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Optimal management of naturally regenerating uneven-aged forests

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ABSTRACT

A shift from even-aged forest management to uneven-aged management practices leads to a problem rather different from the existing straightforward practice that follows a rotation cycle of artificial regeneration, thinning of inferior trees and a clearcut. A lack of realistic models and methods suggesting how to manage uneven-aged stands in a way that is economically viable and ecologically sustainable creates difficulties in adopting this new management practice. To tackle this problem, we make a two-fold contribution in this paper. The first contribution is the proposal of an algorithm that is able to handle a realistic uneven-aged stand management model that is otherwise computationally tedious and intractable. The model considered in this paper is an empirically estimated size-structured ecological model for uneven-aged spruce forests. The second contribution is on the sensitivity analysis of the forest model with respect to a number of important parameters. The analysis provides us an insight into the behavior of the uneven-aged forest model.

1. Introduction

Optimizing the use of forest resources has hundreds of years of history. The infinite horizon model specified in Faustmann (1849), reintroduced by Samuelson (1976) and extended in numerous papers like Kao and Brodie (1979) and Chen, Rose, and Leary (1980) served as a cornerstone both in research and in practical forestry applications. In its generic form the model determines optimal forest rotation, i.e., the length of optimal interval between clearcuts. However, it is seldom noticed that since this model is most suitable for plantations (Yoshimoto & Shoji, 1998), it has directed research to forests that actually cover only 7 percent of the total world forest land area. Our study presents major progress in the line of research that serves developing the management of more natural forest stands that have great potential in solving several pressing problems related to forest environment.

The alternative to plantations is to rely on native tree species, natural regeneration and continuous forest cover, i.e., to manage forests as heterogeneous uneven-aged systems. The rationale of this model depends on tree species, but for shade-tolerant trees the economic outcome may become fully competitive because of natural regeneration and more accurate targeting of cuttings to those trees that are financially mature. Additionally, managing forest resources in more natural and heterogamous state has high potential in coping with problems such as climate change (Field, Barros, Mach, & Mastrandrea, 2014), loss of biodiversity and landscape esthetics (Thompson, Mackey, McNulty, & Mosseler, 2009). Multi-criteria decision making approaches have also been used in the past to meet multiple objectives in forest management problems (Nhantumbo, Dent, & Kowero, 2001; Steuer & Schuler, 1978). Interest in continuous cover forestry is increasing in Nordic countries and UK, for e.g., in Finland it has been released from a 70 year of legislation ban from the beginning of 2014. According to surveys a major problem among forestry professionals is the suspense of the alternative system's economic viability (Valkonen & Cheng, 2014).

While the Faustmann approach describes a chain of exactly similar even-aged cohorts, the model for more natural forests includes the internal structure of heterogeneous trees. As shown in the seminal paper by Adams and Ek (1974) this expands model dimensions and the development of the research has been a struggle against limitations in computing capacity. This has led researchers to develop various simplifications with the cost of losing economically and mathematically sound theoretical structure as already surveyed by Getz and Haight (1989). Most studies still circumvent the problems by studying the fundamentally dynamic problem in a static setup with limited scientific progress and low practical credibility. One problem is in solving a multiple state variable infinite horizon model from any initial stand state.

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A straightforward solution for this problem was given already in Haight and Monserud (1990): lengthen the planning horizon until the approach path towards a stationary state (or cycle) becomes invariant from further lengthening and consider it as an approximation of the infinite horizon solution. Given a single tree species cases this leads to solvable problems with e.g., 200 periods and 24 optimized variables per period; albeit non-linearities and non-convexities require special attention. Besides dimensionality the other problem is that the optimal solution becomes cutting stand every period which does not make sense in the presence of fixed harvesting cost and the fact that too small yield is commercially invaluable. Fixed harvesting cost is taken into account in even-aged models, like Tahvonen, Pihlainen, and Niinimäki (2013), with the implication that optimal number of intermediate cuttings is between zero and five periods (25 years) depending on factors like site fertility and interest rate. However, in the even-aged problem all rotations are similar implying that the time horizon in computation is relatively short (40–150 years) and the number of combinational variables are usually six or lower. In uneven-aged models, Haight and Monserud (1990) take this into account by allowing cuttings every 20 years only. Wikström (2000) includes fixed harvesting cost and computes solutions using Tabu search under the simplification that regeneration is fixed to 50 trees per 5 years period and that stand volume is not allowed to decrease below a level determined by Swedish forest legislation. He does not interpret his results on harvesting interval but it seems to vary between 5 and 20 years without any systematic pattern. In Tahvonen (2011) the model includes fixed harvesting cost which leads to optimal harvesting period of 15–20 years under the constraint that the interval is constant over time.

