Chapter 6
Optimizing Continuous Cover Forest Management

Kari Hyytiäinen and Robert G. Haight

1 Introduction

The practice of silviculture involves the art and science of controlling the establishment, growth, composition, health, and quality of forests and woodlands to meet the diverse needs and values of landowners and society on a sustainable basis (Helms 1998). Silvicultural practices are often divided into two broadly defined management systems, which in North America are usually referred to as "even-aged" and "uneven-aged" management. In the context of this book, "uneven-aged" management is synonymous with continuous cover forestry (CCF). The choice of appropriate management system is guided by case-specific considerations, including ecological requirements of tree species currently present and desired; effects of timber harvest on forest flora and fauna; risk of damage from wildfire, insects, or pathogens; and financial and other landowner objectives for the managed forest. Skillful use of silvicultural practices can achieve the landowner's objectives with greater assurance of success than will reliance on natural processes alone.

Financial objectives are important for both public and private forest land managers. The goal of this chapter is to lay out the theoretical foundations for evaluating the relative economic efficiency of alternative forest management systems and to present an overview of approaches and applications used for studying the economic questions of uneven-aged management. Our review focuses on stand-level economic studies. A forest stand serves as the smallest operational unit of forestry, and is thus the appropriate level for investigating the efficiency of alternative chains of stand management. Like the majority of studies in this field, we consider and formulate

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K. Hyytiäinen (✉)
MTT Agrifood Research Finland, Latokartanonkaari 9, 00790 Helsinki, Finland
e-mail: kari.hyytiainen@mtt.fi

R.G. Haight
US Forest Service Northern Research Station, 1992 Folwell Ave, St. Paul, MN 55108, USA
e-mail: rhaight@fs.fed.us

T. Pukkala and K. von Gadow (eds.), *Continuous Cover Forestry*, Managing Forest Ecosystems 23, DOI 10.1007/978-94-007-2202-6_6,

the forest management problem from the point of view of non-industrial private landowners. Such analysis is relevant for societies where land ownership rights are well established and private forests represent an important share of total forest area.

Profitability is one important factor landowners consider when they make decisions regarding their forest. Basically, the same economic principles apply for continuous cover forestry as for any other forest management system: the forest should provide, in the long run, more benefits than costs, including capital costs. The chains of management activities differ significantly between even-aged and uneven-aged management, and different formulations are needed for evaluating economic performance.

The remaining parts of this chapter are organized as follows. First, we present a method for computing net present value, which serves as a measure of economic efficiency. We provide a general formulation and then, as separate special cases, equations for even-aged management and uneven-aged management. Second, we review the literature in the discipline. Third, we present a detailed study that evaluates the relative efficiency of even-aged and uneven-aged management under the risk of wildfires. The final section presents our conclusions and suggestions for further research.

2 Landowner's Management Problem

A landowner for whom profit is the only objective manages his or her forestland such that the economic surplus from management is the highest possible. This is achieved by planning stand management such that the net present value of the future flow of forest products and services, net of costs, is maximized. For a given stand of trees and chain of silvicultural operations, the net present value, *NPV*, is computed simply by discounting all future revenues and costs, occurring in year t after the present, to the present and taking the sum over all years:

$$NPV = \sum_{t=0}^{\infty} e^{-rt} \left[\sum_{i=1}^{m} p_{it} q_{it} - \sum_{j=1}^{n} C_{jt} \right] \tag{6.1}$$

Annual gross revenues are computed by multiplying the amounts of m forest products and services q_{it} by their prices p_{it}. Products and services may be timber, hunting licenses, or amenity services that are purchased from the landowner. Costs are determined for all n management activities, including harvests and silvicultural activities. Silvicultural activities can be considered as investments that are done to improve production capacity of the stand. The rate of interest is denoted by r. It represents the expected return from alternative uses of capital. Discounting is a financial process making commensurable the costs and revenues occurring in different periods of time. The amounts of goods and services obtained from the stand in year t depend on stand structure Z_t and the level of n harvesting and management activities, $u_{jt}, j = 1, \ldots, n$.

$$q_{it} = f(Z_t, u_{1t} \ldots u_{nt}),\ i = 1, \ldots, m \tag{6.2}$$

For timber harvesting, harvesting intensity, u_{jt}, can be described as a proportion of trees removed from the stand. Prices of products and services, p_{it}, and costs of activities, C_{jt}, are also typically functions of stand structure and activities carried out in that year:

$$p_{it} = f(Z_t, u_{1t} \ldots u_{nt}),\ i = 1, \ldots, m \tag{6.3}$$

$$C_{jt} = f(Z_t, u_{1t} \ldots u_{nt}),\ j = 1, \ldots, n \tag{6.4}$$

In order to predict the future cash flow, we need a model that describes the growth and development of stand characteristics over time:

$$Z_t = f\ (Z_{t-1}) \tag{6.5}$$

The growth model estimates the birth, growth, and mortality of trees. Stand structure, Z, is a scalar (or vector) that describes stand structure by only one (or few) aggregate variables, such as stand basal area or timber volume. Alternatively, Z may be a matrix of more detailed stand description that classifies trees by tree size distribution or other characteristics (see Box 6.1 for descriptions of growth and yield models used in economic analysis).

A profit-oriented forest owner plans the future harvests and investments such that the net present value of the stand is maximized, i.e. he maximizes (6.1) with respect to (6.2)–(6.5). However, this problem formulation is not technically solvable, because planning of activities should be extended to infinity. A more tractable framework for calculating the value of forest land under even-aged management was established in the mid-nineteenth century in Germany (Faustmann 1849). A special feature of even-aged management is that all trees in a forest stand are about the same age and are all harvested in a final clearcutting. After clearcutting a new generation of trees is established by planting, sowing or from naturally regenerated seedlings. Even-aged management chains typically include thinnings and silvicultural activities such as tending of seedling stands. The net present value of bare forestland (Soil Expectation Value, SEV) before the start of stand establishment activities is given by

$$SEV = \frac{\sum_{t=0}^{T} e^{-rt} \left(\sum_{i=1}^{m} p_{it} q_{it} - \sum_{j=1}^{n} C_{jt} \right)}{1 - e^{-rT}} \tag{6.6}$$

Box 6.1: Stand Growth Models

Stand growth models used in economic analysis of forest stand management can be classified based on the level of aggregation. Growth prediction can be made for an entire stand, groups of trees (divided in classes based on tree diameter, age etc.), individual trees or parts of a tree (leaves, branches, bole, roots).

The simplest models of forest stand management describe the development of stand volume or value as a function of time. Such models are classified as density-free whole stand models (Davis et al. 2001) or univariate models (Getz and Haight 1989), and they have been used to study optimal rotation periods under even-aged management. However, to study uneven-aged management including thinnings and selection cuttings, more detailed whole stand models have been developed to include stand density as an independent variable. Such models are called variable-density whole stand models (Davis et al. 2001). Density is typically described in terms of stand basal area, i.e. the total cross-sectional area of trees measured at breast height per area unit (see e.g. Chang 1981). Whole stand models are useful tools especially in theoretical work (Garcia 1994).

Transition matrix or stage-structure models describe the stand state with a tree size distribution. Trees are classified in discrete size classes, typically characterized by tree diameter measured at breast height. Each class is represented by average tree volume, tree height, and number of trees. Growth is described as the transition from one class to another at discrete time intervals. Recruitment and survival functions define in-growth and mortality. Transition matrix models are popular and useful especially in the economic analysis of uneven-aged management. The model structure is reasonably simple, but detailed enough to account for the effects of in-growth and selection harvests.

Individual-tree (or single-tree) models describe a forest stand using a list of tree records. Each tree is characterized by a number of state variables reflecting its current dimensions (diameter, height, crown ratio etc.). The tree vectors evolve over time due to in-growth, growth, mortality and harvesting. With distance-independent individual-tree models, growth and mortality are specified as functions of stand density variables. Each tree in the list is assigned an additional state variable representing the number of its kind in the stand. With distance-dependent (or spatial) individual-tree models, in contrast, growth depends explicitly on a tree's location, height, and crown relative to its neighbors.

The most detailed stand growth models used in the economic analysis are process-based models that describe the biomass production and accumulation in different compartments of the tree. Process-based models describe the causal relationships between the resources (light, water, nutrients) and tree growth. Descriptions of the fundamental ecophysiological processes and morphology make it possible to study, in a detailed manner, the effects of varying harvests on the growth and timber quality of the remaining trees.

Here t refers to stand age. It is enough to optimize the stand management until the first clearcutting only ($t = T$). The later rotation periods are optimally similar as the first one provided that the stand's production capacity is not altered between the rotations. The sum of discounted net revenues from the first rotation is divided by the term $(1 - e^{-rT})$ in order to obtain the net present value of an infinite chain of similar rotation periods.

