Cost-effectiveness of Measures to Improve Biodiversity in Swedish Forests

Hans Ekvall
Faculty of Forest Sciences
Department of Forest Economics
Umeå

Doctoral Thesis
Swedish University of Agricultural Sciences
Umeå 2014

Acta Universitatis agriculturae Sueciae
2014:3

ISSN 1652-6880
ISBN (print version) 978-91-576-7954-3
ISBN (electronic version) 978-91-576-7955-0

Print: Arkitektkopia 2014

Cost-effectiveness of Measures to Improve Biodiversity in Swedish Forests

Abstract

The main objective of this thesis is to analyse the cost-effectiveness of measures, which improve biodiversity among life forms dependent on coarse woody debris (CWD). The amount of CWD in forest land has decreased due to modern forest management.

The wood of the trees is an important source of income for the forest owner and there is an undeniable conflict between increasing the amount of CWD and the economics of silviculture. To gain acceptance among forest owners of an increased retention of trees as potential CWD substrate, it is important that CWD-increasing measures are performed in a cost-effective manner, which means that the cost to attain a specific level of CWD is as low as possible.

Calculations were performed of CWD formed and opportunity costs of forest stands from three regions in Sweden. Norway spruce was the prime study object but analysis of mixed stands of Norway spruce, Scots pine and birch or aspen were carried out as well.

The cost-efficiency of seven conservation measures, which aim to increase CWD in managed forests, was analysed. In all regions the same pattern was obtained regarding ranking order of five measures; retention of snags was the most cost-effective measure, followed by creating high stumps, manual scarification and retention of living trees, and finally prolongation of rotation as the least cost-effective measure. Setting aside a stand as a reserve, and retention of wind-thrown trees showed an increasing cost with increasing land productivity.

Estimating the cost-efficiency factor for different CWD-increasing measures in mixed stands revealed that birch and aspen were more cost-effective than Norway spruce and Scots pine.

In a multiple stand context the least-cost allocation of conservation measures depends on the desired increase in CWD. Analysing the choice of cost-effective CWD-increasing measures on a Norway spruce dominated estate in central Sweden showed that huge improvements in the cost-effectiveness of biodiversity-oriented forestry are possible.

Keywords: biodiversity, conservation measure, cost-effectiveness, CWD, forest estate, forestry, least-cost allocation, opportunity cost

Author's address: Hans Ekvall, Department of Forest Economics, SLU
Skogsmarksgränd, SE-901 83 Umeå, Sweden.
E-mail: Hans.Ekvall@ slu.se

Sammanfattning

Målet med denna avhandling är att analysera kostnadseffektiviteten för åtgärder i skogsbruket, vilka har till uppgift att öka biodiversiteten hos livsformer som är beroende av död ved (CWD). Mängden död ved i skogarna har minskat på grund av hur det moderna skogsbruket bedrivs.

Trädens virke är en viktig inkomstkälla för skogsägaren och det finns en motsättning mellan att öka mängden död ved och lönsamheten i skogsbruket. För att skogsägare ska acceptera en ökad avsättning av träd, som kan bilda en eftersträvad nivå död ved, är det viktigt att välja åtgärder i skogsbruket som är så billiga som möjligt att utföra.

Beräkningar gjordes på den döda vedens volymökning och alternativkostnad för åtgärder i skogsbestånd från tre olika regioner i Sverige. I första hand studerades granbestånd men även blandbestånd av tall, gran och björk eller tall, gran och asp studerades.

Kostnadseffektiviteten, beräknad som kvoten mellan volymökning död ved och alternativkostnaden, studerades för sju olika åtgärder som ökar mängden död ved i den brukade skogen. I samliga studerade regioner visade resultaten på likartade trender för fem åtgärder; lämna kvar torrakor var den mest kostnadseffektiva åtgärden följd av skapandet av högstubbar, manuell markberedning (för att inte förstöra liggande död ved med tunga maskiner) och kvarlämnandet av friska träd. Sämst kostnadseffektivitet beräknades för förlängning av omloppstiden. Att avsätta bestånd som naturreservat eller lämna stormskadade träd visade på en ökad kostnad med ökad bonitet.

Beräkning av kostnadseffektiviteten för olika åtgärder i blandbestånd visade att björk och asp var mer kostnadseffektiva än tall och gran. Tall var minst kostnadseffektiv.

Den optimala fördelningen av åtgärder som ökar död ved så kostnadseffektivt som möjligt bland många bestånd berodde till stor del på vilken total mängd av död ved man ville erhålla på fastigheten som helhet. Vid analys av det optimala valet av åtgärder som ökar mängden död ved på en grandominerad fastighet i mellersta Sverige visade att stora förbättringar av biodiversitetsinriktat skogsbruk kan erhållas till en låg kostnad.

Dedication

To Ewa, Peter, Vilhelm, Rebecka, Hubert and Malkolm.

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Ranius, T., Ekvall, H., Jonsson, M. & Bostedt, G. (2005). Cost-efficiency of measures to increase the amount of coarse woody debris in managed Norway spruce forests. *Forest Ecology and Management. 206* (2005), 119-133.

II Jonsson, M., Ranius, T., Ekvall, H., Bostedt, G., Dahlberg, A., Ehnström, B. & Nordén, B. (2006). Cost-effectiveness of silvicultural measures to increase substrate availability for red-listed wood-living organisms in Norway spruce forests. *Biological conservation.* 127 (4), 443-462.

III Jonsson, M., Ranius, T., Ekvall, H. & Bostedt, G. (2010). Cost-effectiveness of silvicultural measures to increase substrate availability for wood-dwelling species – A comparison between boreal tree species. *Scandinavian Journal of Forest Research.* 25:46-60.

IV Ekvall, H., Bostedt, G. & Jonsson, M. (2013). Least-cost allocation of measures to increase the amount of coarse woody debris in forest estates. *Journal of Forest Economics.* 19 (2013), 267-285.

Papers I to IV are reproduced with the permission of the publishers.

Abbreviations

CBA	Cost Benefit Analysis
CEA	Cost-effectiveness Analysis
CWD	Coarse Woody Debris
FSC	Forest Stewardship Council
LP	Linear Programming
PEFC	Program for Endorsement of Forest Certification
SEV	Soil Expectation Value
XMAI	Maximum Mean Annual Increment

1 Introduction

This thesis is an introduction and overview of four papers, which were published over a time span of eight years, from 2005 to 2013. All papers deal with the problem of applying measures in forest stands to preserve and improve biodiversity by increasing coarse woody debris (henceforth denoted CWD) in the most cost-effective way. When dealing with costs and revenues for the private forest owner the computer program Plan33 was used. Plan33 is presented in the method section. The overall purpose of this thesis is to evaluate the cost-effectiveness of prevailing CWD-increasing practices in Swedish forestry and at the same time analyse the economic relationship between timber production and the formation of CWD.

An increasing world population is demanding more and more of scarce natural resources (United Nations, 2013). Among these resources forest land is, with its abundance of different organisms, most vulnerable when trees are killed, destroyed or extracted without considering the impacts that these events have on existing habitats. This environmental depletion for organisms in the forest may in the long run be a threat to the survival of humanity and therefore it is of utmost importance to limit these damages to nature by conducting certain conservation measures – one of them is preserving CWD.

Biodiversity is the degree of variation of life. In this thesis focus is set on biodiversity among life forms dependent on CWD, which has decreased due to modern forest practice. Many species in boreal forests are saproxylic (Hanski & Hammond, 1995; Siitonen, 2001) i.e. they rely directly on dead wood or on other species that request dead wood during some part of their life cycle (Speight, 1989). In Sweden the number of saproxylic species is at least 6,000 – 7,000 (Dahlberg & Stokland, 2004). On the Red List, comprising all endangered species in Sweden, more than 20% are saproxylic and confined to CWD, which explains why efforts to enhance the conditions for those species have focused on increasing dead wood (Paper II).

CWD is an accepted term for fallen dead trees and the leavings of large branches on the ground in forests (Keddy *et al.*, 1996) and in rivers or wetlands (Keddy, 2010). The natural source for CWD is snags, which are dying or dead trees. The cause of death can be natural, come from disease or insect attacks or from calamitous events such as fires, storms or floods. There is no standard that defines the minimum size required for woody debris. In the literature, the diameter of CWD varies from 2.5 to 20 cm (Lofroth, 1998). In this thesis a minimum diameter of 10 cm is considered necessary to contribute to restoring depleted habitats in Swedish forests, as used by Dahlberg & Stokland (2004). Small trees or harvesting residue seldom meet this specification and consequently cannot be counted as CWD.

CWD is important for nutrient recycling, which makes elements like carbon, nitrogen, potassium and phosphorus turn into vital, more accessible nutrients for living organisms such as bacteria, insects, and for instance, earthworms. Many CWD-dwelling species directly consume dead wood, releasing nutrients by converting them into other forms of organic matter, which can then be consumed by other species. CWD is not particularly rich in nitrogen but conveys nitrogen to the ecosystem by acting as a host for free-living nitrogen-fixing bacteria (Stevens, 1997).

Another significant aspect of CWD is its contribution to biological carbon sequestration. Trees store atmospheric carbon in their wood using photosynthesis. Once the trees die, fungi and other organisms transfer some of that carbon from CWD into the soil. This sequestration can continue in old-growth forests for hundreds of years (Luyssaert *et al.*, 2008). However, CWD accounts for only 5% of the total boreal ecosystem carbon at present (Lorenz & Lai, 2009).

Since the 1970s, forest managers worldwide have been encouraged to allow CWD matter to remain in woodlands, thereby improving biodiversity. The Swedish Forest Agency has been aware of the importance of coarse decaying wood for the survival of many species in the forest landscape. One of the first published papers from Swedish authorities dealing with environmental issues in forestry was a collaborative production between several large companies and other stakeholders of that time. Among many recommendations, forest owners were urged to retain snags, which in any case did not possess any value for either landowner or industry (Anon, 1974).

Forest management in Fennoscandia (Finland, Karelia, Kola Peninsula, Sweden and Norway) has decreased the volume of CWD to 2 - 30% of the quantity found in old-growth boreal forests (Fridman and Walheim, 2000; Siitonen, 2001). Consequently, a great number of saproxylic species have declined and are now considered threatened (Dahlberg & Stokland, 2004).

To maintain CWD at a predefined or desired level, trees (dead or alive) must be left in forests at regular intervals. There is an obvious conflict between increasing the amount of CWD and the economics of silviculture since wood can be sold on the market and deliver a considerable income to the forest owner. To gain acceptance among forest owners of an increased retention of trees as potential CWD substrate, it is important that environmental considerations are performed in a cost-effective manner. A cost-effective environmental manner means that a given amount of money spent on the environment improves biodiversity as much as possible, or that the cost of a given level of biodiversity is as low as possible (Baumol & Oates, 1988).

The connection between CWD and biodiversity is recognised by the Swedish government; in line with Swedish governmental goals, the quantity of CWD in managed forests should increase (Miljödepartementet, 2001). For this reason, several measures are currently taken with the aim of increasing the amount of CWD in the managed forests of Sweden. An example is the wide spread practice of retaining dead or dying trees at the time of a clear-cut (Swedish Forest Agency, 2012).

As is previously mentioned in the first paragraph of the introduction, one goal of this thesis is to analyse the economic relationship between timber production and the formation of CWD or more precisely stated: how much will it cost a forest owner to change forest practice aiming at sole timber production to a more biodiversity oriented forestry? To give an answer to this question several well-known methods or approaches can be considered.

The first method one thinks of is the well recognized cost-benefit analysis (CBA), mainly applied to large projects or decisions targeting societal issues and used many times before in the field of environmental assessments. The goal of a CBA-analysis is to determine the profitability of predefined projects or courses of action. The second method in mind is a sibling to CBA, the cost-effectiveness analysis (CEA), often used in the field of health services. The amount of literature, treating CBA and CEA is huge. Though CBA and CEA have common origin, there are clear differences between the two methods. In CBA, the benefits are expressed in a monetary value while in the CEA-analysis, the corresponding benefit, the effect, is expressed as a non-monetary value, since the effect cannot be evaluated in terms of money (Yates, 1985). Typically the CEA is expressed in terms of a cost/effect ratio where the denominator is an effect and the numerator is a cost.

Since stated Swedish governmental goal is to promote the increase of CWD in managed forests rapidly (Miljödepartementet, 2001), and information of the value of CWD is not available, will favour the CEA-analysis. It felt less adequate to use a normal cost-benefit approach and therefore the cost/effect ratio from the CEA was adopted in analysing measures to increase biodiversity. Thus the approach to estimating the increased costs of biodiversity oriented forestry is via an opportunity cost analysis.

The opportunity cost is estimated as the difference between the present value of timber production without measures to increase CWD and the present value of timber production where measures to increase CWD are considered. Improvement of biodiversity is measured by a conservation indicator, e.g. an increased volume of CWD or increased number of surviving red-listed organisms. The cost-effectiveness of a CWD-increasing measure is then estimated as the quotient between opportunity cost, and the value of the conservation indicator.

Many articles have been written about forest management, aiming to increase the quality and volume of CWD, but very little of that effort has dealt with the subsequent costs of that management. Some studies have been published analysing cost-effectiveness of measures that increase CWD in boreal forests. One previous attempt has considered costs and tree mortality (Wikström & Eriksson, 2000). Kruys and Wikström (2001) modelled wood dynamics and the population dynamics of a liverwort, and Lichtenstein and Montgomery (2003) used the simulated annealing algorithm to estimate a production possibility frontier for biodiversity and timber production for a study area in Oregon, USA. In more recent years Mönkkönen *et al.* (2011) have shown that setting aside whole stands as reserves is a highly cost-efficient CWD-increasing strategy and Tikkanen *et al.* (2012) argued that adaptation of timber producing forestry by omitting thinning operations was a most cost-effective practice for increasing CWD.

There are basically two ways to preserve biodiversity on forest land; forests can be set aside as reserves or the management of a timber production forest can be modified. For various reasons – one is pure economic - only a minor part of forest land in Sweden has been left unmanaged to transform into old growth forests, so adapted management of timber producing forests is probably a more realistic and acceptable option for the successful conservation of forest biodiversity. According to the Swedish Statistical Yearbook of Forestry (Swedish Forest Agency, 2012) about four per cent of the total productive area of forest land in Sweden is protected as national parks, nature reserves, habitat protection areas and nature conservation agreements. Forestry certification organisations, such as the Forest Stewardship Council (FSC) and Program for the Endorsement of Forest Certification (PEFC), play an important role in promoting forestry practices aimed at improving biodiversity in forest land. According to PEFC almost 65% of the productive forest area in Sweden is nowadays tended in accordance with the rules of forest certification organisations and forest owners have, as a consequence, adapted forest practices accordingly (PEFC, 2010). A citation from one of FSC's reports is clarifying: "The goal of FSC is to promote environmentally responsible, socially beneficial and economically viable management of the world's forests, by establishing a worldwide standard of recognized and respected principles of forest stewardship" (FSC, 2009).

Since forest certification standards have a huge impact on current silvicultural practices - around 65% of the productive forest area in Sweden is tended according to rules issued by forest certification organisations and aimed at increasing biodiversity - it must be of general interest to study the economic effects on forestry management which complies with these rules. As the overall purpose of the thesis, stated in the first paragraph of the introduction, is closely related to forest certification standards, this will lead to a number of more well-defined research questions or hypotheses in the respective papers. In Paper I, the main question is how cost-effective different prescribed CWD-increasing measures are, in relation to the formed volume of CWD in monocultures of Norway spruce? The question of whether change in interest rates affects cost-effectiveness is also addressed in Paper I. In Paper I improved biodiversity was measured with a conservation indicator targeting increased volume of CWD and the specific qualities of CWD originating from different CWD-increasing measures was not studied. In Paper II the focus was CWD-quality, so cost-effectiveness was studied in relation to additional conservation indicators, presented in method section '3.5 Estimation of formed CWD'. As monocultures of Norway spruce are not the only type of forest, Paper III addresses the cost-effectiveness, estimated as in Paper II, but in mixed typical stands of Norway spruce, Scots pine, birch or aspen. An additional question posed in Paper III is whether change in timber prices will affect the ranking of different CWD-increasing measures. In Papers I – III, estimations of the cost-effectiveness of CWD-increasing measures were performed on predefined typical stands in different regions in Sweden. But what happens with cost-effectiveness estimations, if the variation in stand characteristics is huge, such as in a larger forest estate comprising hundreds or thousands of stands? In Paper IV, therefore the outcome of applying cost-effectiveness estimations in a multiple stand environment was analysed.

2 Theoretical framework

The description of the theoretical framework is focused on the economics of timber production. The subject is divided into two parts. First an historical background is outlined and then the forest economics that are important for the thesis are presented.

In connection with specific issues in this chapter, certain limitations applied in the thesis are presented and defined.

2.1 Historical background

The problem of deciding the optimal rotation for single stands or multiple stands in a forest or estate context has long occupied foresters and economists. Finding the optimal value of the rotation also implies finding the best combination of silvicultural measures to give the highest present value.

2.1.1 Rotation for a single stand

The German forester Martin Faustmann laid the foundations of modern forest economics when he published his famous article in 1849, describing a formula to calculate the Soil Expectation Value (denoted SEV) by summing up the present value of timber production from an infinite number of rotations (Faustmann, 1849). In practice Faustmann could correctly determine the length of the rotation but the problem of how to demonstrate this mathematically remained. Max Pressler published the mathematical framework for the Faustmann formula (Pressler, 1860). One of the first scientists to recognise the full potential of the Faustmann formula, and who could also mathematically prove that both Faustmann and Pressler were right was the Swedish economist Bertil Ohlin. He solved the rotation problem by maximising the Faustmann formula with respect to time (Ohlin, 1921). The solution prescribes that the optimal rotation is obtained when the marginal revenues, i.e. the current value growth of trees, equal the marginal costs, i.e. the current value of trees plus land multiplied by the interest rate. In this case the marginal cost equals the opportunity cost of delaying harvesting one more year.