Given these studies, the proper solution method and most general solutions for the uneven-aged management problem are still open. This is pressing in the practically most important cases where the initial forest state is a consequence of even-aged management and the problem is to solve optimal path or transition to uneven-aged management. This question has been studied in numerous works with specifications without full generality. In this paper we make a two-fold contribution. As the first contribution we develop a computational method for solving uneven-aged stand management problems that is a large scale mixed integer non-linear program; and as the second contribution we provide an analysis for the uneven-aged stand management model. The solution method for handling the problem is based on the following:

1. A two-level approach with genetic algorithm at the upper level and continuous non-linear programing at the lower level: the approach is faster by more than an order of magnitude in terms of computation time as compared to branch-and-bound method. This supports handling of large scale uneven-aged management problems.
2. Modeling the infinite time horizon uneven-aged stand management problem into a tractable problem by assuming transition and steady states: the assumption causes no loss of generality as the transition and steady state lengths are assumed to be endogenous subject to optimization. For an earlier study on forest management practices where the time horizon is divided into transition and steady states the readers may refer to Salo and Tahvonen (2003).

A faster algorithm allowed us to perform a number of computational studies by varying the parameters in the uneven-aged stand management problem. This provided us an insight into the behavior of the uneven-aged model. These insights may play a significant role in directing future research on uneven-aged management.

The later part of the paper is structured as follows. In Section 2 we discuss the size-structured stand model and introduce the net present value maximization problem. This is followed by the description of the algorithm in Section 3 that is used for solving the optimization problem. Thereafter, in Section 4 we present the results and provide comparisons against the standard approaches that are used to solve uneven-aged stand management problems. Finally, the conclusions are provided in Section 5, where we also highlight the future research directions on uneven-aged stand management. The paper includes appendices that provides additional computational results.

2. Size-structured forestry model

The model being considered in this paper is a discrete infinite time horizon model that involves two kinds of variables that are listed below:

1. Binary variables representing the harvesting stages, i.e., whether to harvest or not to harvest at a particular time stage.
2. Continuous variables that define the state of the forest and the extent of harvests at each time stage, among other variables.

A forest management strategy is shown in Fig. 1 that we want to optimize for maximum net present value (*NPV*) over an infinite horizon in a discrete time framework. The time stages are represented as $t = 0, 1, 2, \ldots$ on an infinite time horizon. Harvesting stages are represented by δ_t that takes values 0 or 1 with 1 denoting that harvesting is done and 0 denoting that no harvesting is done at a given time stage. The forest states and the extent of harvests are represented with vectors x_t and h_t respectively. We discuss forest land of one hectare. Larger forest areas require minor and straightforward modifications which we omit. The size-structured forestry model defined in this section utilizes a number of symbols that are described in the discussions. For ease of reference we have also provided these symbols in Table 1.

Trees in the forest are subdivided into a finite number of size classes s for $s = 1, 2, \ldots, n$ in increasing order. Let x_{st} be the number of trees in size class s at stage t and define vector $x_t = (x_{st})$. For $t = 0$, x_0 is the given initial state of the forest. Let vector $h_t = (h_{st})$ denote the level of harvesting at stage t. Component h_{st} is the number of trees harvested in size class s at time stage t. For all t, let δ_t be a binary variable indicating whether harvesting takes place at stage t ($\delta_t = 1$) or not ($\delta_t = 0$). Then a logical requirement for harvesting levels is

$$h_t = \delta_t h_t. \tag{1}$$

Before stating the optimization problem we introduce a number of endogenous auxiliary variables concerning forest dynamics and cash flow. Martin Bollandsås, Buongiorno, and Gobakken (2008) use Norwegian National Forest Inventory data and estimate uneven-aged models for most common Nordic tree species. In our study we use their data for Norway spruce.

Given basal area b_s of a tree in size class s, the total basal area (per hectare) at stage t is

$$B_t = \sum_s b_s x_{st} \tag{2}$$

and the total basal area (per hectare) of trees in size classes larger than s is

$$B_{st} = \sum_{i>s} b_i x_{it}. \tag{3}$$

Ingrowth ϕ_t of trees in step Δ into the smallest size class 1 as a function of basal area B_t is

$$\phi_t = \frac{S_1 (B_t + B^0)^{-\nu}}{1 + S_2 \exp(\gamma B_t)} \tag{4}$$

where S_1, S_2 , B^0, γ and ν are positive parameters. Mortality μ_{st} is the share of trees dying in size class s in one step Δ. As a function