Bare land is a special case because forest land is bare only over a short period of time between clearcutting and establishment of new tree generation. The net present value of forested stands is computed by discounting the net revenues from the remaining part of the ongoing rotation and the bare land value from the end of rotation:

$$NPV = \sum_{t=t_0}^{T} e^{-r(t-t_0)} \left(\sum_{i=1}^{m} p_{it} q_{it} - \sum_{j=1}^{n} C_{jt} \right) + e^{-r(T-t_0)} SEV \tag{6.7}$$

The initial stand age is denoted by t_0. The value of an even-aged stand can be computed by maximizing (6.6) or (6.7) with respect to (6.2)–(6.5) depending whether the stand is initially bare or forested.

Under uneven-aged management, a forest stand will never be clearcut. Instead, selection harvests aim simultaneously at removing large merchantable trees, retaining vigorous trees of different ages, sizes and species and creating favorable conditions for natural regeneration. One common approach to determining the value of an uneven-aged stand is to assume the stand reaches a steady state within a given time T' (Haight and Getz 1987; Wikström 2000). At steady state, birth and growth of existing trees are in balance with harvests and the time between consecutive harvests, c, is fixed. The stand reaches the same state after every harvest cycle, and the net harvesting revenues from later harvests remain at the same balanced level. The management problem then is to determine the sequence of selection harvests that converts the current stand to an optimal steady-state harvesting cycle. The problem can be formulated as:

$$NPV = \sum_{t=1}^{T'} e^{-rt} \left[\sum_{i=1}^{m} p_{it} q_{it} - \sum_{j=1}^{n} C_{jt} \right] + \frac{\sum_{t=T'}^{T'+c} e^{-r(t-T')} \left[\sum_{i=1}^{m} p_{it} q_{it} - \sum_{j=1}^{n} C_{jt} \right]}{r} e^{-rT'} \tag{6.8}$$

$$Z_t = Z_{t-1}, t = T, T + c, T + 2c, \ldots \tag{6.9}$$

Thus, the value of uneven-aged stand can be computed by maximizing (6.8) with respect to (6.2)–(6.5), and (6.9). The first term in (6.8) denotes the net returns from the conversion or transformation period and the second term net returns after the steady state has been achieved.

The literature has many variations on how to solve (6.8) and which parts of the equation are exogenous and which parts are optimized. The traditional studies solving the steady state harvesting policies (see Sect. 3.1) focus solely on the latter part of (6.8). There are also studies that take the steady state as given and optimize harvesting over the transformation period (Torres Rojo and Sánchez Orois 2005; Yousefpour and Hanewinkel 2009). The steady-state structure of the stand can be optimized simultaneously with the transformation cuttings (see Sect. 3.2 for review of dynamic optimization studies). On the other hand, the steady state condition (the latter part of (6.8)) can be neglected if the planning horizon is long enough such that the system reaches some equilibrium or cycle endogenously (Haight et al. 1985; Tahvonen 2009). Extending the length of the transformation period and removing the restriction of reaching a final steady state may be justified on economic grounds (Haight and Getz 1987; Bare and Opalach 1988) or biological grounds in light of the criticism questioning the stability of reverse J-shaped diameter distributions (Linder 1998, Chap. 2).

The economic efficiency of different management systems can be investigated by setting the same initial state, applying coherently selected cost and price parameter values for alternative stand management systems, and maximizing the net present value for the two sets of equations ((6.2)–(6.6) or (6.2)–(6.5) and (6.7) for even-aged management and (6.2)–(6.5), (6.8), (6.9) for continuous-cover forestry). The first part of the Eq. 6.8 may also serve as a general objective function for both even-aged and uneven-aged management systems provided that removal of all trees (clearcutting) is allowed as an option, both natural and artificial regeneration are possible and the planning horizon is long enough to cover several life cycles of trees. The optimized variables are often described in terms of harvesting rates or diameter distributions of the remaining trees and the numbers of trees.

3 Stand-Level Studies on the Economics of Uneven-Aged Management

Forest economists have thought about uneven-aged management since the 1950s (Duerr and Bond 1952). Economic formulations of uneven-aged management include optimization of steady-state harvesting and dynamic harvesting without steady-state yield requirements. The problem formulations evolved in tandem with models for stand growth and yield (see Peng 2000 for review) and eventually were used to evaluate and compare the efficiency of even-aged and uneven-aged management systems. This section reviews the development of these formulations. See also Table 6.1 for an overview of literature in the field. Studies are listed in

Table 6.1 References of stand-level studies on the economics of uneven-aged management

Study	Approach	Model	Species	Country and region
Duerr and Bond (1952)	1	1	1	USA, South
Adams and Ek (1974)	1,2	2	4	USA, Wisconsin
Adams (1976)	1	2	4	USA, Wisconsin
Buongiorno and Mitchie (1980)	1,4	2	4	USA, Wisconsin
Chang (1981)	1	1	1	USA
Hasse and Ek (1981)	4	4	4	USA, North
Haight et al. (1985)	3	2	4	USA, Wisconsin
Haight (1985)	1,3	2	4	USA, Wisconsin
Mitchie (1985)	3	2	4	USA, North-central
Haight (1987)	3	2	1	USA, Arizona
Haight and Getz (1987)	3	2	2	USA, California
Bare and Opalach (1987)	1	3	2	USA, Idaho
Kaya and Buongiorno (1987)	5	1	4	USA, Wisconsin
Bare and Opalach (1988)	1	2	4	USA, Wisconsin
Hotvedt et al. (1989)	1	1	2	USA, Arkansas and Louisiana
Buongiorno and Lu (1990)	1	2	4	USA, Wisconsin
Haight and Monserud (1990a)	3	3	2	USA, Idaho
Haight and Monserud (1990b)	3	3	2	USA, Idaho
Haight (1990)	5	2	1	USA, California
Gove and Fairweather (1992)	1	2	4	USA, North-central
Haight et al. (1992)	3	3	2	USA, Idaho
Anderson and Bare (1994)	3	2	4	USA, Wisconsin
Gove et al. (1994)	1	2	4	USA, Wisconsin
Buongiorno et al. (1994)	1	2	4	USA, Wisconsin
Buongiorno et al. (1995)	1	2	5	France, Jura mountains
Volin and Buongiorno (1996)	4	2	5	Italian Dolomites
Boscolo et al. (1997)	4	2	6	Malaysia
Lin and Buongiorno (1998)	3	2	4	USA, Wisconsin
Schulte and Buongiorno (1998)	4	2	2	Southeast USA
Kant (1999)	3	2	1	Canada, Ontario
Buongiorno et al. (2000)	4	2	4	USA, North
Wikström (2000)	3	3	1	Sweden
Tarp et al. (2000)	4	1	3	Denmark
Mendoza et al. (2000)	1	2	6	Indonesia, Kalimantan
Knoke and Plusczyk (2001)	4	4	5	Germany, Bavaria
Buongiorno (2001)	3	2	4	USA, Wisconsin
Hanewinkel (2001)	4	4	5	Southwest Germany
Andreassen and Øyen (2002)	4	1, 5	5	Norway
Nord-Larsen et al. (2003)	4	5	4	Northern Germany
Wagner et al. (2003)	1,4	3	4	USA, Northeast
Ralston et al. (2004)	4	2	1	USA, Pacific Northwest
Sánchez Orois et al. (2004)	1,4	2	1	Northwest Spain
Trasobares and Pukkala (2004)	1	3	2	Northeast Spain
Conrad et al. (2005)	3	1	6	Not specified

(continued)

Table 6.1 (continued)

Study	Approach	Model	Species	Country and region
Rollin et al. (2005)	5	1	5	France, Jura mountains
Torres Rojo and Sánchez Orois (2005)	2	2	1	Spain, Galicia
Tarp et al. (2005)	4	2	3	Denmark
Hao et al. (2005)	3	2	4	China, Northeast
Zhou and Buongiorno (2006)	5	2	5	USA South
Jacobsen and Helles (2006)	2	2	3	Denmark
Liang et al. (2006)	5	2	2	USA, Pacific Northwest
Lohmander and Limaei (2008)	5	1	4	Iran, Caspian forests
Yang and Kant (2008)	1	2	4	Canada, Ontario
Tahvonen (2009)	3	2	1	Finland
Yousefpour and Hanewinkel (2009)	2	4	5	Germany, Black forest
Hyytiäinen and Haight (2010)	3	3	2	USA, Idaho
Chang and Gadow (2010)	1	1	2	USA, South Central
Pukkala et al. (2010)	1	3	2	Finland
Tahvonen et al. (2010)	3	2	1	Finland
Xabadia and Goetz (2010)	3	2	1	Spain

Approach
1. Optimizing steady state harvests
2. Optimizing conversion harvests
3. Simultaneous optimization of conversion period and steady state
4. Simulation based comparison of conversion strategies
5. Adaptive harvesting under stochastic conditions

Model or data used for projections
1. Whole stand model
2. Transition matrix model
3. Distance-independent individual-tree model
4. Spatial model
5. Experimental data

Species
1. Conifer
2. Conifer mixture
3. Hardwood
4. Hardwood mixture
5. Mixture of hardwoods and conifer species
6. Tropical forest

chronological order and classified according to the primary approach and the type of growth and yield model applied. Also the country, area and tree species employed in each case study are reported to indicate the geographical coverage of this line of research.