From the middle of the 19th century, in the era of rapid industrialisation in Europe and North America, to the middle of the 20th century, timber production was considered to be the most important use of land suitable for tree growth. But what happens if forestland can provide both timber products and amenity services? In 1976 Richard Hartman suggested that a new term, estimating the present value of amenity services, could be added to the Faustmann formula (Hartman, 1976). According to Hartman the optimal rotation could now be different, as opposed to the older Faustmann solution.

So far estimation of the optimal rotation has been made under the assumption that prices and other conditions are static and can be stated with certainty and with no risks involved. In real life stochastic and dynamic effects are encountered frequently. Consider that prices of timber, which directly affects the stumpage price, tend to evolve over time in an unpredictable way. When the time has come to harvest, the forest owner may face the risk of low prices. Would it have been better to harvest sooner, or to defer the harvest decision? These types of risks can be handled using general stochastic processes (Amacher *et al.,* 2009).

Over time, prices, costs and interest rates will change. Other aspects of land use decisions, such as amenities or carbon stocks, also evolve. Optimal control theory and dynamic programming are useful techniques to solve problems that involve changes over time (Amacher *et al.,* 2009).

Although, incorporating stochastic processes and/or changes over time in the analysis would have been an approach that was closer to reality, a simple deterministic approach (with known prices and technology) was considered sufficient for solving the stated research questions in Papers I - IV.

2.1.2 Rotation for a stand in an estate context

There is no simple formula like the Faustmann rule to establish the optimal rotation for forest stands in an estate context.

In the middle of the 1960s, the Swedish forest economist Göran von Malmborg was deeply involved in research concerning the planning of the optimal management of combined forestry-agricultural firms. Influenced by the works of Heady (1952), Coutu and Ellertsen (1960), Gaffney (1960) and Gould and O´Reagan (1965), von Malmborg finished his doctorial studies with the thesis "Ekonomisk planering av lantbruksföretaget" [Economic planning for the combined forestry-agricultural firm] (von Malmborg, 1967). It was clear that forestry could not be treated as a stand-alone venture. So many things in the environment affected the decisions of the forest management. Linear Programming (LP) was the preferred tool to handle optimisation problems at the time. von Malmborg showed, with help of LP, how a self-employed landowner should allocate his limited working time between work in the forest, and work in the fields or with cattle tending etc. He also showed why it sometimes was more profitable for the landowner to hire skilled forest workers to get silvicultural jobs done than to do them all by himself. von Malmborg also showed, due to income constraints and very high marginal taxes, that the forest owner was unwilling to undertake clear-cutting of stands according to the Faustmann rule. High marginal taxes of more than 80% at that time would have substantially diminished the profit of a clear-cut. The forest owner felt compelled to harvest no more than would be needed for necessary investments on the farm and daily consumption. The rotation tended to be prolonged compared to the Faustmann solution. On the other hand, in a restricted economic situation when money or available capital was scarce, the forest owner had to increase harvest as much as needed within the pale of the law. In this case the rotation tended to be shortened.

2.2 Forest economics - the present value

In order to estimate the many values presented in Papers I – IV and in this thesis, the present value method was used. The method is well known and widely accepted among economists. Its merits and demerits are well documented (Samuelson, 1980).

2.2.1 Some short notes on the present value method

To use the present value method, for instance in a timber production context, and to be able to assess any credibility of presented results, a number of well-known assumptions must be valid:

- Financial capital markets are perfect. The interest rate of borrowing and lending is equal. The forest owner can easily raise loans to finance consumption without distorting management plans.
- Future prices, costs and silviculture technology are known.
- Forest land and forest products can be bought and sold on a perfect market.
- The growth functions, both in volume and in quality, are known.

As we all know, in the real world, none of these assumptions will be entirely met. Knowledge of future prices, costs and technology especially, is often based on conjectures and wishful thinking. Whatever the outcome of a present value estimation, the result must be treated with a sound sceptical approach.

2.2.2 Present value in forest calculations

Generally, the present value of forest management (for timber production or any other use) from forest land is defined by:

$$\Pi = \sum_{j=1}^{J}\left[\sum_{t=0}^{\infty} N\left(M_j, t, j\right)\left(1+r\right)^{-t}\right] \tag{1}$$

Π	Present value of forest management.
j	Stand number j.
J	Total number of stands included in the valuation.
t	Time t.
M_j	Management program for stand j is a series of management activities to be practiced in stand j from time 0 to infinity. Management program M_j can contain any silvicultural measures belonging to normal forestry practice. The notions of normal forestry and normal forestry practice refer to common practices in Swedish forestry at the beginning of this millennium – practices that were also prescribed by the Swedish Forest Act (Swedish Forest Agency, 1994). As an example, silvicultural measures of normal forestry – forestry in which the main objective is to produce timber in the most cost-effective manner - are in this paper divided into three parts, regeneration measures, harvesting measures and miscellaneous measures. Examples of regeneration measures are soil scarification, cleaning of clear felled areas, planting and replanting, control of regeneration (regrowth control) and pre-commercial thinning (cleaning). Thinning and final cutting are harvesting measures. Final cutting is divided into clear-cutting and clear-cutting with retention of seed trees (seed tree method). Fertilization and pruning are counted as miscellaneous measures. Further, M_j can contain measures that aim to increase biodiversity, such as leaving high stumps at thinnings or retaining trees at final cutting, or measures targeting societal commitments.

$N(M_j, t, j)$ Net revenue at time t from stand j. Conditional on management program M_j. The net revenue is defined as the difference between revenues and costs of the measure at time t. If no measure is conducted in stand j at time t, then $N(M_j, t, j) = 0$. The value of $N(M_j, t, j)$ is often negative for regeneration measures and biodiversity increasing measures but mostly positive for thinnings and clear-cuts.

r Interest rate r.

$(1+r)^{-t}$ Discounting factor.

With an even aged stand management system, where all silvicultural measures will be repeated perpetually with an interval of u years, the Soil Expectation Value is then defined as:

$$SEV_j = \max_{u,M_j}\left[\sum_{t=1}^{u} N(M_j, t, j)\cdot(1+r)^{-t}\right]\cdot\frac{1}{1-(1+r)^{-u}} \qquad (2)$$

u Rotation, years.

SEV_j The Soil Expectation Value for stand j. The value of u (rotation) is determined by assuming that the best conceivable (and available) management practices are conducted on the land so that the highest Soil Expectation Value will be produced.

The Soil Expectation Value is the maximum present value according to the Faustmann rule. In the original Faustmann formula there was also a factor estimating the present value of annual fixed costs (and revenues). For the sake of clearness that factor is not included in the previously defined Soil Expectation Value. Managers of forest estates have long considered it difficult to assess those annual fixed costs on stand level in a proper way. According to modern accounting principles unassigned fixed costs from stands have instead been assigned to the appropriate estate level accounts. It must be stressed, that assessing the Soil Expectation Value with the Faustmann formula requires static prices and no change of technology related to forestry management. Newman *et al.* (1985) have made a comprehensive contribution to the knowledge of optimal rotation with evolving prices.

Finally, assuming static prices and no change in technology, the present value of an even-aged stand at age a, is given by:

$$\Pi_j(a) = \max_{T,M_j}\left[\underbrace{\sum_{t=a}^{T}\left[N(M_j,t,j)\right]\cdot(1+r)^{a-t}}_{\text{Initial stand generation}} + \underbrace{SEV_j\cdot(1+r)^{a-T}}_{\text{Consecutive stand generations}}\right] \quad (3)$$

with respect to harvest age T and management program M_j.

j	Stand number j,
a	Current age of stand j, years.
$\Pi_j(a)$	The maximum present value of current and all future net revenues from stand j with an initial age a.
T	Age of initial stand at final felling.
SEV_j	Soil Expectation Value for stand j, estimated using expression (2).

The formula is divided into two parts. The first part calculates the present value of the initial generation of trees in the stand, and the second part is the present value of the Soil Expectation Value according to the Faustmann formula. In this case the Soil Expectation Value can be interpreted as the present value, just after clear-cutting of the initial stand, of an infinite number of rotations.

Note that the effect of taxes is omitted in formulas (1) - (3). Taxes will be treated briefly in the methods section '3.3.3 Income taxes'.

Maximising the present value of an estate forest is far more complicated than single stand maximisation. The valuation process involves huge amounts of planning effort. Different types of constraints have to be added into the management plan of the estate as do the considerable effects of taxes.

A more thorough analysis of estimating the present value of an estate with Plan33 will be presented in methods section '3.4.4 Planning and valuing a forest estate with Plan33'.

3 Methods

In the methods section a number of topics are treated: *i*) Differences between Papers I – IV *ii*) Costs of producing timber , *iii*) Forest management practice, *iv*) The economics of timber production – introducing Plan33, *v*) Estimation of formed CWD *vi*) Simultaneous production of timber and CWD.

3.1 Differences between Papers I – IV

Although all papers deal with the most cost-effective way to create CWD, there are some differences between them that can be useful to bear in mind. As seen in Table 1 each study focuses on specific aspects of CWD, different types of studied stands and tree species, different interest rates and different price levels on timber.

Table 1. Differences between Papers I – IV

	Paper I	Paper II	Paper III	Paper IV
Studied conservation indicators	Volume of CWD	Volume of CWD, Substrate index, Thresholds values	Volume of CWD, Substrate index	Volume of CWD
Region / County	Kronoberg, Gävleborg, Västerbotten	Kronoberg, Gävleborg, Västerbotten	Kronoberg, Gävleborg, Västerbotten	Gävleborg
Studied tree species and types of stands	Typical stands of Norway Spruce	Typical stands of Norway Spruce	Typical mixed stands of Scots pine, Norway spruce and birch or aspen	A forest estate with mixed stands of Scots pine, Norway spruce and birch.
Applied interest rates	2%, 3%, 4%	3%	3%	3%
Sawtimber and pulpwood prices (year)	2002	2002	2002, 1988 (higher prices)	2002

Studied conservation indicators

In all papers the volume of CWD formed was estimated. The quality aspects of CWD, such as substrate index and thresholds values, were studied extensively in Papers II – III, but in this thesis the subject will be very briefly treated in section '3.5 Estimation of formed CWD'.

Region / County

The country of Sweden is very elongated; the distance from north to south is almost 1,600 km. This means that one can expect great differences in climate which will, among other things, affect forest growth and the formation of

CWD. To capture these differences in the areas studied, simulated forest stands were therefore selected from three different regions in Sweden.

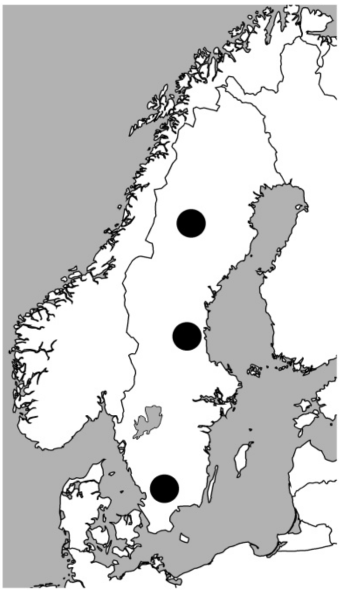

Figure 1. Location of stands and forests studied in Sweden.

The forests studied were situated in the county of Kronoberg in southern Sweden (denoted SS), the county of Gävleborg in central Sweden (denoted CS) and the county of Västerbotten in northern Sweden (denoted NS).

Studied tree species and types of stands

In the thesis, the following tree species will be mentioned: Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea Abies* L.), birch (*Betula pubescens* Ehrh. and *Betula pendula* Roth.), Lodgepole pine (*Pinus Contorta* Dougl.*)*, beech (*Fagus Sylvatica* L.), oak (*Quercus Robur* L.) and aspen (*Populus tremula* L.)

Different types of artificially created stands were studied in Paper I - III. The created stands have been assigned properties very similar to the mean values of the three study regions in Sweden. As Norway spruce, is the most common tree species in Swedish forestry today with 42% of the total growing volume and subsequently will produce the main share of CWD, it was important to choose Norway spruce as the prime study object in all papers. In Papers I - III, the focus is on single stand analysis while Paper IV deals with multiple stands simultaneously. In Papers I and II monocultures of Norway spruce were investigated and in Paper III the analysis comprised mixed stands with three different species in the same stand.

In Paper IV data was provided for the analysis from two merged municipality-owned estates with a total area of 1,967 hectares divided into 716 stands dominated by Norway spruce, in the county of Gävleborg in central Sweden. The volume proportion of different species in the created mixed stands can be seen in Table 2 below. In Paper IV, the Norway spruce proportion was never below 55% and the CWD volume formed was estimated as if each stand consisted merely of Norway spruce.

Table 2. Some properties of stands used in the different papers

Paper	**Area of Sweden**	**Site index**	**Yield, m^3/ha / year**	**Scots pine, %**	**Norway spruce, %**	**Deciduous, %**
I and II	Northern	G16	2.5	0	100	0
	Central	G24	6.5	0	100	0
	Southern	G32	9.1	0	100	0
III	Northern	G16	2.3	45	45	10 (birch)
				45	45	10 (aspen)
	Central	G24	6.4	45	45	10 (birch)
				45	45	10 (aspen)
	Southern	G32	9.1	25	65	10 (birch)
				25	65	10 (aspen)
IV	Central	G13 - G31	2.0 - 8.3	0 - 45	55 - 100	0 - 20 (birch)
		Mean: G22	Mean: 5.9	Mean: 19	Mean: 75	Mean: 6

Site index or site index quality is a measure of the production potential of a stand. In Sweden it is usually presented as G (for "gran", i.e. Norway spruce), T (for "tall", i.e. Scots pine), B (for "björk", i.e. birch, all species and subspecies), and A (for "asp", i.e. aspen, all species and subspecies), followed by a number indicating the average height of the dominant trees in the stand at the age of a reference year, normally 100 years for coniferous trees and 50 years for deciduous trees. Thus, the expression G22 refers to a Norway spruce stand where the dominant trees in the stand will be 22 meters at the age of 100 years (measured at breast height, 130 cm above the forest floor) and B20 is a birch stand that at the age of 50 (measured at breast height) reached a height of 20 m.

According to Table 2 the site index for the forest estate in Central Sweden varied from G13 - G31. As the forming of CWD is closely related to growth potential among trees in a forest stand it is important to know the actual distribution of site indices in the estate's forest.

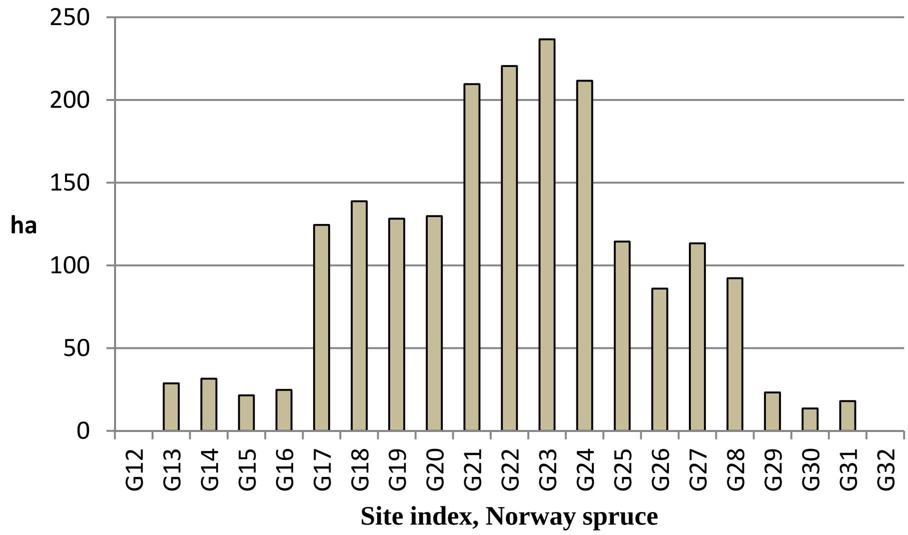

Figure 2. Distribution of site indices on a forest estate in Gävleborg.

As can be seen from Figure 2, site indices from G21 to G24 dominate the forest. The distribution resembles to, some extent, the shape of the statistically normal distribution function, but that is merely coincidental.

In the introduction section, the cost-effectiveness of a CWD-measure was defined as the quotient between opportunity cost and the value of a conservation indicator. The opportunity cost for many CWD-increasing measures is positively correlated with the average volume and diameter of the trees, which means that the opportunity cost will increase with increasing average tree volume and diameter. Table 2 shows the volume proportion of different species for the forest estate and in Figure 3 below the actual distribution is shown with diameter on the x-axis and the total volume of the respective species on the y-axis.

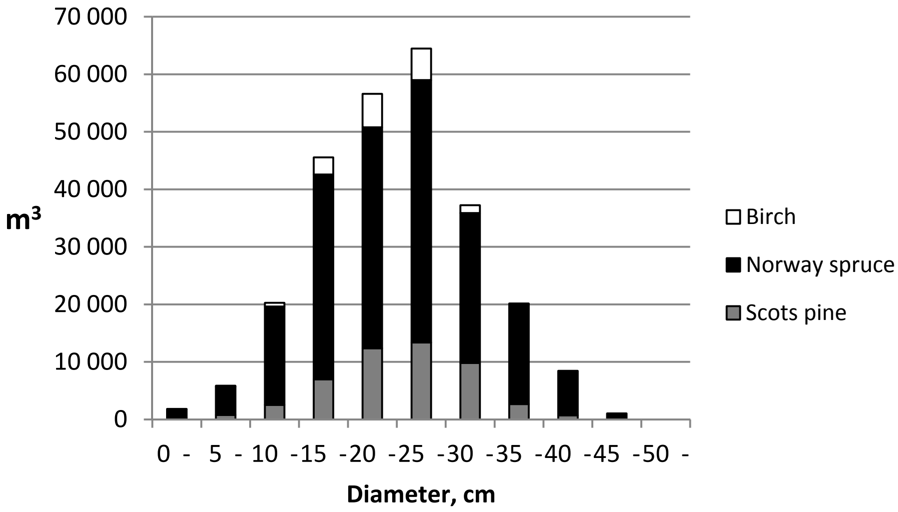

Figure 3. Diameter class distribution across different tree species.

