent et al., 2008a,b). In the present study, a combination of dynamic programming and linear programming was used to develop an adaptive dynamic optimization tool, which can efficiently find an optimal solution. The tool is an adapted version of a similar technique that was originally developed and used by Tarp et al. (1999). Dynamic linear programming (DLP) searches for the most desirable transition path from one management condition to a desired state for each stand and for all stands of the forest enterprise.

1.4. Integration of biodiversity and carbon sequestration

A challenging aspect in the forest optimization procedure arises when the integration of decision criteria like biodiversity and carbon sequestration is part of the forest management problem (Buongiorno and Gilless, 2003; Backeus et al., 2005; Navarro, 2003; Yoshimoto and Marusak, 2007; Zell, 2008; Baskent et al., 2008a,b). It is not only difficult to find and define the related relevant indices but also the economic valuation of these indices causes problems (Kangas and Kuusipalo, 1993; Zhou and Buongiorno, 2006; Yousefpour et al., 2008).

In this study, a newly developed mathematical procedure was used to monetize the Shannon index (Yousefpour et al., 2008), an index of ecological diversity and one of the most widely accepted and used measure of biodiversity (Önal, 1997; Buongiorno and Gilless, 2003). The value of carbon sequestered in the forest was calculated indirectly from dry biomass (Backeus et al., 2005; Yoshimoto and Marusak, 2007; Zell, 2008). The utilities of carbon and biodiversity along with the traditional utility of timber production and a global timber even flow constraint were considered to simulate and optimize the modelling of forest conversion planning on a forest enterprise level.

1.5. Problem formulation and solution

The management problem under investigation in the present study was the conversion from pure even-age stands of Norway spruce into mixed and/or uneven-age stands of Norway spruce and European beech (*Fagus sylvatica* L.). Beech is a native species in large areas of the low mountain ranges of Central Europe such as the Black Forest and is therefore usually the most recommended species for the conversion of pure spruce forests (i.e., Hanewinkel, 1998; Schütz, 2002; Knoke et al., 2008). In the present study, the forest conversion alternatives have been defined according to the approach of Hanewinkel (Hanewinkel, 1998; Hanewinkel and Pretzsch, 2000; Hanewinkel, 2001a,b) in four phases (corresponding to four simulation periods of ten years): i) selective thinning ii) quality improvement cut iii) gap installation and regeneration establishment, and iv) final phase of partial target diameter harvest.

Previous studies e.g. by Buongiorno (2001) quantified the implications of transformation from even to uneven-aged forest stands. Knoke et al. (2008) investigated the admixture of broadleaves to coniferous forests from an ecological and economic point of view. Rojo and Orois (2005) developed a decision support system to optimize conversion paths from even to uneven-aged stands of maritime pine (*Pinus pinaster* Ait.)

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