3.1 Optimization of Steady-State Harvesting

Uneven-aged management is usually defined as the periodic removal of a portion of the trees from a stand while maintaining a balanced uneven-aged structure with three or more age classes of trees (e.g., Smith 1962, p. 467). The ideal stand structure is a downward-sloping diameter distribution containing sufficient trees in each diameter class to produce an unvarying number of trees that are harvested periodically. Harvests include selection cutting (i.e., removing all trees greater than some maximum diameter) and thinning (i.e., removing a portion of the trees in smaller diameter classes) (Smith 1962, p. 482). We use the term selection harvests to include both thinning and selection cutting in uneven-aged management regimes.

The first economic formulations of uneven-aged management problems focused on calculating the optimal level of growing stock of a balanced uneven-aged stand, where optimal stocking was the timber volume that maximized net benefit through periodic harvest of the volume growth. Duerr and Bond (1952) used marginal analysis to show that an optimal growing stock is one in which the marginal value growth percent is equal to the discount rate. Chang (1981) showed that optimal stocking can be calculated by maximizing the difference between the present value of equilibrium harvests and the liquidation value of the residual growing stock, which represents the opportunity cost of holding the residual growing stock. This formulation appealed to forest economists because if the growing stock is viewed as a capital investment, the problem is equivalent to maximizing land expectation value (LEV) as defined by the Faustmann formula (see Chang 1981; Chang and Gadow 2010).

While the analyses above calculated the optimal aggregate growing stock of a balanced uneven-aged stand, they did not address the problem of determining the optimal steady-state stand structure. Adams and Ek (1974) were the first to formulate and solve an optimization problem for a steady-state diameter distribution of the residual growing stock and harvest. They demonstrated a two-stage technique for determining the optimal stand structure. In the first stage, they used a gradient projection method to determine the diameter distribution that maximized stand value growth for a given stand basal area and cutting cycle. In the second stage, having solved this nonlinear program for several alternative basal area levels, they chose the stand structure that satisfied a marginal value growth percent criterion (Duerr and Bond 1952). Adams (1976) subsequently distinguished between the use of value and basal area measures of growing stock as the appropriate constraints for determining investment-efficient diameter distributions. These analyses used a stage-structure model for the growth of uneven-aged northern hardwood stands in Wisconsin (Ek 1974). The model included density-dependent nonlinear equations for the movement of trees between diameter classes, mortality, and regeneration. Extensions of optimization problems with steady-state diameter distributions included determination of the optimal cutting cycle and species composition (Buongiorno and Michie 1980; Bare and Opalach 1987).

Adams and Ek (1974) also addressed transition harvesting for a given initial stand structure. They formulated and solved the transition strategy problem of choosing harvesting levels of diameter classes that maximized present net value with the constraint of achieving a given diameter distribution after a specified number of periods. They used a gradient projection method, but the number of decision variables and constraints exceeded algorithm capacity for problems with more than three transition harvests.

3.2 *Optimization of the Sequence of Selection Harvests*

In a departure from steady-state analysis, Haight et al. (1985) addressed the problem of determining the optimal sequence of diameter distributions and selection harvests for an existing stand without the constraints of steady-state harvest or specified equilibrium endpoint. The objective function was formulated to seek diameter-class harvest levels that maximize the present value of net returns, assuming that all remaining trees are harvested at the end of the planning horizon. No restrictions are placed on the form of the terminal diameter distribution. They coupled a nonlinear programming technique called the method of steepest descent with the stage-structured model of northern hardwood stands developed by Ek (1974) and modified by Adams and Ek (1974) to determine stand-specific management regimes for three different stumpage value functions over a 150-year horizon. Their results suggested that investment-efficient residual diameter distributions determined by Adams (1976) were not optimal in the context of this dynamic problem. In a subsequent mathematical analysis, Haight (1985) showed that steady-state management regimes obtained in the context of a dynamic harvesting problem were not the same as steady state regimes developed with static optimization, which maximizes the present value of equilibrium harvests minus the value of residual growing stock (Adams 1976; Buongiorno and Michie 1980; Bare and Opalach 1987).

When the objectives of timber harvesting include the maximization of present value and the achievement of a steady-state harvest policy, the management problem can be formulated as a dynamic harvesting model with fixed or equilibrium endpoint constraints (Haight and Getz 1987). Fixed endpoint problems involve the determination of a target steady state and a transition regime that reaches the target after a finite transition period (e.g. Adams and Ek 1974). Equilibrium endpoint problems involve the determination of transition and steady-state harvest levels with equilibrium endpoint constraints that do not require the achievement of a specific target stand structure (see (6.8)). Michie (1985) formulated and solved an equilibrium endpoint problem using a fixed parameter matrix model for stand growth and linear programming methods. The resulting steady states depended on the initial stand structure and the conversion period length. Computational limitations prevented the author from solving problems with three or more transition harvests.

Haight and Getz (1987) focused on issues associated with fixed and equilibrium endpoint problems. For a given transition period length, the solution to the equilibrium endpoint problem has a higher present value than the solution to any fixed endpoint problem, since the equilibrium endpoint formulation places fewer constraints on the terminal steady state. The equilibrium endpoint policy depends on the initial stand structure and transition period length. As the transition period lengthens, the cost of the terminal steady-state constraint approaches zero.

Wikström (2000) applied a Tabu search solution algorithm for analyzing and solving uneven-aged and even-aged problem formulations with individual-tree models. He studied different problem formulations with and without steady-state constraints. Approximating the infinite time horizon problem with a finite time horizon turned out better both technically and with regard to the reliability of the results. Tahvonen (2009) and Tahvonen et al. (2010) focused on developing any-aged problem formulations that do not include any restrictions on the forest management system or final state. In these studies, the infinite horizon solutions are approximated by increasing the number of periods until further lengthening of the horizon does not change the solution trajectory toward some steady state or stationary cycle. In some cases, the planning horizon needs to be extended up to between 800 and 1,500 periods. Long run simulations were made technically feasible for Norway spruce (*Picea abies*) stands by the use of transition matrix stand growth models.

3.3 Comparing Economic Returns from Even-Aged and Uneven-Aged Management

The problem of evaluating and comparing the efficiency of even-aged and uneven-aged management systems was first addressed by comparing simulated yields from steady-state management regimes (i.e., a repeated sequence of even-aged stands managed with the clearcut system and a repeated sequence of single-tree selection harvests from a sustainable, uneven-aged diameter distribution). For example, using a simulator for Wisconsin northern hardwoods, Hasse and Ek (1981) compared mean annual increments measured in various physical units for even-aged stands with the corresponding yields from steady-state uneven-aged management regimes. Chang (1981) computed a steady-state uneven-aged management regime that maximized LEV and compared the LEV associated with uneven-aged management to LEVs computed for even-aged plantation management regimes.

These comparisons of the economic returns of alternative management systems did not consider the more general problem of managing an existing stand. For even-aged management this problem is split into conversion and plantation components: (1) determining the timing and intensity of silvicultural treatments for the current stand and determining the time when the stand is clearcut and replaced with a plantation, and (2) determining the timing and intensity of silvicultural treatments and clearcut age for the plantation (see (6.7)). For uneven-aged management the problem involves determining the sequence of selection harvests that converts the current stand to steady-state uneven-aged management (see (6.8) and (6.9)). Haight (1987) described models that allow the comparison of the present values of optimal management regimes that fit these definitions of even-aged and uneven-aged management. The optimization problems included a stage-structured model for growth and yield of ponderosa pine (*Pinus ponderosa*) stands in the western United States.

It is important to caution the reader that defining uneven-aged management as the conversion of an existing stand diameter distribution to an inverse-J shaped diameter distribution may not be justified on economic or biological grounds. Inverse-J shaped diameter distributions may not represent virgin forest structures, which often have bimodal or more complicated distributions, especially in multi-species stands (Chap. 2). Further, the assumption that there is a unique and ideal diameter distribution for an uneven-aged stand cannot always be substantiated by empirical evidence (Chap. 2).