The total volume of Norway spruce trees seems to reach its peak at a diameter class of 25 cm. As expected, birch trees with large diameters are rare, probably due to previous thinnings.

Applied interest rates

Interest rates affect forest management and present values. Traditionally an interest rate of 3% has been applied in forest calculations in Sweden for a very long time. This interest rate was once prescribed (in fact it was in the range of 2.5% to 3%) in the Forest Act of 1948 (Swedish Forest Agency, 1948).The motive for using 3% was that the estimated rotation was consistent with applied forest practice – a practice that yielded the proper dimensions of sawtimber and pulpwood for the market. To capture possible changes in the interest rate, 2% and 4% have been tested in Paper I, in calculations for single stands in central Sweden.

Sawtimber and pulpwood prices

All economic calculations concerning prices of sawtimber and pulpwood are based on price lists for 2002 from Mellanskog, an association of forest owners. Prices of sawtimber in graphical form are presented in Figures 4 and 5. In Papers I – IV the following pulp wood prices are used: 235 SEK/m^3 for Scots pine, 240 SEK/m^3 for Norway spruce, 245 SEK/m^3 for birch and 220 SEK/m^3 for aspen.

It is a well-known fact that prices of timber are very volatile and sudden price changes are common, In Paper III therefore timber prices for 1988 from Mellanskog were also used in a sensitivity analysis. Compared to 2002, the prices in 1988 were around 40% higher for sawtimber and 70% higher for pulpwood.

In Papers I – IV, bio-fuel assortments, such as GROT (GROT is a Swedish acronym for branches and tops), were excluded in the assessment of the cost-effectiveness in measures to increase CWD. The reason for this was that for the measures evaluated in these studies, extracting GROT neither affected the volume of CWD nor the opportunity cost.

3.2 Costs of producing timber

3.2.1 Regeneration and harvesting costs

Regeneration and harvesting costs, valid for year 2002, expressed in Swedish kronor (denoted SEK), were obtained from Mellanskog and can be studied in Table 3 and Table 4.

Table 3. Regeneration costs, year 2002

Regeneration measures	Variable cost, SEK/hour	Fixed cost, SEK	Costs for site index G24 in central Sweden, SEK/ha
Soil scarification, machine	600	–	1,400
Soil scarification, manual	150	–	2,700
Planting and plants, Scots pine	140	1,100 (per 1,000 plants)	5,200
Planting and plants, Norway spruce	140	2,100 (per 1,000 plants)	6,000
Natural seed dispersal (birch and aspen)	0	–	0
Regrowth control	140	–	130
Pre-commercial thinning	320	–	3,100

Table 4. Harvesting costs, year 2002

Harvesting measures	Variable cost, SEK/hour	Fixed cost, SEK	Costs for site index G24 in central Sweden, SEK/ m^3
Manual cutting, thinning	240	–	250
Manual cutting, clear-cut	240	–	200
Thinning with harvester	705	–	95
Clear-cutting with harvester	705	–	63
Transport with forwarder after thinning	550	–	38
Transport with forwarder after clear-cutting	550	–	24
Indirect costs for thinning	300	1,000 (per stand)	12
Indirect costs for clear-cutting	400	1,000 (per stand)	10

In the far right column in Table 3 and Table 4 the regeneration cost per hectare and the harvesting cost per cubic metre for an average site index are shown. The values are estimated using Plan33.

The presented costs in Table 3 and Table 4 are assumed to reflect current market prices for 2002 and they were used in all papers presented and in all three selected regions of Sweden.

3.2.2 Transportation of timber

The forest owner will pay for the transportation of timber from roadside to industry 0.30 SEK/m^3 and km for sawtimber and 0.25 SEK/m^3 and km for pulpwood.

3.2.3 Income taxes

In Papers I – IV, the word tax is never explicitly mentioned. It was understood that all presented costs and present values were estimations of assumed market values from the private forest owner's point of view. One of the goals in Papers I – IV was to show how much a private forest owner would lose, in terms of decreased property value, if they conducted CWD-increasing measures in their forest. A common practice for emulating the market value of an asset is to deduct the expected tax rate from the estimated present value of the yield from the asset. Based on statistics from the Swedish Tax Agency (2004) and Statistics Sweden (2001) the average taxation level (payroll taxes included) for an average forest owner for the year 2004, was estimated by the author as 40%. Therefore, a tax rate of 40% was deducted from all estimated values and costs presented in Papers I – IV. As the tax rate is used as a constant, it will not affect the ranking or choice of CWD-increasing measures.

3.3 Forest management practice

In all four papers it was assumed that forests are tended according to normal forestry practice. The applied silvicultural system can be defined as even-aged timber management that includes regeneration measures, thinnings and a final clear-cut. The notion of normal forestry practice, previously mentioned in section '2.2.2 Present value in forest calculations', can be defined as adopting accepted silvicultural measures and complying with the Swedish Forest Act to achieve production and environmental objectives stated by governmental authorities. Within the boundaries of legislation the forest owner is free to choose from approved silvicultural measures to maximise the present value of normal forest timber production. This means that regeneration is assumed to be conducted using traditional methods, including soil scarification, planting, regrowth control and pre-commercial thinning. A harvester is used for felling, cutting, pruning, and stacking, and transport from the felling zone to the logging road is conducted with a forwarder. Manual cutting, pruning, and stacking are only employed when the number of trees is low, e.g. after a smaller wind-throw event. Logs are transported on lorries by road to the nearest pulp or sawmill. To estimate costs of regeneration measures and harvesting operations, the cost data from Table 3 and Table 4 was used. Regeneration measures were assumed to take place at times recommended by Mellanskog but times for harvesting, both thinnings and clear-cut were determined using the present value formula (3).

3.4 Economics of timber production

This section will deal with valuing timber production within the framework of the computer program Plan33. After a short presentation of Plan33, the focus is on how the net revenue of different management measures in forestry is estimated. The next issue is growth. Growth in forest stands is usually expressed as change in volume, but other types of change, strictly connected to volume growth, such as changes in diameter, height, quality and proportion of assortments, are all important to making a qualified estimation of the net revenue. Finally a large proportion of this section will deal with the planning and valuation of a forest estate.

3.4.1 Introducing Plan33

The purpose of presenting a rather comprehensive introduction to the computer program Plan33 is to facilitate evaluation of the economic calculations made in Papers I – IV.

Plan33 has its roots in old Swedish valuing traditions. Influences from American agricultural economists in the 1950s, using Linear Programming (Coutu & Ellertsen, 1960), and Finnish forest economists in the 1990s, using stochastic and non-linear optimisations techniques (Valsta, 1992a; b), have accelerated the development of Plan33.

Plan33 was developed with the sole purpose of being an analysis tool for forest economists. The word "Plan" is short for Planning and the digits 33 stands for the number of years it took to finish the first version of the program. The project started somewhere around 1968 on the initiative of the forest economist von Malmborg.

Way back in the 1960s when von Malmborg was working on his thesis (von Malmborg, 1967), he found that there were no practical tools for assessing the economic value of forest stands and forest estates. The available methods of valuing forest resources were not consistent with scientific results and findings. The main objective of the methods in those days was to appraise the market value of the asset and almost any method, often not supported by scientific findings, was justified to achieve this objective. Foresters in particular considered the present value method to be untrustworthy. It presented values that were too low and rotations that were too short compared to accepted practice. A common practice was to tamper with the Faustmann formula, for example by changing the interest rate upwards or downwards until the present value targeted the expected market value. Another common feature was to let the discount rate increase with the increasing age of a stand.

What annoyed von Malmborg the most was the refusal, by officials employed by the Swedish Forest Agency, to use the opportunity cost notion or principle, when valuing incurred costs of environmental intrusions on forest properties. In brief, the opportunity cost principle means that the cost is estimated as the loss of a forgone opportunity. The forgone opportunity is calculated as the difference in present values of the stand before and after intrusion. The officials stuck stubbornly to the old direct valuation approach. This approach meant that only the intruded area was valued.

Due to the awkward valuing customs of that time von Malmborg began to develop a planning and valuation tool, later called JU-Plan (JU is an acronym for Jordbrukets Utredningsinstitut, Agricultural Research Institute. JU was owned by the farmer's association in Sweden), for forest stands and forest estates. This tool was based on scientific foundations, i.e. knowledge and methods approved by science (von Malmborg *et al.*, 1970). To solve management problems, JU-Plan used linear programming together with present value calculations. His planning and valuation tool was further improved and in 1986 the software tool PLAN-20 (Ekvall, 1986), and in 1990 PLAN-30, were launched (Ekvall, 1990). In both PLAN-20 and PLAN-30 agricultural perspectives were minimised, compared to von Malmborg's works, and pure forest issues were emphasised. The difference between PLAN-20 and PLAN-30 was, apart from different computer platforms, that PLAN-30 utilised more modern growth functions - the same growth functions adapted in the "Stand method" from The National Land Survey of Sweden (1988).

In 2001 the first version of the program Plan33 was launched (Ekvall, 2001). Since that time several amendments of the computer program have been published on the internet and it is nowadays downloadable as freeware.

Experience gained from using PLAN-30 in teaching and research work, resulted in 2001 in a licentiate thesis, "Plan33 - a tool for economic analysis of timber production in the forest company" (Ekvall, 2001). With the capabilities of Plan33, the user of the program is able to create optimal management plans for individual stands and entire estates. This ambition implies maximising the present value. The main problem is deciding how the forest-owner should achieve the stated objectives and simultaneously take constraints into account.

Plan33 helps, generally speaking, the forest-owner to choose from a large number of production opportunities. Achieved objectives and the possibility of catching a glimpse of future consequences for the forest lead the forest owner in their decision-making. Like the JU-Plan, developed by von Malmborg, Plan33 uses LP to solve certain types of management issues at the estate level and at the stand level optimisation is carried out with the help of the non-linear Pattern Search (Hooke & Jeeves, 1961), which is a subclass of the wider concept of what is called Direct Search Methods (Kolda *et al.*, 2003). How a linear and a non-linear optimisation technique are merged together into one working unit will be briefly treated in section '3.4.4 Planning and valuing a forest estate with Plan33'.

3.4.2 Estimating net revenues of management measures in Plan33

The net revenue for a specific measure is calculated in Plan33 in discrete time. That means that all revenues or expenses related to a specific measure, whenever they occur or are posted during a year, are compiled and summarised to a total revenue and total cost (for that measure) on the last day of the accounting year.

$$N(m,t,j) = TR(m,t,j) - TC(m,t,j) \tag{4}$$

$N(m,t,j)$	Net revenue of measure m at time t in stand j, SEK/ha.
$TR(m,t,j)$	Total revenue of measure m at time t in stand j, SEK/ha.
$TC(m,t,j)$	Total cost of measure m at time t in stand j, SEK/ha.

Each factor in the net revenue definition (4) consists of two variables; variable and fixed revenues, with respectively variable and fixed costs.

Typically there is no revenue for a regeneration measure, so the net revenue will be negative. The revenue in harvesting is roughly equal to market price per volume unit multiplied by volume wood extracted from the forest. The final payment to the forest owner depends upon delivered assortments and their quality class distribution. Stand factors such as species, mean diameter and mean height also play an important role in assessing the price. In Plan33 revenues can be estimated for sawtimber, pulpwood and wood for fuel purposes for up to 25 different trees species.

Assessing revenues for forest owners

Normally timber and fuel wood are the only products from the stand that will generate income for the forest owner and can accordingly be accounted for as revenues.

Sawlog price

Market prices for different assortments are usually derived from price lists published by forest industries or forest owners associations. The applied sawlog price lists for Scots pine and Norway spruce used in this thesis and Papers I – IV can be studied in Paper III. To fit into the calculation scheme of Plan33 a typical price list for sawlogs has to be transformed from discrete values for specific diameter classes to a continuous function, based on weighted moving average, valid for any mean diameter. The weighting of discrete sawlog prices, to form a continuous function, is based on estimated diameter distributions for typical Swedish forest stands (Nilsson, 1976). Figure 4 shows five price functions for Scots pine corresponding to five quality classes (Q1 to Q5) and Figure 5 shows four price functions for Norway spruce with four quality classes (Q1 to Q4). Specification of quality classes for coniferous sawtimber can be found in the Swedish Statistical Yearbook of Forestry (Swedish Forest Agency, 2012).

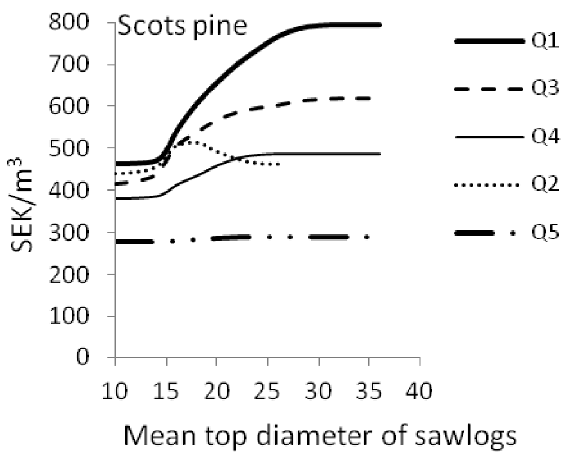

Figure 4. Price functions for sawlogs of Scots pine.

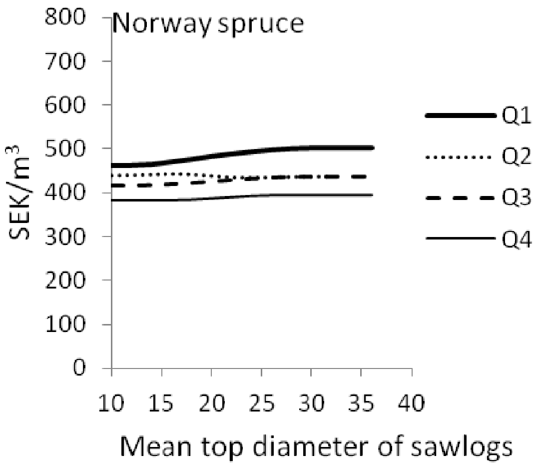

Figure 5. Price functions for sawlogs of Norway spruce.

As can be seen from Figure 4 the premium for larger diameters, that is increasing price with increasing mean diameter, shows a distinct increase with increasing mean top diameter for most quality classes of Scots pine , but Figure 5, depicting Norway spruce price functions, the premium for larger diameters is fairly small. Timber prices in the price lists are often expressed in SEK per m^3 (bark excluded) and the mean diameter of the stand includes bark. The mean diameter value therefore has to be transformed by a function to the mean top diameter of sawlogs. The function's parameter values were developed by the National Land Survey of Sweden (1988).

In Papers I – IV attached to the thesis, it is assumed that only logs of Scots pine and Norway spruce are sold as sawn timber.

Pulpwood price

Sawlog and pulpwood prices are often published simultaneously by pulp- and sawmill industries. The pulp wood price is expressed in SEK per m^3 (bark excluded) and is differentiated for three or four species, usually Scots pine, Norway spruce, birch and other broad leaf species.

Fuel wood price

Wood for fuel and energy purposes is a very important by-product from logging residues (tops and branches) and is sold as bio-fuels. Treetops, branches and twigs are parts of the tree that used to be left on the ground many years ago but nowadays constitute the assortment GROT (GROT is a Swedish acronym for branches and tops). The income from the GROT assortment is an essential contribution to the net revenue of a harvest operation. Extracting GROT with a diameter ≥ 10 cm will diminish the amount of available CWD in the stand since only coarse wood is counted as CWD (Paper I). The GROT price is usually expressed in SEK per ton or SEK per m^3. The assortment is not differentiated on tree species. The volume of GROT in normal Norway spruce stands is estimated as c.a. 25% of the standing volume. The corresponding figure for Scots pine and broad leave species is around 16% (Swedish Forest Agency, 2008).

Timber price dynamics

If changes in the market price of timber are expected in a specific way in the future, then those assumed changes can be anticipated in Plan33. For example, any type of trade cycle can be simulated and applied in assessing present values in Plan33. Generally, market changes and inflation cause changes in timber prices. Assessing the Soil Expectation Value with the Faustmann formula requires static prices and no change in technology related to forestry management. Timber price dynamics will therefore only occur in Plan33 in the first planning period. Planning periods in Plan33 are treated in section '3.4.4 Planning and valuing a forest estate with Plan33'.

Assessing costs for forest owners

The cost of any measure in forestry consists of three parts, variable cost, strictly fixed cost and semi-fixed cost. The variable cost is for instance directly proportional to harvested volumes or the treated area of a regeneration measure while the strictly fixed costs, such as set-up costs, are independent of volumes of timber, area of the stand or other stand site qualities. The semi-fixed costs are to some extent proportional to volume cut and treated area, and reflect the fact that it is profitable to engage more machinery resources and skilled forest workers in larger stands than in smaller stands. Transportation of sawtimber and pulpwood from roadside to wood industries will induce additional costs to the forest owner.

Finally there is a class of costs that cannot be assigned to a specific stand or silvicultural measure - unassigned fixed costs. They usually refer to planning, marketing, selling efforts, road maintenance, office rental and administration. Data for assessment of unassigned fixed costs is obtained from National Land Survey of Sweden (2002).

Technological and cost dynamics

If changes in technological systems used in silvicultural measures are expected, then those changes can be inserted into Plan33. This particularly applies to changes in harvesting efficiency and soil scarification efficiency. Improved technical solutions and decreasing fuel consumption for heavy logging machines will often lead to improvements in harvesting efficiency. A machine will cut more, or scarify more, per time unit. It is not only technical solutions that are improved. It can be expected that logging crews improve their operating skills with machinery through a trial and error approach and in that way improves harvesting efficiency. In Plan33, a variable called 'technological changes over time' captures all types of changes in harvesting efficiency.

On the other hand, technological improvements also have costs and machines can therefore be expected to be more expensive to use year by year. Not only do machinery costs change, but manual labour costs also change. Generally, changes in costs are caused by market changes and inflation. In Plan33 both those changes will be captured in just one variable, called 'change of cost over time'.

Costs of harvesting operations

Costs of harvesting operations can be divided into three parts; variable costs referred to as direct costs, variable costs referred to as indirect costs and strictly fixed costs. Variable direct costs arise in connection to the felling and transportation of timber to roadside, indirect variable costs arise in connection with other essential work such as assessing and marking trees to be cut, providing moveable shelter for rest and breaks, providing tools and machines, building temporary strip roads, main haul roads and landings, road fees, scaling and the transportation of forest workers. Fixed costs are usually a lump sum reflecting the cost of moving the entire harvesting unit between cutting areas.

The variable direct cost in the net revenue of a harvesting operation is dependent on the estimated harvesting efficiency, m^3/hour, and the market price, SEK/hour, for machines and skilled forest workers. Dividing the market price by the harvesting efficiency and multiplying by the extracted volume from the stand will give the cost per hectare value. Note that harvesting efficiency must be calculated for every type of machinery used in a specific cutting, e.g. a harvester for felling and a forwarder for transport.

A harvesting efficiency model was developed from data from the Forestry Research Institute of Sweden and is used in Plan33 (Brunberg, 1995; Brunberg,1997; Brunberg, 2004). Details in the model designed for the estimation of costs of harvesting operations can be seen in Appendix 1.

Costs of timber and fuel-wood transportation to industries

Transportation of sawtimber and pulpwood by lorry from the roadside to wood industries will induce additional costs to the forest owner. The cost of hauling is often paid as a discount to the final payment from the pulp- or sawmill. Like costs of harvesting operations, hauling costs can be altered in accordance with assumed future technological and market price changes. The previously mentioned cost for hauling, SEK 0.30 per m^3 and km for sawtimber and SEK 0.25 per m^3 and km for pulpwood, does not reflect the total cost of road transportation. Apart from the payment from forest owners, the industry will pay its share and under certain conditions the government will subsidise the rest. Transportation costs for bio-fuels are usually included in the offered price.

Costs of regeneration measures

For most regeneration measures indirect variable costs and fixed costs are very low and because of that they are assumed to be zero. The variable direct costs of regeneration measures are divided into two types; costs for man-machinery systems and costs for seeds or plants. The cost factor for a man-machinery system is given by multiplying the market price for the measure in SEK/hour, with the estimated time consumption, hours/ha, from a regression model. The model was developed specifically for Plan33 based on data from the Forestry Research Institute of Sweden (Fryk, 1985; Bergstrand, 1986; Andersson et.al., 1990). Costs for seeds or plants are estimated by multiplying the market price per unit (of plants or seeds) with the unit quantity per hectare prescribed by the Swedish Forest Agency. Details in the time consumption model designed for estimations of the costs of regeneration measures can be found in Appendix 2.

3.4.3 Estimating growth in forest stands

The Plan33 program estimates changes in volume, diameter, height and timber quality throughout the entire growth period.

Volume growth

An accurate growth function is an imperative for the forest manager. A well-structured growth function or model provides the forest manager, not only with volume increments but also with other aspects of growth such as changes of diameter, height and if possible quality distribution over time.

A great number of volume growth models have been developed since forest production became important to land owners, wood consuming industries and society. These models can be divided into two distinct classes; statistically calibrated models and process-based models. The former adjusts the model's parameters so the model will fit obtained empirical data with the smallest errors possible. In the latter case the model will be built on known biological processes in trees and between trees, e.g. how adjacent trees compete with each other (Hyytiäinen *et al*., 2004). Both types of models have been proven to be useful and the choice depends on the task or problem to be solved. In Sweden, the National Land Survey has chosen a statistically calibrated model for valuing stands and estates while the Swedish University of Agricultural Sciences has chosen a combination of process-based growth models and statistically calibrated models for its Heureka project (Elfving, 2010). In the Heureka project it is vital to make projections of volume growth very precisely.

In Plan33 volume growth in forest stands is projected by using the Chapman-Richards growth function (Richards, 1959). N-E Nilsson first used the function in Sweden in the middle of the 1970s when he made survey growth calculations for the whole country (Nilsson, 1978). The National Land Survey of Sweden later adapted the function in its new forest evaluation method "Stand Method" launched 1988. The function was parameterised for almost all timber producing species in Sweden and is, as mentioned, used in Plan33 (National Land Survey of Sweden, 1988). The function will estimate, at a given stand age, the total stem volume (i.e. volume above the stump, including the bark and the top and excluding all branches, twigs, needles and leaves) of living trees in the stand. The dynamics of natural regenerated trees and natural dying trees are excluded in the growth function which makes it more like a yield function than a pure growth function. The original Chapman-Richards growth function, adapted to forest growth, is written:

$$Q(t) = a \cdot \left(1 - b^{-\frac{t}{T}}\right)^{c} \qquad (5)$$

t	Age of stand.
T	Rotation, equals year of maximum mean annual increment.
$\frac{t}{T}$	Relative age of the stand.
$Q(t)$	Total volume production of a stand at age t.
a, b, c	Constants.

In Plan33 the Chapman-Richards growth function is adjusted to fit actual stand growth as follows:

$$Q(t) = 1.6416 \cdot \left(1 - 6.3582^{-\frac{t}{T}}\right)^{2,8967} \cdot XMAI \cdot T \qquad (6)$$

XMAI   Maximum mean annual increment, m^3/ha and year.

Note that in equation (6) there are no correction functions dependant on the actual volume of the stand or actual performed thinning regime.

The values of constants, XMAI (maximum mean annual increment), and T (rotation) are obtained from an algorithm developed at the National Land Survey of Sweden (1988). XMAI is a function of location in Sweden (County), site index quality (SI) and the proportion of conifers in the stand. T is a function of site index quality (SI) and the tree species most suitable for the site i.e. having the best volume production. For example, if XMAI is set to 6 m^3/ha and year and rotation T to 80 years the following picture will appear.

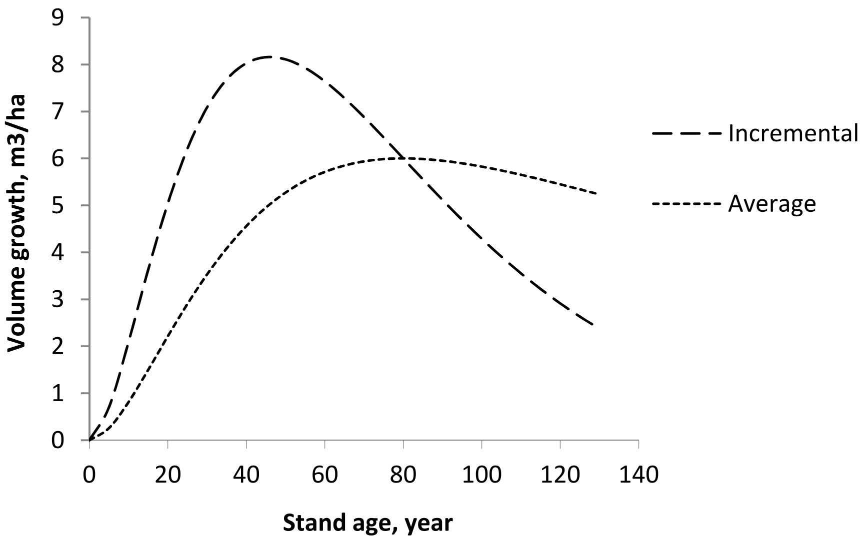

Figure 6. The relationship between incremental and average growth.

Note that the average growth reaches its maximum (XMAI = 6.0) at stand age 80 years (T = 80).

Volume growth in actual stands

Maximising the present value of an actual stand involves applying the stand growth model of course. Actual stand properties affecting the values of XMAI and T in the growth function will have a significant effect on the length of the rotation and outcome of estimated volumes and qualities of sawtimber, pulpwood and fuel wood. The volume of the growing stock in a stand varies, caused by previous cuttings and calamities, such as attacks from insects, windfalls and stem ruptures. To make as correct an estimation of growth as possible, the actual stand tree volume is compared with a base-volume, derived from a “Norm-Volume-Function”. The “Norm-Volume-Function” is based on data from the Swedish National Forest Inventory and was developed at the National Land Survey of Sweden (1988), and it predicts an expected volume for stated stand properties. If an actual stand has a greater volume than the base volume, the growth rate increases. If volume is smaller, growth rate decreases. If a thinning operation is conducted, what is known as a thinning reaction is expected. Growth will first increase slowly a few years after thinning, then more rapidly and finally resume normal growth rate. This thinning reaction gives an S-shaped curvature to the growth function for a few years.

Today there are six different basic growth functions, each connected to a particular species. Specifically it is the variables T (Rotation) and XMAI (maximum mean annual increment) that vary with the dominant species, proportion between tree species and site index. Available main types of species from which to choose are: Scots pine, Norway spruce, birch, Lodgepole pine, beech and oak. For other species, such as aspen, the forest manager has to assign one of the pre-specified basic growth functions to the species and if necessary add a few corrective constants.

The adopted thinning regime, used in Papers I – IV, can serve as a good example. In Plan33 the forester can let the program choose between the minimum and maximum value of thinning restrictions during a rotation. The diameter quotient, defined as the mean diameter of felled trees in a thinning divided by the mean diameter of the remaining growing trees, can vary from 0.7 to 1.3, the mean diameter at breast height from 8 to 40 cm, the per cent cut from 1 to 45%, the cut volume in a thinning from 30 to 100 m^3/ha, the number of years between thinnings from 4 to 30, the number of thinnings from 0 to 5 and the net revenue of a thinning normally from 0 SEK/ha without no upper boundary.

If one assigns a negative number to the lower boundary of the net revenue of a thinning, for instance -1,000 SEK/ha, it might imply a higher net present value, since a first thinning is then allowed to be unprofitable and as a consequent can be conducted sooner, which may lead to higher profits from consecutive thinnings and the final clear-cut.

A valuable thinning feature worth mentioning is the possibility of letting the Plan33 program choose the best combination of harvested species through all thinnings. The choice of species of the first thinning will have an impact on all subsequent thinnings.

In Figure 7, a regime with five thinnings and one with no thinning is shown. The interest rate applied is 3%, the site index is set to G24 and the stand is assumed to be situated in central Sweden.

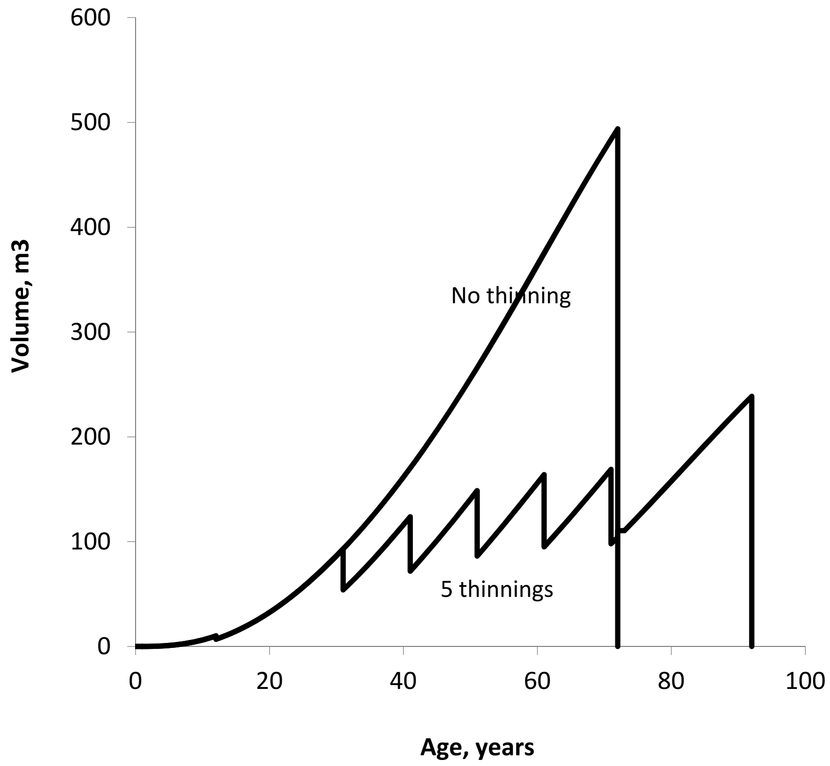

Figure 7. Thinning regime affects volume growth.

As clearly can be seen from Figure 7, a five thinning regime results in a much longer rotation (91 years) compared to a regime with no thinning (71 years). Other differences between the two regimes can be seen in Table 5.

Table 5. Differences between two thinning regimes

Variable	Number of thinnings	
	0	5
Soil Expectation Value, SEK/ha	-210	174
Rotation, years	71	91
Average production, m^3/year	6.8	5.8
Average standing volume (through the entire rotation), m^3/ha	213	100
Volume at clear-cut, m^3/ha	481	236
Mean diameter at clear-cut , cm	23.4	31.4
Net revenue of clear-cut, SEK/m^3	160	270

Note the negative Soil Expectation Value for the alternative with no thinning. The meaning of a negative Soil Expectation Value is that the forest owner will have a lower rate of return on invested capital than 3%, which is the minimum acceptable rate of return in this case. The difference in supply of timber is striking. In the short run the regime with 5 thinnings is superior but in the long run the regime with no thinnings at all will annually produce one cubic meter more, a difference of 17 per cent.

Both regimes in Table 5 can be labelled as extremes for Swedish conditions. No thinnings will probably lead to long and slender stems and increase the risk of stem rupture by ice and heavy wet snow. Five thinnings on the other hand will increase the risk of an increasing amount of stem ruptures caused by hard wind and wind thrown trees. Many thinnings will also increase the risk of fungus infections through bare wood exposure on newly created stumps or damaged root systems. To minimise referred risks normal silviculture practice prescribes one or two thinnings for almost all sites in Sweden.

Diameter growth and height growth

Both the mean diameter and the mean height growth for tree species in the stand are estimated by algorithms from the National Land Survey of Sweden (1988). The diameter estimation is dependent on the dominant species in the stand, an estimation of the maximum mean annual increment, XMAI, and the relative age of the stand, t / T. The height estimation is dependent on the actual, previously determined, mean diameter, dominant species and site index quality, SI.

The functions for mean diameter and mean height cannot be differentiated so the growth rate has to be calculated as the difference in values between two adjacent years. In Figure 8 diameter and height growth for two thinning regimes are illustrated.

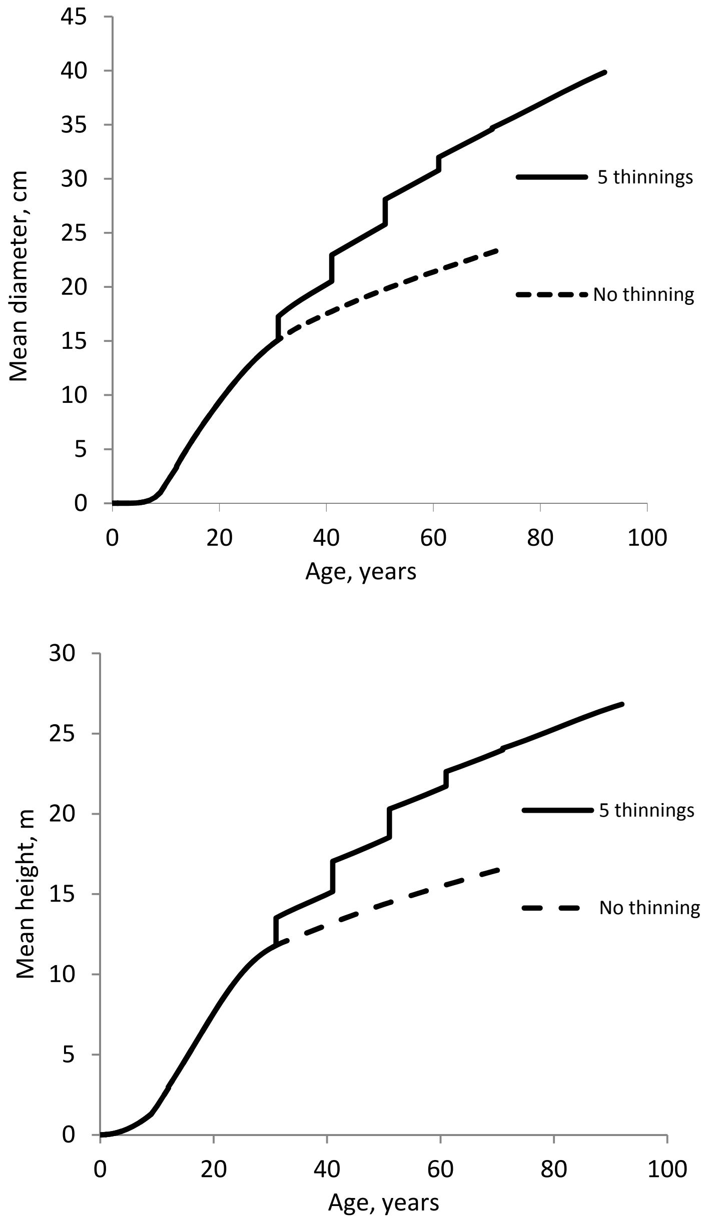

Figure 8. Diameter and height growth of two different thinning regimes.