To address uneven-aged management problems without steady-state constraints, Haight and Monserud (1990a) developed an any-aged management formulation and applied it to mixed-conifer stands in the Northern Rocky Mountains. The any-aged management problem is to determine the best time sequence of harvests and plantings without constraints on the stand age or size structure. With no constraints, optimal management may prescribe stand structures that vary from even-aged to irregular, and thus regimes are termed any-aged. Because the any-aged management problem includes even-aged and uneven-aged management problems as special cases, optimal any-aged regimes should be superior to regimes that fit these standard definitions of stand management. In a departure from previous models, Haight and Monserud (1990b) developed an optimization procedure for application to a single-tree stand simulator, which was becoming the standard model for growth and yield projection in the United States.

The existing results on the economic superiority of even-aged versus uneven-aged forestry are mixed. According to Haight and Monserud (1990b), optimal any-aged management regimes for conifer cultures in the Rocky Mountains tend to converge to a sequence of selection harvests that maintain a multispecies, uneven-aged stand structure. However, optimal transition regimes depend on initial stand structure, and may include sections of even-aged forestry. Clearcutting and planting are practiced for understocked stands with basal area lower than 5 m^2/ha. However, with natural regeneration and repeated diameter-limit cuts, even the monocultures finally evolve to mixed-species uneven-aged stands.

Wikström (2000) found even-aged management superior for Norway spruce stands in Sweden. Depending on the type of the steady state constraints and initial stand structure, the maximized net present values of uneven-aged management varied between 67% and 95 % from the maximized net present values of even-aged management. However, optimal solutions for uneven-aged management were constrained by either an upper bound for thinning intensity (30%) or a lower bound for residual volume (150 m^3/ha). The level of in-growth was also relatively low (10 trees/ha/year). Relaxing these constraints and making in-growth depend inversely on stand stocking would obviously have improved the relative profitability of uneven-aged management. Tahvonen et al. (2010) relaxed any constraints on harvesting and carried out similar optimizations for Norway spruce in a neighboring country, Finland. They found that uneven-aged management gives somewhat lower timber yields in the long-run than even-aged management, but becomes economically superior for most initial stand states when the costs of regeneration and harvest, interest rate, and the price differential between the saw timber and pulpwood, are accounted for. The properties of the growth, in-growth and harvesting models that drive the optimality of uneven-aged vs. even-aged management have been studied by Chang (1981), Tahvonen (2009), and Khazri and Lasserre (2011).

3.4 Simulation-Based Comparisons of Transformation Strategies

Converting single species even-aged conifer stands into more irregular stand structures involving multiple species has recently become a widespread management objective in Central Europe (Gadow et al. 2002; Pommerening and Murphy 2004). The potential environmental benefits associated with this objective are improved soil properties, water quality and habitat quality and reduced susceptibility to natural hazards. Interest in this objective has increased the demand for research investigating the economic and ecological consequences of transformation strategies. The approach used to investigate these consequences has been to select one or several initial stand states and project stand development associated with various conversion strategies for comparison with a conventional management strategy (typically even-aged management). The analysis is completed by comparing and analyzing the economic and ecological outcomes of the exogenously selected management regimes (Buongiorno 2001). Knoke et al. (2008) review the literature on admixing broadleaved to coniferous trees species.

Knoke and Plusczyk (2001) and Hanewinkel (2001) combined empirical data and growth projections produced with the spatial growth model Silva to investigate the economic effects of transforming stands dominated by Norway spruce in Germany. Transformation regimes included a chain of selection harvests and occasional enrichment plantings in forest gaps generated by snow breakage or thinnings. The transformation strategy was found to lead to smaller net incomes than even-aged management. However, the incomes occurred earlier and were more evenly distributed over time, which made the transformation strategy a financially viable option especially at higher rates of interest. Tarp et al. (2005) carried out a similar comparison of an even-aged, shelterwood natural regeneration regime of beech (*Fagus sylvatica*) to a conversion regime based on target diameter harvesting. They found very little difference in the economic profitability of those regimes. The regime using target diameter harvesting and leading to an uneven-aged stand structure was superior for interest rates of 2% and higher.

Alternative chains of stand management have also been evaluated according to non-timber benefits. For example, Schulte and Buongiorno (1998) projected the development of loblolly pine (*Pinus taeda* L.) using eight different management guidelines, and evaluated the outcomes in terms of economic performance, timber production divided by assortments (sawtimber and pulpwood), and tree-species and tree-size diversity. Some studies compare several transformation strategies and select the best one based on single or multiple criteria.

3.5 Adaptive Optimization of Cuttings Under Stochastic Conditions

Most studies on optimal forest stand management assume that forecasts of economic parameters and stand growth are known with certainty. However, several model components and parameters that are treated as fixed values in optimization models are in fact stochastic. Timber prices, in particular, fluctuate greatly over time. Studies that recognize inherent uncertainties in some of the key parameters employ stochastic optimization to design adaptive timber management strategies and account for unpredictable changes in market condition or stand state.

In adaptive optimization, the optimal decision at each point in time is made conditional on the stand and market state. A Markov decision process, or discrete time stochastic control, provides a framework for formulating such problems, and dynamic programming provides a means to solve them. Kaya and Buongiorno (1987) determined the optimal cutting intensity for different combinations of stand basal area and timber price. The two state variables were defined by three levels of timber price and five levels of stand basal area. Later, Markov decision models were developed to include different tree sizes and species groupings (Lin and Buongiorno 1998; Rollin et al. 2005) and natural hazards (Zhou and Buongiorno 2006). Dynamic programming proved to be a powerful tool to solve stand management problems in which the stand state can be described by a few discrete state variables. For more complex problem formulations involving four or more state variables, the computational burden of dynamic programming becomes overwhelming (Bellman and Dreyfus 1962).

There are other methods for developing adaptive cutting rules with fluctuating timber prices. Haight (1990) employed stochastic simulation to develop feedback thinning rules for uneven-aged stands of white fir (*Abies concolor*). Stumpage price was assumed to evolve over time according to a stationary random process. The decision variable, given as a function of timber price, was thinning intensity. Adapting the harvest removal to timber price increased the expected net revenues significantly compared with a harvest policy that did not account for random price changes. Jacobsen and Helles (2006) developed a vector autoregressive model for timber assortment prices and used stochastic dynamic programming to determine the optimal timing of selection harvests for seven different harvest guidelines for beech. They found that adapting the harvesting decisions to price fluctuations changes the ranking of alternative management strategies compared with the results of deterministic optimization.

Stochastic problems can also be formulated such that the inherent variation in the model parameters is accounted for but without adjusting the harvest decisions to the stand or market state at each point in time. Bootstrap simulation with response surface analysis is one such approach (Liang et al. 2006), and simulation-based optimization is another (Hyytiäinen and Haight 2010). The benefit of an anticipatory approach to uncertainty is that it can be easily applied to complex stand growth models involving several sources of uncertainty and state variables. The disadvantage is the limited potential to adjust the decisions with changes in the stochastic variables.

3.6 Joint Optimization of Timber and Amenity Benefits

Forests provide multiple benefits. Some of these benefits are tangible products, such as timber, the value of which is determined in competitive markets. However, forests provide a number of other products and services that may be of high value for the landowner and society, but which are more difficult to quantify and account for in the economic analysis. Watershed protection and water purification are examples of non-market values of forests. Forests are also subject to non-use values that derive from the pleasure people feel from the knowledge that the forest ecosystem functions well and provides a sustained flow of goods and services for the present and future generations. While a wide range of advanced techniques (e.g. cost-based methods and contingent valuation) have been developed to estimate the monetary value of non-market and non-use benefits of natural resources (Freeman 2003), monetary estimates of non-market and non-use values are subject to considerable measurement uncertainties (see Merlo 2005, p. 17–35 for application of total economic value for forests).

Amenity benefits have been inserted in optimization formulations of uneven-aged stand management as constraints in dynamic (Haight et al. 1992) and static models (Buongiorno et al. 1994, 1995; Lin and Buongiorno 1998). Amenity benefits have also been inserted in the objective function and given a weight reflecting its value to the landowner or society (Yousefpour and Hanewinkel 2009). An alternative approach is to insert the undesirable environmental effects of timber harvesting as penalties or costs (Khazri and Lasserre 2011). There are also studies that optimize stand management with respect to a diversity index (Gove et al. 1994) or with respect to both ecological and economic criteria for comparison of the outcomes (Liang et al. 2006).

Out of a wide array of non-timber benefits, habitat quality has been the most common service accounted for in economic problem formulations. The most popular measure of habitat quality has been the Shannon index, which accounts for diversity in tree sizes and tree species composition (e.g. Lin and Buongiorno 1998; Rollin et al. 2005). The value of carbon sequestration is accounted for in some studies (Boscolo et al. 1997; Yousefpour and Hanewinkel 2009; Pukkala et al. 2011). Berries and mushrooms are important non-timber forest products that have been included in some recent formulations of even-aged (Palahí et al. 2009; Miina et al. 2010) and uneven-aged (Pukkala et al. 2011) management.