The ordinates show centimetres for diameter and metres for height. Note the clear difference in diameter and height growth between the two thinning regimes. A thinning can affect the diameter and height increment in two ways. First to be mentioned is the immediate selection effect, which implies choosing thick or thin trees for cutting. When thin (and low) trees are chosen the thinning is said to be from below and the opposite is thinning from above, i.e. choosing thick (and high) trees. The value of the diameter quotient determines the thinning type. If the value is less than one the trees cut are chosen from below and a value greater than one indicates thinning from above. The second effect of a thinning is manifested in the long run. Foresters know from practice that a short time after a thinning the width of annual growth rings and leading shoots begin to increase and accordingly the diameter and height of the trees also increase. Foresters use to claim that this thinning effect is caused by more light and that more nutrients will be available for the remaining trees. After some years this effects reverts to almost normal levels. If the trees left for further growth are of superior growth potential compared to trees cut, the long term effect on diameter growth will last longer.

Figure 8 shows a typical sequence of thinnings from below, which indeed increase the mean diameter and height of trees left for further growth. See also the optimal diameter quotient in Table 6.

Table 6. A five thinning regime

Thinning number	**Age, years**	**Diameter Quotient**	**Cut volume, m^3/ha**	**Net Revenue, SEK/ha**
1	30	0.70	39	-800
2	40	0.74	52	2,400
3	50	0.79	62	7,000
4	60	0.91	69	11,200
5	70	0.99	71	13,900

As an example the optimisation algorithm in Plan33 has yielded the values presented in Table 6 in order to maximise the Soil Expectation Value. The chosen years to conduct thinnings, the chosen diameter quotient and the chosen cutting volume, will all together give the estimated net revenues. Note that the first thinning shows negative net revenue. Although the forest owner will conduct an unprofitable first thinning, the following thinnings (and the final cut) will fully compensate for that temporary loss.

Sawtimber and pulpwood proportions change over time

Normally wood of sawtimber is more valuable for the forest owner than pulpwood and wood for energy purposes. With increasing age and diameter the relative share of sawtimber in the stand increases and accordingly the relative share of pulpwood decreases. To capture this change over time a special function, dependent on mean diameter and mean height, from the National Land Survey of Sweden (1988) is used in Plan33. To illustrate the general shape of this function, Figure 9 shows an example of a five thinning regime for a Norway spruce stand with site quality G24.

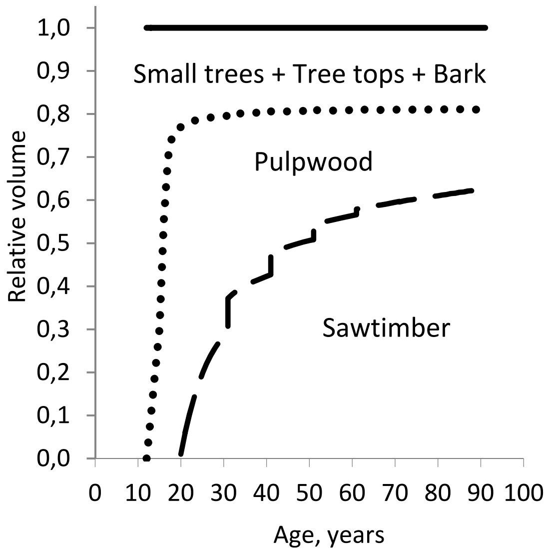

Figure 9. Relative shares of sawtimber and pulpwood change during growth.

Because of the immediate selection effect, in this case caused by thinning from below, a staircase-like shape is emerging from the sawtimber and pulpwood assortments in Figure 9. Note that the total sum of usable timber amounts to a relatively stable value around 0.8 from year twenty to the end of the rotation. If, for instance, the cutting volume is 50 m^3 of a thinning at age 50, the extracted volume of sawtimber amounts to 0.5 • 50 = 25 m^3 and the volume of pulpwood to (0.8 - 0.5) • 50 = 15 m^3. The remaining 10 m^3, consisting of small trees, treetops and bark, can be used as fuel wood or perhaps be left on the ground and to some extent increase the volume of CWD (if the diameter of the residues are larger than 10 cm).

Sawlog quality change over time

Unfortunately there are very few studies that can help the forester to assess sawlog quality change over time. In Plan33 a very simple model is implemented, created by the author, which simulates sawlog quality change. The model consists of a number of nodes connected to each other with straight lines. The forest manager provides the nodes with the expected quality class distribution at different mean diameters over the rotation. Note that there is a strong relationship between the age of a stand and the mean diameter, explained by the value of the site index, and it is assumed that the mean diameter variable will also take the time aspect into account. In Table 7 the quality class distribution for Norway spruce, used in the thesis, is shown.

Table 7. Distribution of quality classes across diameters for Norway spruce

	Mean diameter, cm			
Quality Class	**15**	**20**	**30**	**40**
1	0%	5%	10%	15%
2	30%	25%	20%	15%
3	20%	30%	35%	40%
4	50%	40%	35%	30%

The per cent values in Table 7 are obtained from statistics published by local measurement societies. For instance, in a stand with a mean diameter of 30 cm sawlogs of quality class 1 represent 10% of the total volume of sawlogs. If the stand's mean diameter diverges from the values in the table, Plan33 will interpolate. Note that for a given diameter the total sum of different quality class percentages must equal 100%. The values from Table 7 are accumulated, starting from quality class 1, and plotted in Figure 10.

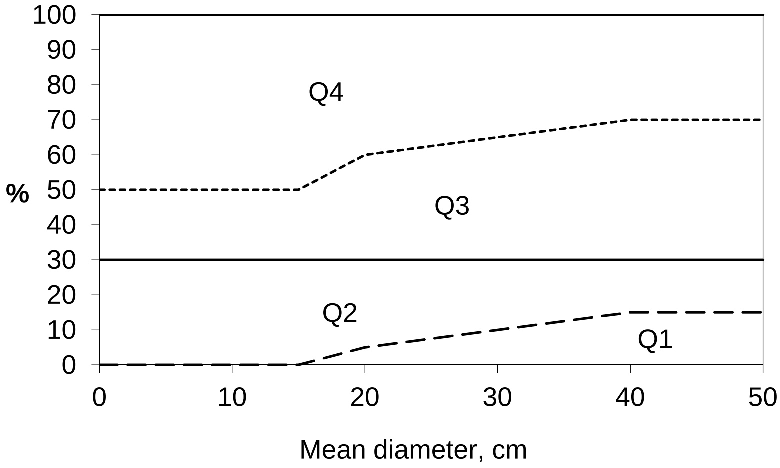

Figure 10. The distribution of sawlog qualities for Norway spruce stands.

As can be seen from Table 7 and Figure 10, nodes are situated at the mean diameters of 15, 20, 30 and 40 cm.

The most valuable sawlogs belong to quality class 1 (Q1), while quality class 4 (Q4) logs are the least valuable. In quality class 2 (Q2) only logs with sound knots on the stem can be included. Note that the forester, in this case the author himself, evidently expects that quality class 1 (Q1) and class 3 (Q3) will increase their shares of the total supply of sawlogs with increasing mean stand diameter (and age).

3.4.4 Planning and valuing a forest estate with Plan33

If only one even-aged stand is considered, the Faustmann formula is sufficient to assess the optimal rotation as well as the maximum present value. In an estate level calculation one sometimes has to deviate from the optimal choice of silvicultural measures and rotation for some stands for the sake of estate wide concerns, e.g. to sub-optimise the silviculture efforts for a number of single stands to achieve higher or more complex objectives.

Planning horizon

In Plan33 the planning horizon is divided into three planning periods; the first period (T1) usually covers the present owner's time of managing the estate, the second period (T2) ranges to year one hundred and finally period three (T3) continues into eternity. In the first planning period, which can last from a few months to more than 50 years, income constraints will have an essential effect on harvesting decisions and consequently rotation will be affected. During planning period two harvesting decisions are made according to the Faustmann rule but rotation can be changed for some stands to correct an undesirable age class distribution. In planning period three harvesting decisions are merely based on the Faustmann rule.

Assets, liabilities and equity

In the first planning period the valuation of the forest estate will follow a balance sheet model, obtained from the outlines of common annual financial statements.

$$\text{Fixed Assets} + \text{Working Capital} = \text{Borrowed Capital} + \text{Equity} \tag{7}$$

In a forest estate the most important fixed asset is the Forest Capital, denoted PVF. Other types of fixed assets, usually called miscellaneous fixed assets, are buildings, harvesting machines and equipment, lorries, tractors and cars. The latter assets will be omitted in the following analysis, because of clarity and of their relative small effect on silviculture decisions in a non-industrial private forest. Working Capital, denoted WC, consists mainly of cash at hand and money deposited on different bank accounts. All types of liabilities, such as loans and deferred tax payments, are borrowed capital. The equity, finally, is the net worth of the estate.

Rearrange expression (7) and set equity as the dependent variable.

$$\text{Equity} = \text{Fixed assets} + \text{Working capital} - \text{Borrowed capital} \tag{8}$$

The model above (8) is commonly known in account reporting but in Plan33 the model will help in valuing the forest.

Replace the term Fixed assets in expression (8) with the term Forest Capital, PVF (Miscellaneous Fixed Assets assumes to be zero), replace Equity with present value of the estate, PVE, and use the proposed acronyms

$$PVE = PVF + WC - BC \tag{9}$$

The PVE now equals the present value of incomes from forestry PVF (and other sources related to forestry, such as hunting fees, on the property), plus working capital minus borrowed capital.

Over time working capital varies from month to month and from year to year. All the incomes and expenditures of the estate are assumed to be paid via the working capital accounts. The most important source for increasing working capital is timber sales.

All types of liabilities can be defined as borrowed capital. Loans have to be repaid according to an instalment schedule and during the repayment period of a loan interests is paid. Timber sales will be the main source of working capital, to finance the repayment of loans.

At the very start of the planning process it is assumed that the values of Working capital and Borrowed capital are known. Forest capital is unknown and its value will be estimated using optimisation methods.

Main objectives

Using Plan33 the forest owner can choose between three main objectives to achieve a management plan and ensuing valuation of the forest.

1. The first objective will maximise the equity (denoted PVE) value according to the going concern principles, i.e. the owner continues with normal management operations as usual and has no intention of transferring the property to a new owner in the foreseeable future. This objective maximises the wealth of the estate owner, which means that the present value of the forest might be sub-optimised.
2. The second objective seeks to maximise the forest capital (denoted PVF) in an estate context. To achieve this objective the economic contributions, from timber production to the rest of the company, will be held at a minimum. No extra harvest operations will be conducted with the pure aim of optimising working capital accounts. As much of the growing stock as possible will be kept in the forest and the choice of harvesting objects will cease when the present value is maximised. An estimated present value of the forest according to objective two therefore often shows a higher present value than objective one will do.
3. The third objective seeks to maximise the sales value, i.e. when the forest owner transfers the property to a new owner. The difference between objectives one and three is that in number three all liabilities are assumed to be paid at the date of selling. Selling the property entails among other things paying capital gains tax and the costs of selling. These costs will reduce the equity left for the owner. Tax planning some years before selling can diminish the effects of capital gains tax, but details of the complicated Swedish taxation system will not be investigated any further here.

An optimisation algorithm

The algorithm contains three main blocks; a control program, an LP-program that allocates measures to different stands and the non-linear Pattern Search program (Hooke & Jeeves, 1961), which maximises present values of stands.

Given the chosen objective the search for a maximum present value comprises several steps in a loop:

1. Calculations concerning planning period 1. First the non-linear optimisation program will maximise present values for different measures conducted in each stand. Linear programming (LP) is then applied to select forest stands for different measures, such as harvesting, regeneration and CWD-increasing purposes, in an optimal way for each year. The consequences of these optimal selections affect the future silviculture practices in planning period two and three and correspondingly the present value for those planning periods will be affected.
2. Calculations concerning planning period 2. The Pattern Search algorithm is applied to determine optimal management measures and estimate present value and rotation for the stands. It is optional to use age class constraints.
3. Calculations concerning planning period 3. The Pattern Search algorithm is again applied to determine management measures and estimate present value and rotation for each stand. There are no constraints present.
4. Sum up the total present value for all three periods.
5. The control program will examine the status of the solution. If no further enhancements of the present value can be expected a global maximum is assumed and the optimisation process is terminated, otherwise the program continues with the next step. The control program uses algorithms according to the Pattern Search to test whether, among other things, the proposed solution is stuck in a local maximum or not.
6. Jump back to step 1.

The optimisation process mentioned in steps 1 - 3 above is briefly outlined:

Maximise

$$PVF = \underbrace{\sum_{t=1}^{T1}\left[\sum_{j=1}^{J}\left\{N(M_j, t, j)\right\}\right]\cdot(1+r)^{-t}}_{\text{Planning period 1}} + \underbrace{\sum_{t=T1+1}^{T2}\left[\sum_{j=1}^{J}\left\{N(M_j, t, j)\right\}\right]\cdot(1+r)^{-t}\cdot(1+r)^{-T1}}_{\text{Planning period 2}} + \underbrace{\Pi_j\left(a_j\right)\cdot(1+r)^{-T2}}_{\text{Planning period 3}} \qquad (10)$$

subject to the following constraints:

$$\sum_{j=1}^{J}\left[Vol_{CWD}\left(M_j, j\right)\right] \geq Vol_{CWDprescribed}$$

Comments: If this constraint is employed, present value decreases and rotation may be prolonged.

$$\left[\sum_{j=1}^{J}\left\{N(M_j, t, j)\right\}\right] \geq NS_t \quad \text{for } t = 1 \ldots T1$$

If these constraints are employed, the values assigned to NS_t affect present value and rotation.

PVF	Present value of forest.
t	Time, t.
T1	Time T1 is the end and the length of planning period 1.
J	Total number of stands included in the valuation.
j	Stand number j.
M_j	Management program for stand j is a series of management activities to be practiced in stand j through all planning periods.
$N(M_j, t, j)$	Net revenue when management program M_j is applied at time t in stand j.
r	Interest rate, r.
T2	Time T2 is the end of planning period 2. The length of planning period 2 is T2 minus T1.
a_j	Age of the j^{th} stand in year T2.

$\Pi_j(a_j)$	Present value of stand j in year T2. This term is defined according to expression (3).
NS_t	The smallest amount of net revenues the forest estate must gain from silvicultural operation (mainly harvesting income) at a specific year t. Income requirement from the forest owner, amortization, unassigned fixed costs and payment of interests on loans will probably increase NS_t. Income of work outside the estate, pensions, leases, rents and income of capital, e.g. from bank-accounts, may decrease NS_t.
$Vol_{CWD}(M_j, j)$	Expected average volume of CWD in the long term in stand j. Choice of CWD-increasing measures is constrained by stand age and silvicultural activities.
$Vol_{CWDprescribed}$	The minimum volume of CWD that should be attained from stands on the estate.

3.5 Estimation of formed CWD

In all four papers a number of measures are undertaken in the forest to increase the volume of different CWD qualities by preserving naturally dying snags or protecting downed trees from being destroyed by the heavy machines used in modern forestry, or creating artificial wood substrates that can eventually be transformed into suitable CWD matter. The formed volume of CWD was predicted by a simulation model, similar to a model presented by Ranius *et al.* (2003). The simulation model used information on forest growth, provided by Plan33, data on tree mortality and a model that describes the decay process of CWD. The simulation process ranged over several rotations, which meant about 400-500 years, but output data from the model was only considered from the last rotation and the obtained CWD-volume equalled the average CWD-level from that last rotation. This procedure was carried out to avoid any effect from CWD-volumes present at the starting point of the simulation.

The CWD simulation model predicts amounts of CWD which are good estimates of the amounts actually observed in managed forests in Sweden (Ranius *et al.*, 2003). Note that dynamic changes of the CWD level through time are not analysed.

In Paper IV, where many different stands were involved, a regression model estimating the average volume of CWD was developed. This model was based on 117 simulated stands and each stand was randomly assigned a specific measure (listed below in Table 8) that increased the volume of CWD. The relationship between simulated average volume of CWD and forest stand properties (biological properties such as site index and non-biological properties such as slope and roughness of the ground) and type of measure was established using a stepwise regression procedure (Draper & Smith, 1981).

Different saproxylic species need different kinds of dead wood. In the papers the quality of a CWD object is defined by the following properties: Tree species, position, diameter, decay class, light regime and growth rate. Details can be studied in Paper II.

Improved biodiversity quality is measured by a conservation indicator. Three types of conservation indicators are applied across Papers I – IV.

1. One conservation indicator, common to all papers, measures the increase of CWD volume.
2. In Papers II and III, an additional conservation indicator is used; Substrate index. Briefly, when conducting a CWD-increasing measure, substrate index is estimated as the increased number of preserved red-listed species multiplied by the substrate volume each species needs for its survival.
3. Many red-listed species need a specific minimum volume of a specific quality of CWD-substrate to survive. This minimum volume is referred to as a threshold level, and the number of red-listed preserved species as the threshold value. In Paper II this conservation indicator was introduced, and the threshold level was defined as the CWD volume a CWD-increasing measure will produce in re1ation to CWD from an unmanaged old-growth forest. For example, a threshold level of 10% means that a CWD-increasing measure has to produce at least 10% CWD as compared to an unmanaged old-growth forest. If a CWD-increasing measure fails to attain the prescribed threshold level of CWD, there is a impending risk of extinction of red-listed species needing just that threshold volume, at least in the stand in which the CWD-increasing measure was conducted.

From Papers II and III, results indicate that the ranking of different CWD-increasing measures using conservation indicators CWD-volume or substrate index or thresholds levels will not differ substantially (Paper II; Paper III). For this reason substrate index and threshold levels will be omitted in further analysis in this thesis and CWD-volume will be used as the sole conservation indicator.

The proposed CWD-increasing measures are defined and prescribed by the forest certification organisation FSC. These measures, assumed CWD qualities and assumed time lag between the time of conducting a CWD-increasing measure and its effect on the amount of produced CWD are listed in Table 8.

Table 8. CWD-increasing measures and their effect on the quality of CWD

Measure	**Gives CWD-quality**	**Assumed time lag**
Retention of snags at final cutting (denoted Snags)	Older sun exposed	None or very short
Retention of newly formed CWD in a year with high natural mortality (denoted Wind thrown or Wind)	Fresh	Short
Artificial creation of high stumps during thinning operations and at final cutting (denoted High)	Fresh sun exposed	Short
Retention of living trees at final cutting (denoted Ret)	Almost all types	Long
Complying with the FSC-standard (denoted FSC)	Fresh and old, sun exposed	Short to long, depending on measure
Manual scarification just after final cutting to avoid destruction of CWD (denoted Scar)	Late decay stages	Short
Setting aside a stand as a nature reserve (denoted Res)	All types	Long to very long
Prolongation of the rotation (denoted Pro)	Large diameter, slow growing, shady	Long

The time lag between a CWD-increasing measure and its effect must be considered because of the scarce supply of CWD in managed forests today. Many red-listed saproxylic species stand on the brink of extinction and it may be imperative to choose measures that increase the volume of CWD rapidly. With all measures some proportion of the increase in CWD takes place at once when conducting a CWD-increasing practice. For three measures (manual scarification, creation of high stumps and retention of naturally dying trees), that proportion is large, while for the other measures (retention of living trees at harvest, set aside a stand as a nature reserve and prolongation of the rotation) the proportion of immediately available CWD is smaller and the increase takes place over a longer period. None of the four papers estimates the dynamic change over time, including time lags, of CWD-volume, mainly due to limitations in the CWD-simulation programs. Only average levels of CWD could be obtained.

To maintain a rich and diverse flora and fauna in saproxylic species a sufficient supply of CWD and a balanced proportion of all types of CWD qualities are needed. As can be seen from Table 8 there is no one measure that can meet all demands for increased CWD alone.

3.5.1 CWD-increasing measures - volumes and accrued costs

Retention of snags at final cutting. Snags are dying or dead trees still standing. In forestry without conservation concerns, snags with an economic value will be harvested and the rest downed either actively or incidentally at final felling. These downed logs are then destroyed during scarification operations by heavy machines. In more environmentally aware forestry it is assumed that 80% of the snags will remain standing after the final cut. The increase of CWD varied from 0.6 m^3/ha in northern Sweden to 1.8 m^3/ha in the southern Sweden. This measure will increase costs for forestry, from 10 SEK/ha in the north to 50 SEK/ha in the south, because harvesting and scarification machines have to slow down or make detours to avoid the snags. This measure is not treated in Paper I.

Retention of newly formed CWD in a year with high natural mortality. If large quantities are generated, for example by wind-throw or snow breakage, the forester often removes damaged trees of two reasons. One is to save commercial values in damaged trees and the other is to diminish the risk of attacks from insects on remaining undamaged trees. The event that caused the calamity is assumed to occur between the last thinning and final cut. Four different scenarios were presented in Papers I and II, where a certain volume is assumed to be wind-thrown (20 m^3/ha or 5 m^3/ha) and a specific share (100% or 1 m^3/ha) of that volume is retained. This measure will decrease volumes of commercial timber and slow down harvesting machines since they have to avoid snags and downed trees. Due to very small harvested volumes, not more than 20 m^3/ha, and consequentially small revenues, the fixed cost will reduce the net revenue substantially and make the harvest of wind-thrown trees unprofitable. This means that in many cases, it is more profitable to let trees remain untouched on the ground (if the risk of attacks from insects does not increase). The increase of CWD-volume varied from 0.2 to 7.7 m^3/ha and the costs from -1,660 to 960 SEK/ha. The average CWD-level in the long run was a bit higher in the north than in the south because of a higher rate of decay in the south. The negative cost of -1,660 SEK/ha (a profit) is incurred by not harvesting 20 m^3/ha wind-thrown trees in the northern part of Sweden. This measure is only treated in Papers I and II.

Artificial creation of high stumps during thinning operations and at final cutting. The FSC standard prescribes the creation of a few high stumps per hectare (FSC, 2000). High stumps usually have a height of 3 – 5 m. In this study, the height was assumed to be 4 m, and the average diameter equal to the cut trees. The CWD volume of a high stump was set to 30% of a whole stem. As there is no data available on the timber quality of trees chosen as high stumps, it was assumed that they were always created from trees of the lowest timber quality class. Creating high stumps reduces harvested volumes and slightly increases harvesting costs and avoiding high stumps decreases harvesting efficiency. In Papers I and II the number of high stumps was set to 3, 10 or 20 per hectare. In Paper III, dealing with several tree species in each stand, the number of high stumps was set to 3 per hectare and in Paper IV, dealing with a whole estate forest, the number of high stumps could vary from 3 to 20 per hectare. The total formed volume of CWD was strongly correlated with the number of high stumps created. Greater CWD volume was formed in the south since trees are larger in the south than in the north. As conifers were slightly larger than deciduous trees, the CWD-volume from Norway spruce and Scots pine was slightly higher than the CWD-volume from birch and aspen. The formed volume of CWD varied from 0.06 m^3/ha in northern Sweden (3 high stumps per hectare of aspen at a cost of 13 SEK/ha) to 4.3 m^3/ha in southern Sweden (20 high stumps of Norway spruce per hectare at a cost of 290 SEK/ha).

Retention of living trees at final cutting. When the FSC standard (FSC, 2000) is applied, living trees covering at least 5% of the stand area are normally retained at final cutting, both as individual trees and in small groups of trees. In Papers I – III, it was assumed that in retained areas the site index and the volume of standing trees equalled 75% of the average value of the stand. In other words, the forest manager chooses an area with the lowest timber producing potential for retention. In Papers I and II the retained area is set to 1, 5 or 9%, in Paper III to 5% and in Paper IV to any value between 1 and 20% of the actual stand area before retention. In Paper IV the relative production level of the retained area is allowed to vary from 0.75 to 1.25. The value 0.75 equals the FSC standard and the value 1.25 implies a 25% higher volume production in the retained area compared to the average volume production of the stand. For instance, if the retained area is set to 5% and the relative production level to 1.25, the relative production level for the remaining 95% of the timber production area will be smaller (98.7%) than the average volume production of the stand. The relative production of 98.7% equals expression (100•1.00 - 5•1.25) / 95. Tree retention at harvest reduces extracted timber volumes because the area is lost for timber production. Moreover, harvesting will be more expensive, expressed as SEK/m^3, since setup costs associated with felling machines will not decrease when the area becomes smaller. On the other hand regeneration costs will be lower since scarification and replanting is not necessary in the retained area. It is also assumed that at the end of each consecutive rotation the forester will ensure that the prescribed percentage of stand area with living trees aimed for retention is maintained. The volume of CWD formed is strongly correlated with percentage of the retained area and the site index. In Papers I – III the minimum volume of added CWD amounted to 0.30 m^3/ha (site index G16, 1% area retained at a cost of 190 SEK/ha) in northern Sweden and the maximum volume of added CWD amounted to 9.3 m^3/ha (site index G32, 9% area retained at a cost of 3,850 SEK/ha) in southern Sweden. In Paper IV the maximum volume of added CWD amounted to 50 m^3/ha (site index G31, 20% of the most productive area retained at a cost of 5,800 SEK/ha) in central Sweden.

Complying with the FSC-standard is only treated in Paper IV and means that three different measures are used in each chosen stand; creating 3 high stumps during thinning and final cutting operations, retention of living trees at final cutting on 5% of stand area and avoid destroying snags at final cutting. It is assumed that the area chosen for retention of living trees yields only 75% of the stand's average yield. The impact of complying with the FSC-standard on revenues and costs of forestry equals the sum of changed net revenues from each of the three measures included. In the forest estate from central Sweden, used in Paper IV, the outcome of this measure, for volume CWD, showed variation from 2.4 m^3/ha (site index G13 and at a cost of 370 SEK/ha) to 13.3 m^3/ha (site index G29 and at a cost of 620 SEK/ha)

Manual scarification just after final cutting to avoid destruction of CWD. In cutting operations and mechanised scarification, heavy machines are used which destroy CWD. According to the FSC standard (FSC, 2000), forestry operations should take care to preserve CWD and, if possible, mechanised scarification should be avoided (although mechanised scarification it is not forbidden). A study in Finland shows that 58% of the younger CWD, and 88% of the older CWD is destroyed if mechanised scarification is carried out, while with no mechanised scarification the loss is 15% (Hautala *et al.*, 2004). Scarification by hand will decrease working efficiency considerably compared with the normally chosen man-machine system. The volume of CWD formed is strongly correlated with site index. In Papers I – III the minimum volume of added CWD amounted to 1.90 m^3/ha (site index G16, at a cost of 510 SEK/ha) in northern Sweden and the maximum volume of added CWD amounted to 3.7 m^3/ha (site index G32, at a cost of 1,200 SEK/ha) in southern Sweden. Much of the total cost per hectare for conducting manual scarification is mainly due to the difference in costs of engaging heavy machines or a manual labour force. According to Table 3 the difference is 1,300 (2,700 – 1,400) SEK/ha for a spruce stand with site index G24 in central Sweden.

Setting aside a stand as nature reserve is not an ordinary operational measure but rather a decision made by the forest manager. This measure is similar to retention of living trees at final cutting, the difference being that setting aside a nature reserve is done only once. It should be emphasised that setting aside stands as nature reserves, involves much more than just the creation of dead wood, since many species other than saproxylic dwellers will be favoured by this action. The cost of this measure equals the present value of timber production from the stand at the time of decision. Site index has an evident impact on formed CWD-volume. The volume of CWD formed varied from 60 m^3/ha (site index G16 at a cost of 9,900 SEK/ha) in the north to more than 90 m^3/ha (site index G32 at a cost of 70,000 SEK/ha) in the south.

Prolongation of the rotation means an increasing amount of CWD because the period when the living trees are large enough to potentially generate CWD becomes longer and destruction of CWD due to cutting occurs at longer intervals. Prolongation of the rotation implies that the forest owner must wait longer for the revenues of the future clear-cut and that the average volume production of commercial timber will probably decrease. In Papers I and II the prolongation period was set to 10, 25 or 50% of the optimal rotation, in Paper III 25% was the only option and finally in Paper IV stands were assigned prolongation times between 5 to 50 years. The increase of CWD varied from 0.8 m^3/ha in northern Sweden to 13 m^3/ha in southern Sweden. This measure increases costs for forestry, from the lowest value, 620 SEK/ha (G16, 10% prolongation) in the north to the highest value, 26,000 SEK/ha (G32, 50% prolongation) in the south, mainly due to costs accrued whilst waiting for the final cut. In Paper IV, the added volume of CWD varied on the merged estate from 0.05 to 21 m^3/ha at a cost of 30 SEK/ha respectively 23,500 SEK/ha.

3.6 Simultaneous production of timber and CWD

In Papers I – IV simultaneous production of timber and CWD is studied. This approach is an example of multiple use of forest land and this type of management has been a topic among foresters, economists and policy-makers since the 1960s (Klemperer, 1996). First the close connection over time between measures promoting valuable timber production and production of

CWD will be analysed. After that the cost-effectiveness quotient, used in Papers I – III, will be presented and finally the least-cost allocation procedure, used in Paper IV, will be briefly reviewed.

3.6.1 Production of timber and CWD is connected over time

Measures to increase the amount of CWD are differently allocated during a rotation. In Figure 11 below, normal silvicultural measures and measures to increase the amount of CWD on an even-aged stand are distributed over a time-span equal to a rotation.

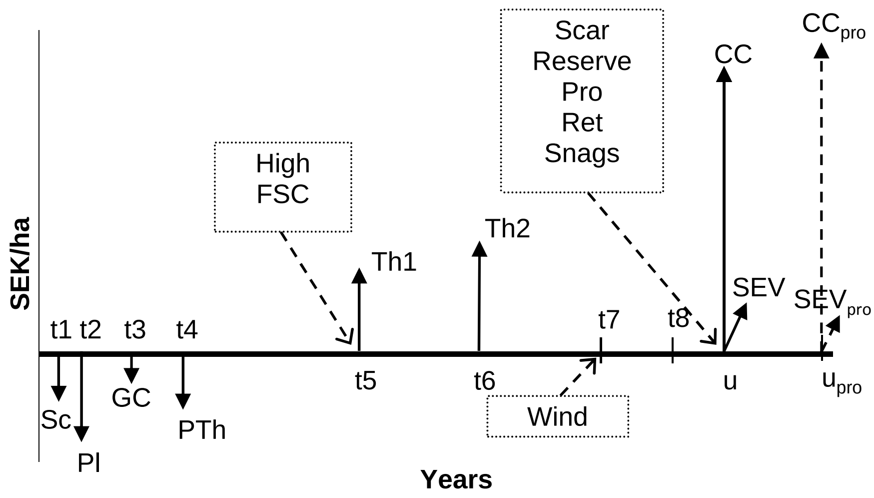

Figure 11. Measures that increase CWD during rotation.

Note that it is assumed that for a specific stand only one of the eight defined measures to increase CWD can be chosen.

The year to conduct a regeneration measure is obtained from the forest owners' association, Mellanskog. In year t1 soil scarification, denoted Sc, is conducted. At t2 planting, denoted Pl, occurs. Some years later at point t3 growth-control denoted GC, is undertaken, and finally pre- commercial thinning, denoted PTh, will follow in year t4.

Regeneration measures produce negative net revenues and are therefore represented by downward pointing arrows. The proper year to conduct harvesting measures in single stands is determined by maximising the Faustmann present value. Somewhere just before the middle of the Faustmann rotation u, year t5, a first thinning operation, denoted Th1, is conducted. Some years later the optimisation of the present value may show that additional thinning operations are profitable to conduct. In Papers I – IV, timber production was carried out with at least one thinning and the maximum number of thinnings was five with a minimum interval of 4 years. In Figure 11, a second and last thinning, denoted Th2, is performed in year t6 and finally a clear-cut, denoted CC, ends the rotation year u. The cutting measures show positive net revenues and are accordingly represented by upward pointing arrows. At year u a perpetual number of rotations begin and the present value of this infinite series is SEV (the Soil Expectation Value).

In Figure 11 there are three boxes, pointing at years t5, t7 and u on the x-axis. They contain the aliases of different measures intending to increase the amount of CWD: see definitions in Table 8. At these points in time selected measures are assumed to start the processes that form an increasing amount of CWD. For Papers I – III, those points in time represent the base-years to which all future net revenues are discounted. In other words the base year for the present value, as well as being the starting year for a CWD forming process also coincides with the age of analysed stands. At age t7 a large number of trees are simulated as wind thrown, creating a considerable amount of CWD. Age t7 is positioned between the last thinning and the final cutting, t7 = (t6+u)/2. Age t8, which is positioned at ninety per cent of the rotation, indicates the lowest age at which clear-cut is allowed to be conducted, according to the Swedish Forest Act. In Paper IV, the notion of a valid stand is introduced. This means that among all stands in an estate forest, only those which are as old as, or older than, age t5 (age of first thinning) are considered for CWD-increasing measures high stumps (High) and complying with the FSC-standard. Stand age must equal or be greater than age t8 for all other CWD-increasing measures to be carried out. Finally, the denotations u_{pro}, SEV_{pro} and CC_{pro} refer to the CWD-increasing measure prolongation of rotation.

3.6.2 Cost-effectiveness

The cost-effectiveness of a CWD-increasing measure is estimated as the quotient between the opportunity cost and the increased CWD-volume. In Papers I – III this quotient is used as a ranking device – the higher the value the lower the cost-efficiency. Normally, CWD-increasing measures with low cost-efficiency values are preferred to those with higher values.

$$\text{CostEfficiency} = \frac{\Delta \text{Cost}}{\Delta \text{CWD}} \equiv \frac{\text{PV}_0 - \text{PV}_x}{\text{CWD}_x - \text{CWD}_0} \tag{11}$$

ΔCost Opportunity cost defined as the difference of present values $(PV_0 - PV_x)$ between two management regimes; one for which no active management action to increase CWD is taken and one for which CWD-increasing measure x is conducted.

ΔCWD Added CWD is defined as the difference of CWD-levels $(CWD_x - CWD_0)$ between two management regimes; one for which CWD-increasing measure x is conducted and one for which no active management action to increase CWD is taken.

In a forest stand, expression (3) was used to estimate both PV_0 and PV_x.The values of CWD_x and CWD_0 were estimated in Papers I – III with a previously mentioned simulation model (Ranius *et al*., 2003), and in Paper IV a regression function, based on Ranius model, was instead used for this purpose.

There is an essential difference in calculation of the opportunity costs in Papers I – III and Paper IV. In all papers the reference case, the present value of normal timber production, is calculated in the same manner. This calculation will yield the length of rotation, optimal values for all silvicultural measures and also their placement in the time-span of the rotation. When it comes to calculating the costs of measures to increase the amount of CWD in Papers I – III, the length of the optimal rotation and thinning regime for normal timber production will be reused, i.e. the same rotation and thinning regime will be used for both the reference case and the case when the amount of CWD is increased. The reason for this was to omit expected prolongation of rotation due to increased costs of conducting CWD-increasing measures. There is one exception to this practice and it applies to the prolongation of rotation measure.