4 A Case Study for Mixed Conifer Stands in the Rocky Mountains: Effect of Fire Risk on Efficiency of Even-Aged vs. Uneven-Aged Management

In this section we describe in detail a study that evaluates the economic efficiency of even-aged and uneven-aged management under the risk of wildfires (Hyytiäinen and Haight 2010). First we present the case study and introduce the distance-independent individual-tree model to simulate stand growth and fire effects. Then, we develop an optimization method that accounts for uncertainties both in tree growth and occurrence of wildfire. We describe the relative efficiency of the two management systems with and without fire risk. Finally, we add a diversity index to the model of Hyytiäinen and Haight (2010) and demonstrate the environmental consequences of continuous cover forestry as opposed to traditional even-aged management.

4.1 Case Study

The case study is a mixed conifer stand located in Idaho Panhandle National Forest in the Rocky Mountains. The stand is a mature two-storied stand that can be either converted to even-aged conifer plantation by immediate clearcutting and artificial regeneration or managed with selection harvests. The species present in the stand initially include Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), subalpine fir (*Abies lasiocarpa*), western hemlock (*Tsuga heterophylla*), western larch (*Larix occidentalis*), and western redcedar (*Thuja plicata*). The stand belongs to the western hemlock habitat type with an elevation 880 m above sea level. The initial basal area is 28.6 m^2/ha and the average top height is 30 m. The species considered for even-aged management is Western white pine (*Pinus monticola*).

Wildfires pose a threat of damage and economic loss to landowners especially in regions with hot and dry seasons. Wildfires may cause total destruction of the stand by killing all trees, or may cause only minor damage to some trees, or any degree of damage between these two extremes. This chapter demonstrates how anticipating the fire risk and its negative consequences affect the choice of management system.

4.2 Simulation Model

Simulation models are needed for predicting stand structure development as a consequence of growth of existing trees, regeneration, harvests, silvicultural activities, and natural and catastrophic mortality. In this study, stand growth was predicted by using the Forest Vegetation Simulator (FVS), and its model version validated for mixed conifer stands in northern Idaho (Dixon 1989, 2002). The fire effects on stand structure were simulated using the Fire and Fuels Extension of the FVS (Reinhardt and Crookston 2003).

FVS is a family of forest growth simulation models developed by the USDA Forest Service. The first versions of the simulator date back to the early 1970s. The original version of the simulator was called the Prognosis model (Stage 1973) and it was developed for northern Idaho and western Montana. Later on, data from other geographic areas became available and were used to develop new model variants. In the early 1980s, Prognosis was renamed the *Forest Vegetation Simulator* (FVS) and was adopted by the USDA Forest Service National Forest System as the national standard for forest growth and yield modeling. At present, FVS consists of more than 20 variants calibrated for different geographic areas, and soil and weather conditions in the United States and Canada. Prognosis and FVS have been applied actively in the economic analysis of forest management (Bare and Opalach 1987; Haight and Monserud 1990a, b; Haight et al. 1992).

Each variant includes thousands of state variables describing trees and fuels and predicts tree growth and mortality as functions of natural factors (such as competition, aging, wildfire) and human intervention (harvesting and silvicultural activities). The northern Idaho variant used in Hyytiäinen and Haight (2010) also contains a full establishment model (Dixon 2002). It adds in-growth periodically during the simulation, and pulses of regeneration following significant stand disturbances. It is also possible to add trees by planting. The northern Idaho variant of FVS can be applied for simulating both even-aged and uneven-aged management regimes.

FVS variants are distance-independent, individual-tree models. The structure of the forest stand is described using a list of tree records. Each tree is characterized by a number of state variables reflecting its current dimensions (e.g. diameter, height, crown ratio) and an additional variable representing the number of trees of its kind in an area unit (typically number of trees per acre). The variable values evolve over time due to growth, mortality and harvesting. Tree growth is described as function of stand density variables and shading by neighboring trees.

Figure 6.1 shows the general flow of operations within FVS. A projection of stand development begins by reading the tree and stand level inventory records and the description of management schedule. If measured data on past growth are available, the increment equations are calibrated to better reflect the forest growth capacity of the stand. The tree basal area growth equations are scaled such that the predictions match the actual increment core measurements on the trees in the stand (Stage 1973). After this, the first projection cycle begins. The growth cycle length can be adjusted. The default length is 10 years.

Each projection cycle starts with a check to see if any harvesting or silvicultural activities have been scheduled for the particular growth cycle. This is followed by computing periodic diameter increment, periodic height increment, and periodic mortality rates. These estimates are then adjusted for effects of insects and pathogens. Tree records resulting from regeneration within the cycle are created

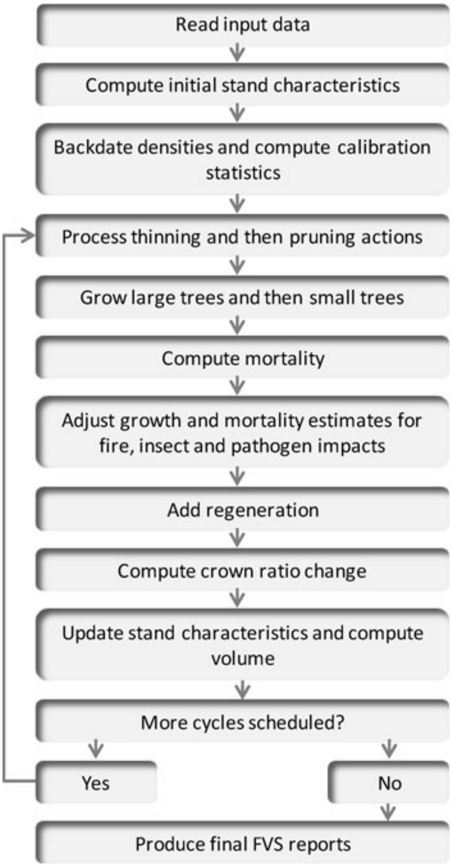


Fig. 6.1 Overview of the general FVS processing sequence (Adapted from Dixon 2002)

next, and changes in crown ratios are computed for each tree record in the projection. Finally, the tree attributes are updated, tree volumes are calculated, and tables that summarize projected stand conditions are compiled.

The stochastic features in tree growth are assigned to the distribution of errors associated with the prediction of tree diameter increment. The random component of change in tree diameter is treated by (1) adding a random deviate to the basal area increment of each tree record, and (2) augmenting (tripling) the number of tree records for consecutive periods for stands with small initial number of tree records. The random variables associated with each tree record are saved until the following cycle in order to account for serial correlation (Stage 1973). Simulations can be replicated with different random number seeds to obtain scenarios of stand development.

Several extensions have been developed for the FVS in order to predict the effects of wildfires and specific insects or pathogens on stand and tree development and mortality. Fire and Fuels Extension to the FVS (Reinhardt and Crookston 2003) integrates FVS with elements from existing modes of fire behavior and fire effects. It simulates the effects of stand development and management actions on fuel dynamics, fire behavior, and fire effects. The model predicts fire intensity and fire type, which can be surface fire, passive crown fire or active crown fire. Fire intensity and tree mortality are predicted as functions of the vertical distribution of fuels, tree characteristics (e.g. crown length, diameter, and species), stand characteristics (e.g. slope) and environmental variables at the moment of fire (fuel moisture, wind speed, temperature). The probability of fire arrival does not depend on stand state or prior management, and must be given separately to the model.

FVS and its extensions are publicly available tools for analyzing stand management. Links to technical documents, software, samples of data, and support and training services can be found on the USDA Forest Service web site: http://www.fs.fed.us/fmsc/fvs/.

4.3 Approach

The approach used in this study is simulation-based optimization. In this approach, the expected value of the objective function is estimated via stochastic simulation until suitable approximations of the optimal values of the decision variables are found. The first step is to estimate the expected value of the objective function for a given set of decision variable values. This sample average is computed using a set of scenarios where each scenario is composed of random samples from the distributions of the random variables. The second step is to search for a solution that provides a suitable approximation to the optimal values of the decision variables.

One advantage of applying simulation optimization to forestry questions is that the model of stand dynamics can be used without modification in the search of the best management regime. A disadvantage is its computational intensity: a large number of replications may be required to obtain a useful estimate of the expected value of the objective function for each management regime. Another disadvantage of this approach is that the optimal stand management regime is decided in advance and is independent of future fire occurrences.