In Paper IV, dealing with multiple stands in an estate context, the applied least cost optimisation program will, without the rotation constraint applied in Papers I – III, allocate measures in an optimal way to produce least-cost allocations. This may lead to prolongation of the rotations and to different thinning regimes.

3.6.3 Least-cost allocation of CWD-increasing measures

In Paper IV the optimisation algorithm, intended to allocate CWD-increasing measures in proper forest stands to the least-cost, was presented formally. Below, the same optimisation is briefly outlined, but now adapted to computer programming within Plan33. The main objective of the optimisation program was to attain a predefined volume of CWD on the forest estate to the lowest cost. The cost was measured as the decrease of the present value of the forest on the estate. To achieve an optimal solution, two different sub-programs will assign values to cells in an LP matrix containing many equations and constraints. The first sub-program uses Plan33 and provides the objective function and subsequent and subordinate equations with data for the present values of timber production without and with CWD-increasing concerns for each valid stand. The second sub-program provides other subsequent and subordinate equations with data concerning volumes of formed CWD for each valid stand, using the regression-function in Paper IV. When the matrix was filled with appropriate values, the optimisation algorithm could start the LP program aiming at maximising the present value of the forest according to expression (10), previously presented in section '3.4.4 Planning and valuing a forest estate with Plan33'. In this case, the LP program did not employ the constraints for the smallest amount of total net revenues the forest estate must gain from silvicultural operation at a specific year t, NS_t.

The results of using the optimisation algorithm on the estate are shown in Paper IV, Figures 4 to 6. When the prescribed total volume of CWD was increased step by step, more CWD was created and more forest land was engaged. Finally the volume of CWD was increased by 15,900 m^3 and the present value of the estate was decreased by SEK 2.3 millions.

4 Comments and discussion on presented results

This section will present some additional aspects of the research results, which are not included in Papers I – IV. Specifically the underlying causes as to why results regarding cost-effectiveness show similarities and differences in Papers I – IV will be discussed.

4.1 Factors affecting CWD-volume and accrued costs of creating CWD

A number of factors affect the formed volume of CWD and the costs of creating more CWD. Rotation, stumpage value, timber price level, change of interest, chosen measure, site index and topographic variables are examples of factors that impact the CWD-level and they will accordingly be discussed in the next sub-sections.

4.1.1 Rotation affects volume of CWD

In advanced text-books, covering different aspects of the Faustmann Soil Expectation Value, such as Economics of Forest Resources (Amacher *et al.,* 2009), endogenous and exogenous variables affecting the length of the rotation are analysed in detail. For this thesis, currently indisputable established relationships between on the one hand, variables such as net revenue and interest rate, and on the other the present value of timber production and the length of optimal rotation, are used in the analysis of produced results. For example, an increase in the net revenue of any measure conducted in a forest stand will increase the present value and shorten the rotation. Opposite, a decrease of any net revenue will decrease the present value and prolong the rotation. An increase in the interest rate will decrease the present value and shorten the rotation, while a decrease in the interest rate will have the opposite effect. As snags are the basis for all CWD, a shortened rotation implies somewhat smaller snags, which entails less volume of CWD. Normally, conducting a CWD-increasing measure within normal forestry practice will have three increasing effects on the level of CWD; (1) the (often) immediate increase of the CWD, due to conducting the measure itself; (2) prolonged rotation (due to decreased net present value) makes snags and retained trees coarser; and (3) more CWD is preserved since the average time between employing heavy CWD-destroying harvesting and scarification machines is prolonged. Normally the effect of decreased net present value on the prolongation of rotation is very small, often one or two years, seldom more than five years, and this effect was therefore omitted in calculations connected to Papers I – III. In Paper IV the prolongation effect was greater, sometimes more than six years, mainly due to the fact that the costs of creating CWD could vary over a wider range. In Paper IV it is possible to let the computer program choose between intensity levels for specific CWD-increasing measures such as 3 – 20 high stumps, 1 – 20 per cent stand area for retention of living trees and prolongation of rotation in the range of 5 – 50 years.

4.1.2 Stumpage value affects costs of CWD-formation

Stumpage values, estimated using Plan33, for average stands of site index 24 m, in the county of Gävleborg, are shown in Figure 12. The estimates are based on the default timber price lists of 2002 from Mellanskog and cost data from Table 3 and Table 4. Stumpage value is defined as the net revenue of a hypothetical clear-cut and the stumpage value can be considered an essential indicator of the commercial price of wood and consequently an essential indicator of the opportunity cost of dead wood retained in the forest.

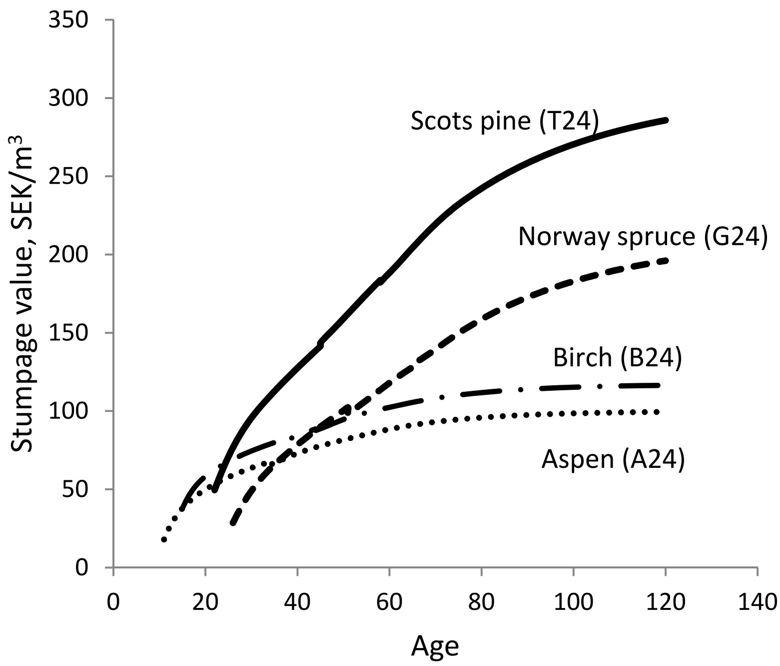

Figure 12. Change of stumpage values due to increasing age of stands.

Normally the stumpage value is expressed in SEK/ha but to better understand the results of the estimations of volume and costs for creating CWD, a stumpage value expressed as SEK/m^3 is shown. As Figure 12 indicates, Scots pine is the far and away most valuable tree-species, while the value of older aspen is around 40% that of Scots pine. From the curves in Figure 12, one concludes that it will probably be much cheaper to retain older aspen trees than older Scots pine trees for CWD-increasing purposes. Note the slight changes in stumpage value (small notches), due to thinning operations, in some of the curves.

The stumpage value at the end of the rotation is especially important, since many decisions concerning CWD-increasing measures are taken in connection with the final felling. For example measures creating high stumps, retention of living trees and prolongation of rotation strongly affect tree values produced by normal forestry at the end of each rotation. In Figure 13 below stumpage values for different site indices and regions in Sweden are shown. Stumpage values, for the average site index for northern, central and southern Sweden are shown as squares.

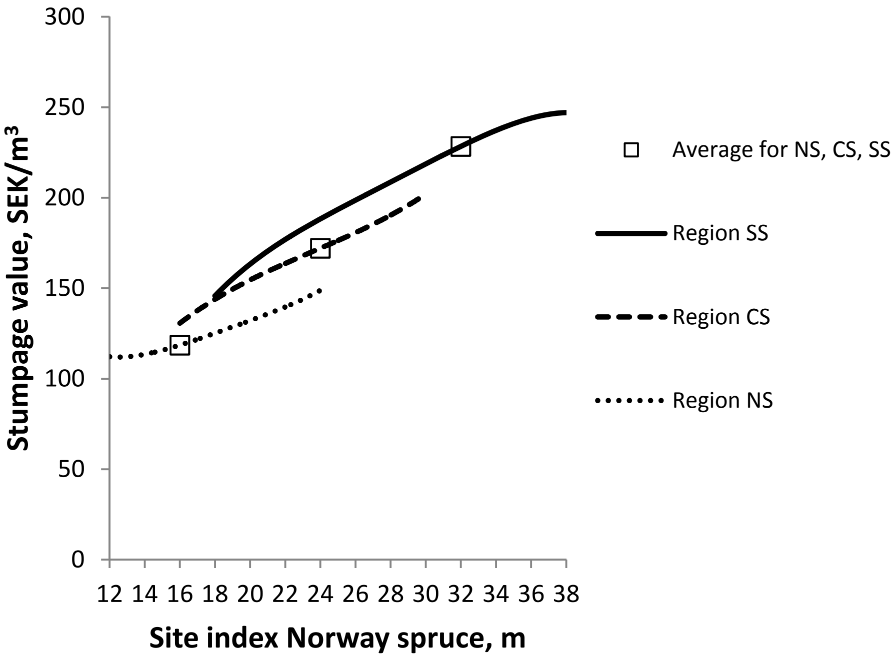

Figure 13. Stumpage values at the age of the optimal rotation for Norway spruce.

Wood planned for CWD from stands of high production or situated in southern Sweden is more costly than wood from low productive stands or from the northern part of Sweden. The curves presented show different shapes across site indices, due to the optimal choice of thinning regimes and rotation, made by Plan33.

4.1.3 Other factors affecting CWD-volume and costs of CWD

Measures with low efficiency value are preferred to those with higher value. How the efficiency value is affected by level of timber prices, level of interest, CWD-increasing measures chosen and stand characteristics, such as site index and topographic variables, is shown in the next paragraphs.

Timber prices increase: In Paper III, timber prices from 1988 were applied, which meant that prices of sawtimber were increased by approximately 40 per cent and pulpwood by approximately 70 per cent. A higher timber price, compared to the price level of 2002, implies that all CWD-increasing measures using commercial valuable wood, as creating high stumps, retention of living trees and prolongation of rotation increased the ΔCost value (the present value of the CWD-increasing measure (PV_X) was decreased), while CWD-increasing measures using dead wood, such as retention of snags and manual scarification changed $\Delta Cost$ very little. However, the relative ranking, between different measures at high timber prices, is the same as the relative ranking at lower price levels.

***Change of interest rate**:* 2, 3 and 4% interest rates were applied in Paper I. Increasing the interest rate meant shorter rotations, less CWD and a lower opportunity cost (mainly due to the discounting effect) for choosing a CWD-increasing measure. A decrease meant the opposite; prolonged rotations, more CWD and higher opportunity cost for a CWD-increasing measure. As both the numerator and denominator in the cost-efficiency formula varied in the same direction (when changing interest rate), it meant that the change of cost-effectiveness was very small.

Chosen measure: The forest manager's choice of CWD-increasing measures has a powerful impact on cost-effectiveness. Papers I – III showed, assuming average site index for the chosen regions, the same pattern regarding ranking of measures to retain snags (Snags), create high stumps (High), manual scarification (Scar), retention of living trees (Ret), and prolongation of rotation (Pro). These measures are seen in Figure 14.

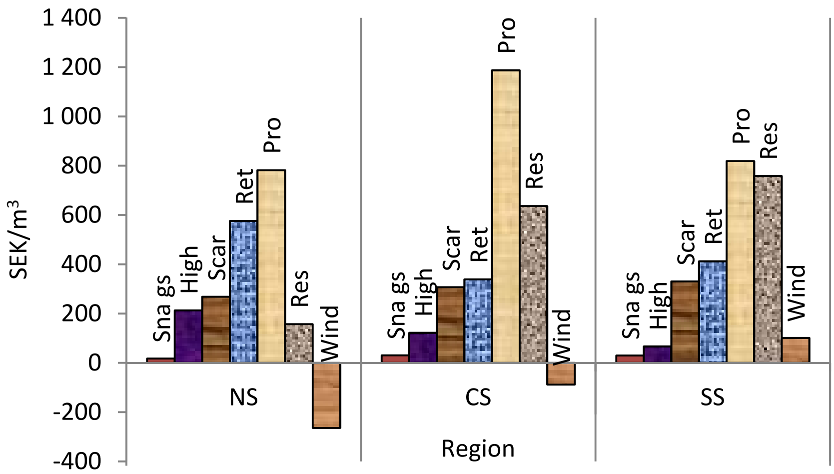

Figure 14. Cost-effectiveness of CWD-increasing measures in Papers I – III.

The measure setting aside a stand as a reserve (Res), shows an increasing cost per cubic metre with increasing site index. In northern Sweden setting aside a stand as a reserve is a very economical choice, due to small trees and low volume per hectare, but the further south (with higher site indices), the more costly creating a reserve will be. A wind-throw (Wind) event in the northern and central parts of Sweden seems to be a profitable source of CWD, while wind-throw trees in the southern areas implies costs for the forest owner. The difference across regions is mainly due to assumed timber values of wind-thrown trees.

In Paper IV another set of CWD-increasing measures was used. The FSC measure was introduced and the possibility of using a wide range of intensity levels for the CWD-increasing measures of high stumps (High), retention of living trees (Ret) and prolongation of rotation (Pro) opened up a huge variety of combinations. In Figure 15 the variation of cost-efficiency values for different CWD-increasing measures is shown.

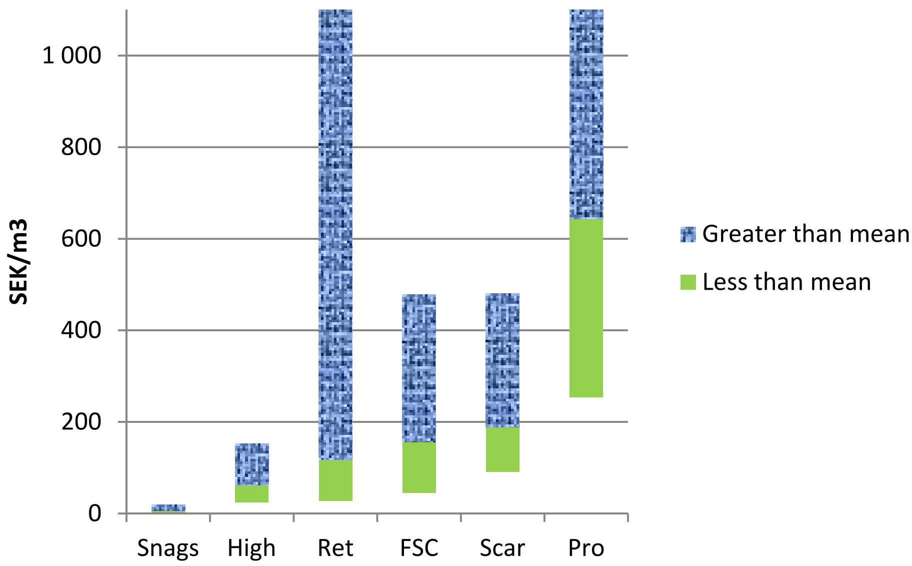

Figure 15. Variation of cost-efficiency values for different CWD-increasing measures.

The CWD-increasing measures are ranked from left to right in average cost-efficiency order. As shown in Papers I – IV, retention of snags (Snags) is the most cost-effective choice and prolongation of rotation (Pro) the least cost-effective. Creating high stumps (High) is the second best choice, as also established through all papers, but one has to comment further on third place for retention of living trees (Ret). In Papers I – III (see Figure 14) manual scarification (Scar) was more cost-effective than retention of living trees but in

Paper IV the opposite holds - manual scarification was less cost-effective than retention of living trees. There is a reason for this; when estimating the cost-efficiency quotient the retained area could be extended by up to 20% of the total stand area (maximum 10% in Papers I – III) and the relative productivity of the chosen area was assumed to be up to 25% higher (always 25% lower in Papers I – III) than the average production of the stand. As can also be seen in Figure 15 the cost-efficiency value for the retention of living trees shows a large variation, due to variation in intensity levels.

Site index: Paper IV shows that among all stand characteristics, site index has the strongest correlation with formed volume of CWD and costs incurred in connection to measures aiming to increase the CWD volume. This means that stands with increasing site index will produce more CWD and will be more costly to treat. As the covariance between ΔCost and ΔCWD is very high in this case, the change in cost-efficiency will be very small. However, results reveal (weakly) that CWD-increasing measures in Norway spruce stands with site-indices in the middle-range (G16-G20) are less cost-effective than less productive or more highly productive stands (Figure 3 in Paper IV). The relationship between site-index and CWD also holds for Papers I, II and III.

Topographic variables: Paper IV showed that topographic variables, such as slope and roughness of the ground and distance to the nearest forest road, had a weaker correlation with formed volume of CWD and incurred costs, than did the site index variable. The explanation of this connection is that worsened terrain specification will decrease harvesting and silvicultural efficiency and thereby decrease net revenues, which implies prolonged rotation and more CWD. But as the percentage increase of CWD-volume is higher than the percentage increase in costs, the cost-efficiency factor will decrease and make it more profitable to conduct CWD-increasing measures in stands with bad soil conditions, steep slopes and situated far from forest roads.

4.2 Cost-efficient production of CWD in a forest estate

In Paper IV, CWD-increasing measures were allocated to those stands that together produce a prescribed level of added CWD in the most cost-efficient manner. The analysis starts with a prescribed level of zero m^3 added CWD – that is the base level, which corresponds to timber production without considering measures to increase CWD – goes on with incremental steps of 10% increase in CWD and ends with a prescribed level of CWD more than 320% (actually 322%) above the base level. The result of this step-wise incremental of prescribed level of CWD is best reproduced by Figure 16.