Applying simulation based optimization with the FVS turned out to be computationally intensive. A typical simulation of harvests and wildfire requires 10–30 s on a laptop computer, and hundreds of simulations may be needed to stabilize the expected objective function value. Therefore, a number of simplifications were made in the problem formulation in order to reduce the computational burden. First, a small number of discrete decision variables were developed separately for even-aged and uneven-aged management. Second, the minimum step lengths for decision variable values were increased. Third, harvesting was made to take place on a 20-year interval rather than the 10-year prediction interval allowed by the simulator. Fourth, wildfire occurrences were discretized such that a fire may occur once during each 20-year period.

These simplifications reduced the set of possible harvesting regimes compared to earlier studies of any-aged stand management (e.g. Haight and Monserud 1990a) and made it possible to use FVS and its Fuels and Fire extension in the analysis. In this study, the focus is on the management decision in the first period: whether the stand is retained under uneven-aged management or converted to an even-aged plantation.

The net present values of stands were computed as follows. First it was assumed that the initial stand can be either retained under uneven-aged management by repeated diameter-limit harvests or converted to even-aged management with an immediate clearcut followed by artificial regeneration and an infinite series of rotations. The expected present value of the initial stand is computed separately for each management system. The optimization problem for each management system is to select the values of the decision variables (denoted by a vector *x*) to maximize the expected net present value of the stand, *E(NPV)*, under risk of wildfires and stochastic tree diameter growth:

$$\max_{x} \quad E\,(NPV) = \sum_{i=1}^{m} \sum_{j=1}^{n} pr_{ij}\,(\lambda)\; NPV_{ij}\,(x, \chi, \lambda) \tag{6.10}$$

The probability distribution for *NPV* is estimated by repeating the simulations for *m* fire scenarios and *n* sequences of tree growth predictions (see Fig. 6.2 for illustration on the structure of simulation optimisation framework). For each set of decision variable values *x*, *E(NPV)* is estimated by first computing NPV_{ij} for the *ij*th scenario of fire and tree growth, then multiplying NPV_{ij} by the probability of occurrence of scenario *ij* (pr_{ij}), and finally summing the products over the *mn* simulations. The probability of fire occurrence in a period is denoted by λ ($0 \leq \lambda < 1$). The seed random number used in diameter growth predictions, χ, is specific for each simulation.

It is assumed that fire enters the stand by spreading from outside. Thus, the occurrence of wildfire does not depend on stand characteristics or prior management. The period length *w* is 20 years and the number of periods *q* is 6. Let ψ_k be a dummy variable with value of 1 or 0 for whether or not a fire occurs during period *k*. The probability that a wildfire occurs in period *k* is $P(\psi_k = 1) = \lambda$ and the probability that the wildfire does not occur is $P(\psi_k = 0) = 1 - \lambda$. The simulations are repeated for all $m = 2^q = 64$ possible realizations of fire occurrences. The probability of each fire scenario *i* and sequence of diameter growth predictions, *j*, is:

$$pr_{ij} = \frac{1}{n} \prod_{k=1}^{q} P(\psi_k^i), \quad i = 1, \ldots, m,\ j = 1, \ldots, n \tag{6.11}$$

With uneven-aged management, the decision variable *x* is the diameter limit of selection cutting (given in cm). A diameter-limit cut removes all trees above a

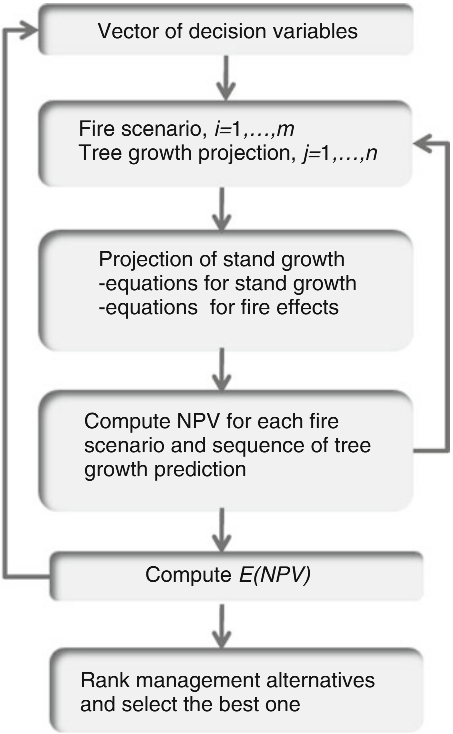


Fig. 6.2 Steps in simulation based optimization framework

minimum diameter. In addition, we assume that 15% of smaller trees not exceeding the diameter limit are removed by thinning. These include inferior quality stems and those stems that are damaged during the logging operation. With even-aged management, *x* is a vector that consists of three decision variables: (1) planting density (trees/ha), (2) residual basal area in thinnings, (m^2/ha), and (3) rotation period (years). After clearcutting, the stand is replanted immediately. The new tree regeneration is thinned to the same residual basal area after every 20 years and clearcut at rotation age. Thinnings are assumed to remove equal proportions of trees from all tree records until the target residual basal area is reached. For additional details and specific cost and price parameters see Hyytiäinen and Haight (2010).

Finally, a Shannon index (see e.g. Rollin et al. 2005) is linked to the model to demonstrate the development of habitat quality for alternative chains of stand management. The Shannon index, *S*, reflects habitat quality and describes a stand's richness with respect to tree sizes and tree species (assuming that these two characteristic of trees are independent of each other).

$$S = -w_{sp} \sum_{u=1}^{y} \frac{B_{ku}}{B_k} \ln\left(\frac{B_{ku}}{B_k}\right) - w_{size} \sum_{v=1}^{z} \frac{B_{kv}}{B_k} \ln\left(\frac{B_{kv}}{B_k}\right) \tag{6.12}$$

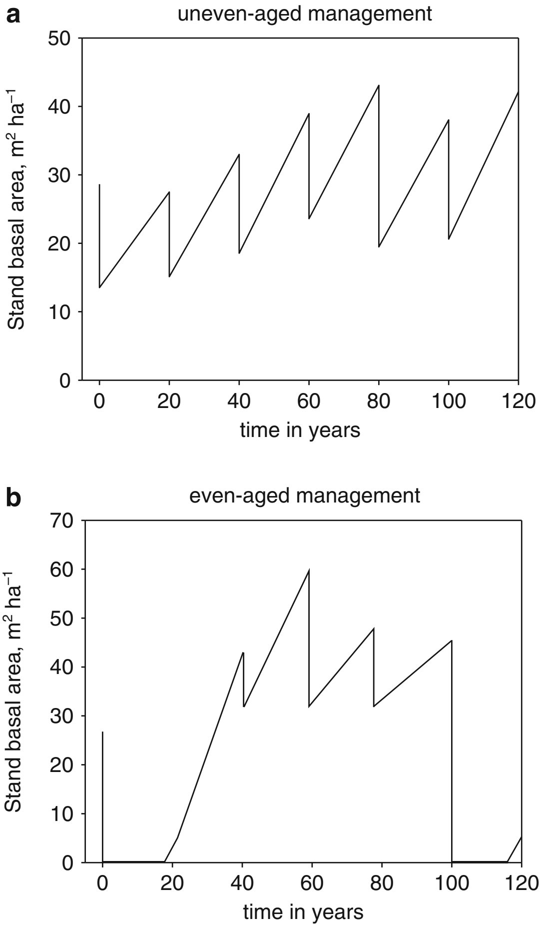


Fig. 6.3 Projections of stand development for optimal management under (**a**) uneven-aged management and (**b**) even-aged management without the risk of wildfires

The weights of species and size diversity are denoted by w_{sp} and w_{size}, respectively. B_k is the total basal area at the period k, B_{ku} is the total basal area of trees of species u, and B_{kv} is the basal area of trees of diameter class v.

4.4 Economic Efficiency of Even- vs. Uneven-Aged Management

Optimal chains of stand management and the efficiency of alternative stand management systems are first evaluated in case of no fire risk. The default rate of interest used in computations is 3%. With uneven-aged management, the optimal management regime is to carry out selection cuttings to the diameter limit of 35 cm. The development of stand basal area for a given initial state and such harvest is shown in Fig. 6.3a for the first 120 years. The selection cuttings are repeated at a 20-year interval. The retained basal areas vary from 14 to 21 m^2/ha.

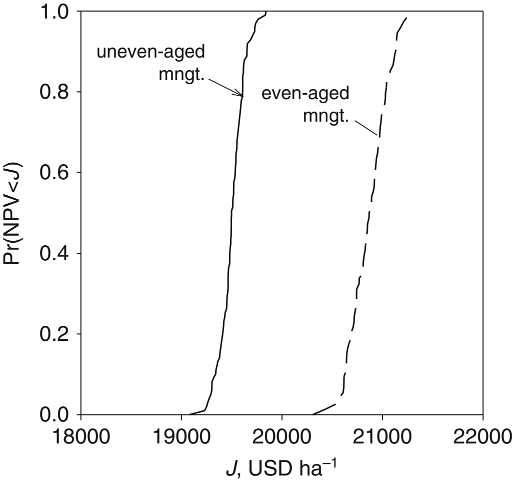


Fig. 6.4 Cumulative probability distributions of net present values for optimal continuous cover forestry and even-aged management with no risk of wildfire

With even-aged management the optimal management regime is to plant 1,500 seedlings per hectare at the time of regeneration, to thin the stand to a residual basal area of 34 m^2/ha at a 20 year interval and to carry out the final clearcutting at stand age of 100 years. Figure 6.3b shows one projection of stand basal area for this management regime.

Figure 6.4 shows the cumulative probability distributions of net present values for the two management regimes shown in Fig. 6.3. Carrying out an immediate clearcutting, planting the stand with white pine and performing even-aged management leads to higher expected net present value than uneven-aged management. The stochastic feature in tree growth, as accounted for in FVS simulator, contributes to only a small variation in the net present values. The distributions of present values of the management systems do not overlap and even-aged management is clearly the favored system for forest owners interested in timber production. The expected net present value of uneven-aged management is about 93% of the expected net present value of even-aged management.

Inclusion of fire risk reduces the profits of forest management and alters optimal stand management. Risk of losing commercial trees to fire damage makes it rational to cut more trees earlier. Under uneven-aged management, inclusion of fire risk of $\lambda = 0.4$ reduced the diameter limit of selection cutting from 35 to 30 cm. Under even-aged management, inclusion of fire risk reduced planting density from 1,500 to 1,000 trees per hectare and shortened the rotation length from 100 to 80 years.

Figure 6.5 demonstrates the effects of alternative realizations of wildfires on stand development for optimal harvesting regimes of both management systems. Figure 6.5a shows one stand development without fires (black line) and three developments with one fire event in each for optimal continuous cover forestry. The red, green and yellow lines denote stand developments for fires occurring at 10, 50 and 90 years after the initial time. The level of mortality and the size of trees killed by a wildfire depend highly on stand properties. Wildfire causes high mortality if the

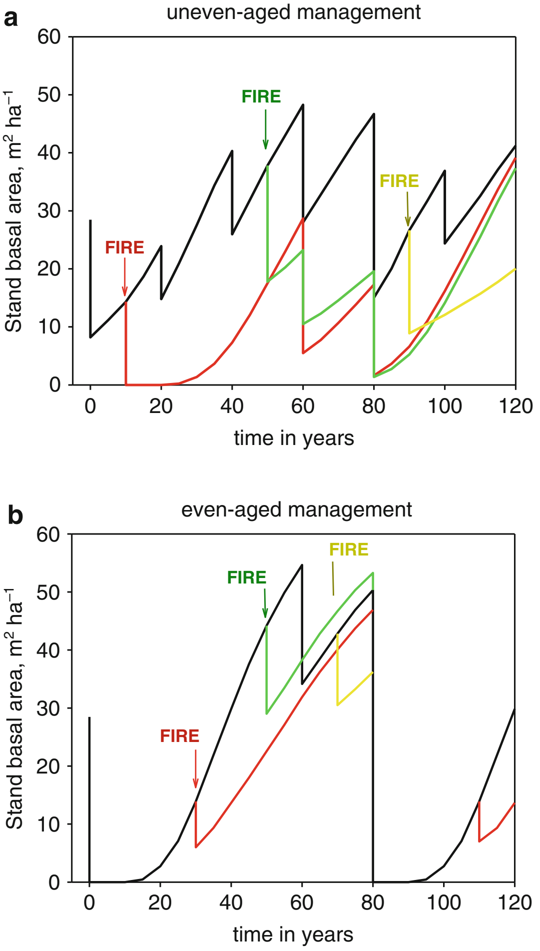


Fig. 6.5 Development of stand basal area for optimal regimes under four different realizations of wildfires. The *black line* denotes stand management without fires and *red*, *green* and *yellow lines* the developments where one wildfire occurs 30, 50 and 70 years after the initial time, respectively

levels of ladder and crown fuels are high enough to trigger an active crown fire. This is the case in stands that are dominated by young trees. In Fig. 6.5a, full mortality occurs if a fire occurs 10 years after the first selection harvest. At this stage, the stand has a large number of small understory trees and ladder fuels following a heavy diameter limit cut 10 years earlier. However, in uneven-aged stands that are dominated by older and taller trees, ladder fuels are limited making those stands less vulnerable to fire damage. This is the obvious reason why later fires (at 50 and 90 years after initial time) lead only to partial damage.

Figure 6.5b shows corresponding stand developments for even-aged management. Under even-aged management, tree mortality is 100% if wildfire occurs at a seedling phase (not shown). However, tree mortality declines with stand age and elevated canopy base. Fires occurring at later ages lead to only partial damage. Also, the level of mortality under even-aged management is lower compared with the mortality under uneven-aged management.

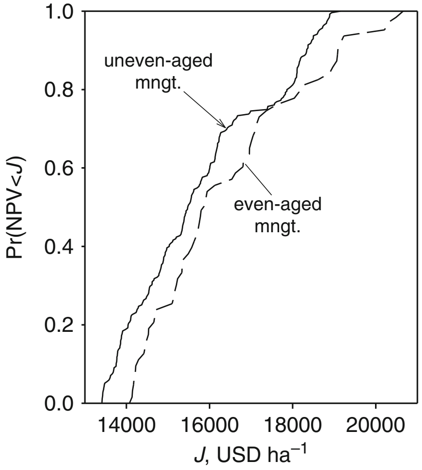


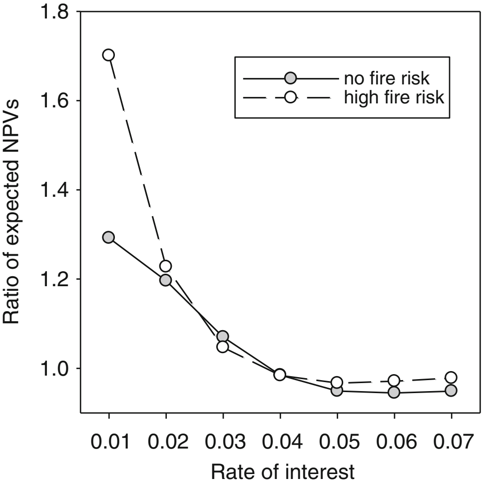
Fig. 6.6 Cumulative probability distributions of net present values under the optimal management for continuous cover forestry and even-aged management with a $\lambda = 0.4$ risk of wildfire

Once a wildfire occurs, it typically reduces the amount of harvestable timber and causes economic damage. In some exceptional cases wildfires may have positive economic effects by reducing the number of less valuable species and reducing the damage of future fires by consuming fuels. The cumulative probability distributions of net present values with wildfire risk of $\lambda = 0.4$ are shown in Fig. 6.6. Fire risk reduces expected net present value and widens the probability distribution (compare Figs. 6.4 and 6.6). Another important consequence is that the probability distributions for the two management systems are now overlapping. The expected net present value is still higher with even-aged management. However, the difference in the expected values is small compared to the variation in net present values. This implies that in regions with high fire risk, the choice of management system may be economically less important than considering ways to reduce the risk of wildfire.

The interest rate is an important factor affecting the relative efficiency of alternative management systems. Figure 6.7 shows the ratios of expected net present values of converting the stand to even- and uneven-aged management under alternative rates of interest. The values exceeding one indicate that even-aged management is superior to uneven-aged management. Two levels of fire risk are considered: no risk ($\lambda = 0$) and high risk ($\lambda = 0.4$). Even-aged management is the superior management system at low rates of interest less than or equal to 3%, while uneven-aged management is superior for higher rates of interest. The most obvious explanation is that small but frequent revenues from uneven-aged management become more favorable than larger and infrequent revenues from even-aged management at high rates of interest (Chang 1981).

According to Fig. 6.7, an increasing fire risk improves the relative efficiency of even-aged management for both low rates of interest ($r \leq 0.02$) and high rates ($r \leq 0.05$). Fire risk improves the relative profitability of even-aged management at high rates of interest because even-aged management allows for immediate harvest

Fig. 6.7 The ratio of expected net present values between even-aged management and continuous cover forestry for two levels (zero and high) of wildfire risk



of the initial stock without the risk of losing any trees. However, this result is likely to change if the forest stand under consideration is younger and not yet mature for clearcutting. At low rates of interest, fire risk improves the relative profitability of even-aged management because stand structures composed of an even-aged cohort of trees are, over the course of the entire rotation, less vulnerable to fire damage than uneven-aged stands containing more than one cohort. The fuel structures in even-aged stands are less likely to promote intense fires with high levels of damage than fuel structures in uneven-aged stands.

In addition to the rate of interest, there are many other factors affecting the relative profitability of management systems. One critical factor is the relative price of planted species under even-aged management in relation to prices of naturally regenerating species and the species mixture in naturally regenerating stand. Here the planted species is white pine, which is a commercially valuable species. The computations were also carried out for two other common plantation species: Douglas-fir (*Pseudotsuga menziesii*), and lodgepole pine (*Pinus contorta*). These two species show similar growth rates as white pine, but the stumpage prices are clearly lower. If either Douglas fir or lodgepole pine was the species considered for planting, uneven-aged management turned out superior to even-aged management at all rates of interest (relative present values from even-aged management varied between 0.7 and 0.95 compared to uneven-aged management). On the other hand, the good economic outcome of uneven-aged management depends on the existence of valuable naturally regenerating trees. For this case study of a mixed conifer stand in Northern Idaho, a mixture of Western red cedar, which is more valuable than any of the planted species, makes uneven-aged management a financially competitive alternative to white pine plantation.

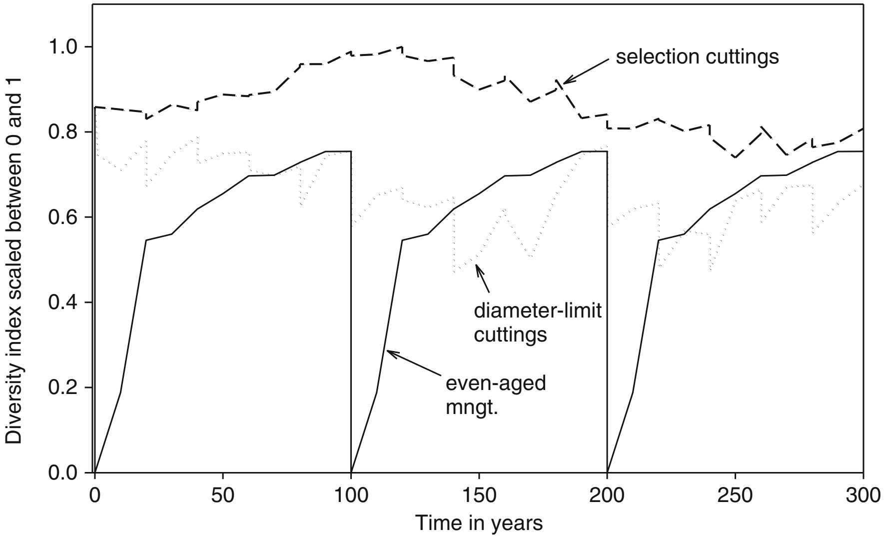


Fig. 6.8 Development of stand diversity index for a mixed conifer stand over a 300-year simulation period for three alternative chains of stand management

4.5 *Environmental Considerations*

Earlier examples shown in this chapter assume that timber is the primary forest product with value. Here, we investigate the consequences of alternative stand management systems on stand diversity as measured by the Shannon index (Eq. 6.12), which reflects habitat quality and describes a stand's richness with respect to tree sizes and tree species. Figure 6.8 shows the development of stand diversity index for such even-aged and uneven-aged management regimes that are optimal at a 3% rate of interest and zero risk of wildfire. In addition, development of diversity is shown for a sequence of selection harvests that develop and maintain a reverse J-shaped diameter distribution. In this regime, the residual basal area after a selection harvest is 14 m^2/ha and the q-ratio of the residual trees in adjacent diameter classes is 1.4. Trees are arranged in 10 cm diameter classes and equal weights are applied for species and size diversity ($w_{s\ p} = w_{size} = 0.5$). In Fig. 6.8, the Shannon diversity index values are scaled between 0 and 1 to better demonstrate the relative differences between the compared management regimes.

Based on the NPV with low interest rate, the ranking of the management systems is: (1) even-aged management, (2) uneven-aged management with diameter-limit cuts (7% reduction in expected net present value) and (3) selection harvests that maintain the inverse-J shaped diameter distribution (37% reduction in expected net present value). However, the ranking is reversed if stand diversity is used as the ranking criteria. Uneven-aged management with diameter-limit cuttings and selection harvests that maintain the inverse-J distribution retain high species and tree size diversity throughout the planning horizon. With even-aged management, on the contrary, the diversity fluctuates considerably during a rotation period. Wildfires cause temporary reductions in the diversity index for all management systems. However, these reductions are typically followed by a peak during the subsequent periods (not shown).

According to Fig. 6.8 and empirical results (Fuller et al. 2004), carefully planned selection harvests may provide more valuable flows of non-timber benefits than even-aged management. On the other hand, continuous cover forest management does not guarantee environmentally desirable forest structures. Unconstrained diameter limit cuttings may lead to very low stocking levels and stand structures that deviate considerably from those of natural forests. In the case of private landowners practicing continuous cover forestry, additional compensation for retaining the species composition and stand stocking at appropriate levels (Chap. 3) or legal restrictions banning undesirable harvesting practices may be needed to ensure adequate provision of non-timber benefits.

5 Conclusions

The problem of how to manage a forest stand optimally has been considered over centuries – at least as long as forests have been managed in an organized manner for timber production purposes.

Research on the economics of continuous cover forestry was initiated in the USA in the 1950s and expanded in the 1970s in tandem with developments in the fields of forest growth modeling and mathematical programming. The interest spread to Europe in the mid 1990s in response to the public's desire to convert conifer monocultures to mixed-species stands and increase environmental benefits (Knoke et al. 2008). Recently, studies of the economics of uneven-aged management have been undertaken worldwide (Table 6.1).

Interpretation of optimization results from the point of view of practical forestry requires careful consideration. Individual studies show results from models that are tailored to only one or a few forest stands and specific economic conditions. Replicating the computations with different initial states and soil qualities would facilitate the development of more general management guidelines. Sensitivity analysis with respect to economic variables is needed to derive guidelines for different regions and landowners. Comparison of the results obtained with alternative stand growth models would give a forestry practitioner better assurance of the reliability of model outcomes.

The relative economic performance of alternative stand management systems is driven by several factors. One critical factor for the desirability of uneven-aged management is the initial state: repeated selection harvests have been found to suit best those stands that include trees of different sizes, ages and species at the beginning of the planning horizon (Haight and Monserud 1990a; Wikström 2000). In addition, there are several economic, biological and technical factors that affect the relative profitability of even-aged vs. uneven-aged management. Important economic factors include timber prices and costs of silvicultural activities. The rate of interest also may become decisive: a low rate of interest tends to favor even-aged management and high rate of interest uneven-aged management (Chang 1981; Tarp et al. 2000; Knoke and Plusczyk 2001; Pukkala et al. 2010; Hyytiäinen and Haight 2010). Important biological factors include the amount, species composition and spatial distribution of natural regeneration (Haight and Monserud 1990b; Tarp 2000) as well as tree growth and mortality in different shading conditions (Tahvonen 2009). Technical considerations include costs of different harvesting technologies and damages to the remaining trees (Mendoza et al. 2000).

Central questions related to the financial feasibility of continuous cover forestry include the following: How costly are selection harvests compared to thinning and clearcutting of even-aged forest? How will the market demand of plantation vs. naturally regenerated tree species evolve in the future? How much and what type of logging damages do alternative stand management systems cause to the remaining trees? Does the growth of suppressed trees recover soon after more light becomes available? Is natural regeneration distributed evenly over the forest, or does regeneration occur in patches leaving large empty areas with no seedlings? Does natural regeneration include shade tolerant and economically valuable tree species? Should species mixture be steered through planting, slashing or other silvicultural activities, and how costly are these activities? How does the probability of damage after natural hazard, such as insect damage, windfall or wildfire, differ between alternative management systems?

Existing literature has addressed some, but not all of these questions. One important topic for further research, which is inadequately addressed in present papers, is the economic effects of the spatial distribution of trees. It is typical for most uneven-aged stands that tree regeneration concentrates in patches, which leads to irregular spatial arrangement of trees of different sizes. Spatial stand growth models (Kurttila 2001; Pretzsch et al. 2002) and possibly gap models (Bugmann 2001) would serve as appropriate tools for accounting for the spatial irregularities and their economic consequences in any-aged formulations. Further, spatial growth models might enhance the characterization of habitat quality and the impacts of alternative harvest strategies on habitat quality.

One striking feature in the geographical coverage of the economic studies of uneven-aged management is the scarcity of case studies specified for the fragile soils of the tropics (Boscolo et al. 1997; Mendoza et al. 2000; Conrad et al. 2005). The interesting and important feature of sensitive forest ecosystems is the dependence of sustained production capacity on the type and intensity of management (Favrichon 1998). The potential for environmentally friendly forest management is at its highest in such conditions.

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