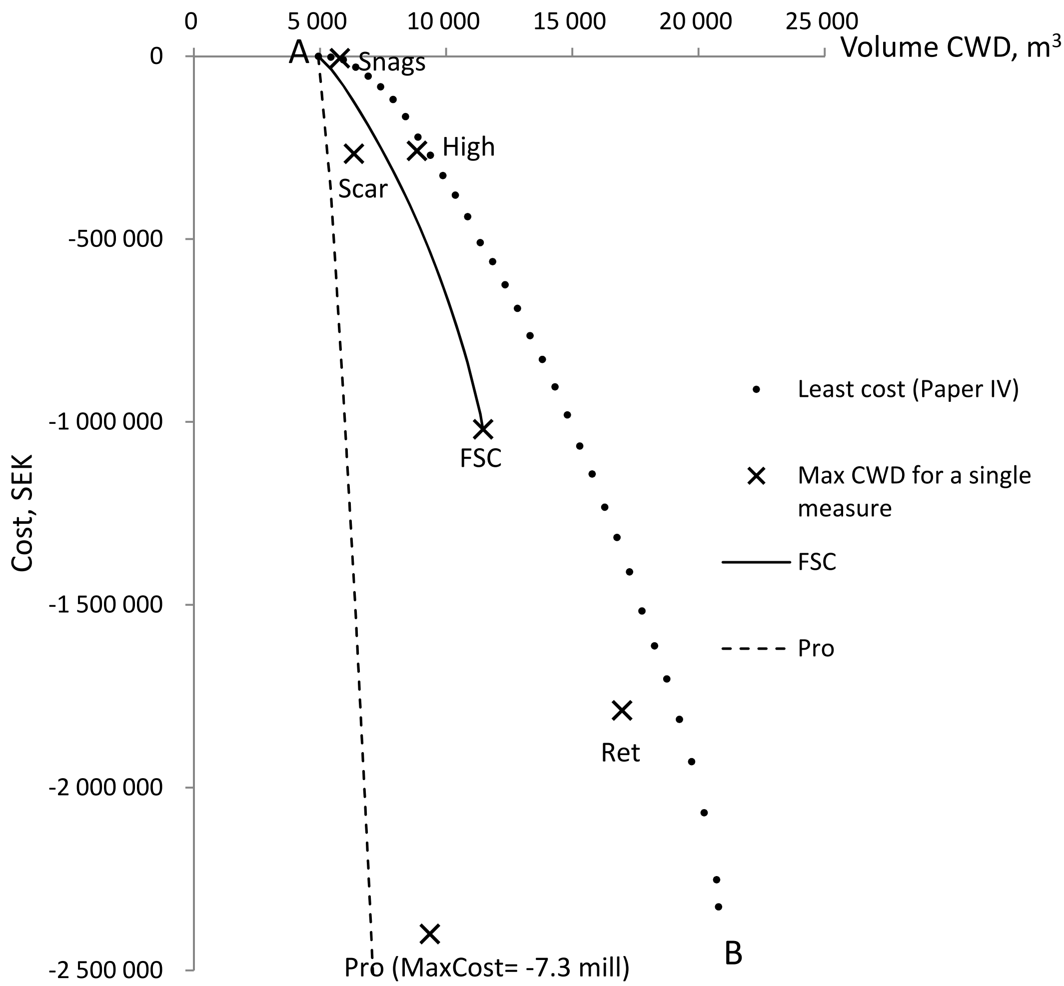

Figure 16. Total cost to produce CWD on an estate forest.

From Point A to Point B the step-wise incremental, built on data and estimated values from Paper IV is shown. Figure 6 in Paper IV shows the same curvature as in Figure 16, but with percentage change instead of absolute values on the abscissa and the ordinate. Cost-effectiveness is defined as the slope of the curve. Each dot in Figure 16 represents the result of an optimisation calculation. Together the dots from A to B form a least-cost frontier. Given the available measures to increase the volume of CWD, the actual state of the forest, and economic and technological conditions, no other combination of measures could be more cost- effective than the values representing the least-cost curve. This curve also represents the least-cost allocation of resources aimed at increasing the volume of CWD. In the figure there are six crosses, each representing an available measure to increase CWD. The crosses are positioned at points where each measure alone produces maximum CWD. As a matter of fact, these crosses are endpoints in different paths, all equally steep or steeper than the least-cost curve, all starting from Point A where no CWD-increasing measures are conducted. The least-cost path for the measures of prolongation of rotation and complying with the FSC-standard are clearly seen in the figure. The prolongation of rotation curve is so steep and elongated that the endpoint is positioned far below the scoop of the ordinate.

As can be seen from Figure 16, there are two inferior measures; manual scarification (Scar) and prolongation of rotation (Pro). Regarding manual scarification, this measure is entirely overruled by measure creating high stumps (High), which seems to produce more CWD and at a lower cost than manual scarification does for any prescribed level of CWD. The maximum volume CWD from prolongation of rotation will be extremely expensive to obtain, more than SEK 7.3 million. Prolongation of rotation is also far overruled by measures complying with the FSC-standard and retention of living trees (Ret).

The maximum CWD volume from retention of snags (Snags) is actually positioned on the least-cost curve and at small prescribed levels of CWD retention of snags is the only selected CWD-increasing measure. Creating high stumps (High) is close, but not aligned to the least-cost curve, and that means that creating high stumps will never be a standalone measure, as retention of snags was at low prescribed CWD levels. Retention of living trees (Ret) and complying with the FSC standard are measures that can potentially produce large amounts of CWD and therefore suitable options at higher demands of CWD. The optimal combination of different CWD-increasing measures at different prescribed CWD levels is shown in Paper IV, Figure 4.

5 Future improvements

In this section two proposals are discussed. They are both dealing with improvements that lead to a more effective allocation of CWD-increasing measures to proper stands. The first proposal deals with the possibility to attain a more cost-effective production of CWD by introducing new CWD-increasing measures in the calculations and the second proposal improves biodiversity by introducing enhanced volume constraints in the optimisation algorithm. Moreover, the latter proposal solves the problem why some CWD-increasing measures that produced valuable CWD for biodiversity preservation were rejected from the optimal solution.

5.1 Improvements of cost-effectiveness

A more cost-effective production of CWD. The most cost-effective allocation of CWD-increasing measures is probably not yet known. In Paper IV six different single measures were applied that aimed at increasing the volume of CWD. Only the FSC measure was a combination of several measures. Other possible combinations were not examined and some single measures were totally omitted from the optimisation analysis, for example setting aside a whole stand as a reserve. Another option worth testing is the proposal of Tikkanen *et al.* (2012) to omit thinning operations from forestry practice and thereby creating significant amounts of CWD. In Figure 17 below, a hypothetical least-cost frontier is shown.

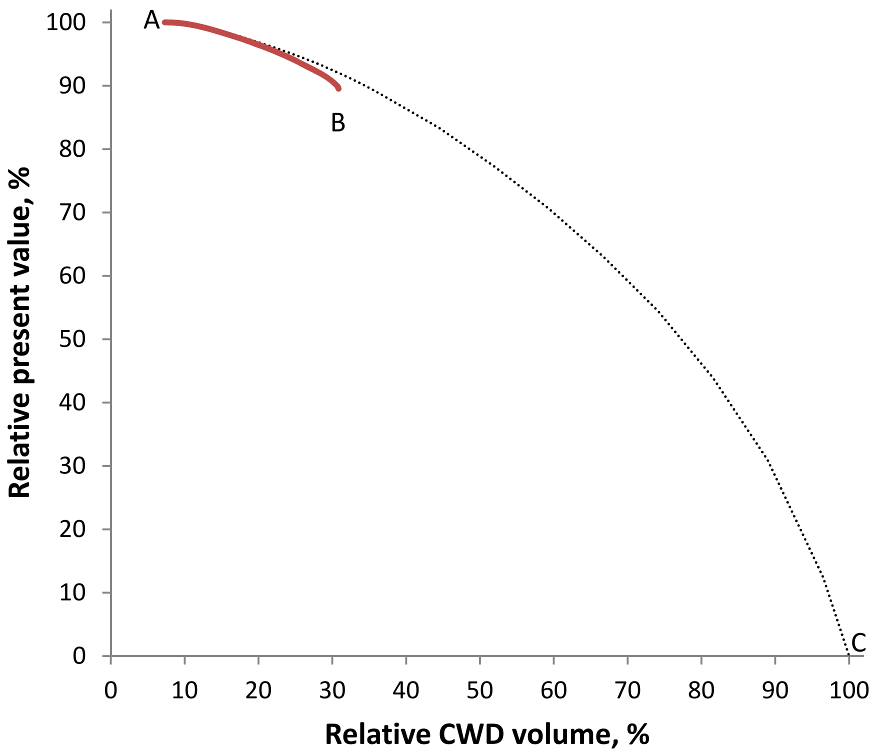

Figure 17. Trade-off between volume of CWD and present value of timber production.

Figure 17 outlines the trade-offs between relative present values of timber production and relative volumes of CWD produced on a large non-industrial forest estate in central Sweden. Points A and B are the same as in Figure 16, and the value of Point C is built on estimations from Paper II. A simulated spruce stand of site index G24 will achieve an estimated CWD level of 68 m^3/ha and that value is used as an estimate of CWD-volume/ha for the entire estate´s forest if it were transformed to old growth. At Point C the entire forest is assumed to have been transformed into old growth stage – a forest unmanaged for a long time, which means that all normal timber producing activities have ceased. On the other hand an assumed average volume of 68 m^3/ha CWD can be expected from the forest land. The maximum present value of timber production occurs at Point A, which implies that the average volume of CWD in the forest will amount to 4.9 m3/ha, corresponding to around 7% that of an old growth forest (Paper IV). As only normal forest practice is conducted at Point A, a few natural dying trees now and then are considered too expensive to harvest and consequently these snags will contribute to set the level of CWD. In the interval A to B, more and more measures and areas are added to increase the level of CWD in the most cost-effective manner. From values in Table 6 in Paper IV, the average volume of CWD at Point B is estimated to 20 m^3/ha corresponding to a 30% CWD level in comparison to the old growth forest and the total cost to achieve this level is around 10% of the estate's present value at Point A (Paper IV). The trade-offs between volume of CWD and present value of timber production in the interval B to C have not been investigated, but a wise guess is that the dotted hypothetical line from A to C could be the shape of a yet more cost-effective allocation of CWD-increasing measures. For example, if the measure setting aside a stand as a nature reserve had been an option in the optimisation process, then the least-cost curve might have taken the shape of the hypothetical curve from A to C.

5.2 Improvements of biodiversity quality

Optimisation with enhanced volume constraints. As in Paper IV, only the total volume of CWD from CWD-increasing measure has been considered on the estate forest. Due to an unfavourable relationship between accrued costs and formed CWD-volume certain CWD-increasing measures will not be chosen in the allocation of CWD-increasing measures to the proper stands. In this case the risk increases that several quality types of CWD will be depleted in the forest. In the optimisation of a Norway spruce dominated estate two of six available CWD-increasing measures (manual scarification and prolongation of rotation) were inferior and thus omitted from the solution. According to Table 8, late decay stages of CWD after manual scarification, and large slow growth and shady CWD after prolongation of rotation could thus be in short supply over time. Saproxylic species need a wide variety of different wood substrates to survive and wood from different species, diameter classes, decay stages, light regimes and growth rates could provide for that need. A straightforward solution to provide for a variety of CWD-qualities is to add several volume constraints concerning CWD to expression (10). Each constraint would target a specific CWD-increasing measure with, for example, a minimum attained percentage share of the total created CWD-volume. When solving the least-cost problem with a new set of constraints, all preferable CWD-increasing measures will be a part of the solution and this may lead to a small but significant improvement in biodiversity.

6 Summary of the papers

General point of view. The issue of cost-efficiency in the production of CWD can be investigated at the stand, forest estate, and forest landscape level (none of the papers will however treat the forest landscape level). Paper I focused on the question of cost-efficiency at the stand level by simulating the effects on present value and CWD of different measures that will increase the amount of dead wood in Norway spruce forests at different sites in Sweden. Paper II expanded this further by analysing the amount of substrate for red-listed saproxylic species that would be increased if different conservation measures were applied. Both studies concede that the relative cost-efficiency of the measures differed in different parts of Sweden. In southern Sweden, the number of red-listed species needing dead Norway spruce trees was low, and therefore it would probably be better to concentrate conservation efforts on other tree species, e.g. deciduous trees which host a larger number of red-listed species. In northern Sweden, forest land was so inexpensive that an attractive way to increase the amount of CWD would be to set aside more managed forests as reserves. Finally, in central Sweden more focus should be given to increasing the amount of Norway spruce CWD in managed forests in comparison to the other regions. Both studies ranked the different CWD-increasing measures that can be conducted within the managed forest in a similar way in terms of cost-efficiency; retention of snags, creating high-stumps and retaining wind-thrown trees were cost-efficient measures while increasing the rotation was expensive. Thus far, only Norway spruces has been analysed for its ability to improve biodiversity. In Paper III mixed stands of Norway spruce, Scots pine and birch or aspen were modelled and analysed. As in Paper II the cost-effectiveness was measured as increased volume of CWD and as an index reflecting substrate availability for red-listed saproxylic organisms. The results show a clear difference regarding cost-effectiveness between species in different parts of Sweden.

Methods used in a stand level approach, as in Papers I – III, yielded a straightforward ranking of different measures for a few specific average stands. This will not be sufficient at the forest estate level since data from different stands varies a great deal and the forest management may also have to achieve specific stated goals. Methods must be modified to capture this complex variety. In an estate forest it is necessary to consider stands with low and high productivity, age and standing volumes, a variety of topographic conditions and so on. In Paper IV economic cost and production of CWD were modelled at the estate level, explicitly taking such variability in stand characteristics into account. In all papers the economic calculations were made with help from the computer program Plan33 (see methods section).

6.1 Paper I

Changing silvicultural methods in managed forestland to improve habitat quality for forest organisms has become one of the main means to preserve forest biodiversity in Fennoscandia. In boreal forests, CWD is an important substrate for red-listed species. The cost-efficiency of five management measures was analysed, which aim to increase CWD in managed forests: retention of living trees at final cutting, artificial creation of high stumps during thinning operations and at final cutting, manual scarification just after final cutting to avoid destruction of CWD, prolongation of the rotation, and retention of newly formed CWD in a year of high natural mortality. For Norway spruce stands in different parts of Sweden, the present value and predicted amounts of CWD which will be present that will be present if the same management method is used over a long time were calculated. To retain reasonable amounts of naturally dying trees after calamities was never expensive, and in central and northern Sweden it was more economical to retain them than to harvest them. Creation of high stumps was a cost-efficient method of increasing the amount of CWD. Prolongation of rotation was the most expensive way to increase CWD. It was concluded that adopting several different measures to increase CWD in managed forests, as prescribed by certification standards today, is a good concept, but to be cost-efficient the focus should be on different measures in different parts of Sweden.

6.2 Paper II

It is important that measures to maintain biodiversity are taken in a way that is cost-effective for the landowner. The cost-effectiveness of silvicultural measures was analysed - measures which aim to increase the substrate availability for red-listed (species that are threatened, near threatened or where species are probably threatened but data is deficient) saproxylic (wood-inhabiting) organisms. Stands of Norway spruce were modelled in three regions of Sweden using computer simulations and a data-base listing the substrate requirements of saproxylic beetles and cryptogams on the Swedish Red-List. Conclusions about the cost-effectiveness of silvicultural measures depend on the extinction thresholds of the species they are intended to conserve; measures that generate only small amounts of CWD may provide too little substrate to be useful for species with high extinction thresholds. In northern Sweden, forestland is relatively inexpensive, so a cost-effective strategy to increase the amount of Norway spruce CWD was to set aside more forests as reserves. In central and southern Sweden, more emphasis should instead be given to increasing the amount of CWD in the managed forest. The regulations of the Forest Stewardship Council (FSC) could be made more cost-effective by prescribing creation of more high-stumps and retention of larger numbers of dying trees in a year of high naturally mortality. Large CWD, CWD from slow-growing trees and CWD in late decay stages are substrate types that were particularly rare in managed forests as compared to unmanaged forests. Manual soil scarification and retention of living trees are measures that can increase the proportion of these underrepresented CWD types.

6.3 Paper III

The cost-effectiveness of silvicultural measures that increase substrate availability for saproxylic (wood-dwelling) species was analysed. Mixed stands of Norway spruce, Scots pine and birch or aspen in three regions of Sweden were modelled. Cost-effectiveness was calculated as a quotient in two different ways; (1) the calculated opportunity cost associated with a CWD-increasing measure in the numerator is divided by the estimated increase of volume CWD in the denominator; and (2) the opportunity cost is divided by an index reflecting substrate availability for red-listed saproxylic beetles and cryptogams. Applying quotient (1) favoured conifers, while use of quotient (2) increased the cost-effectiveness of using deciduous species in CWD-increasing measures. Tree species had a large impact on the cost-effectiveness of retention of living trees: Scots pine was the most costly tree species to retain and aspen and birch the most cost-effective. Tree species also had an impact, albeit smaller, on the cost-effectiveness of the artificial creation of high stumps during thinning operations and at final cutting. It was most cost-effective to create high stumps from birch and aspen in southern Sweden, whereas in northern Sweden it was more cost-effective to create high stumps from Scots pine and Norway spruce. When increasing the amount of CWD, deciduous trees should therefore be targeted in southern Sweden more than in the north. However, it is important that CWD is created from all tree species, because different tree species support different assemblages of saproxylic species. As regards measures that are not associated with particular tree species, retention of snags at final cutting is a cost-effective measure in all regions whereas prolongation of the rotation is both most costly and less cost-effective. Prices of sawtimber and pulpwood are evolving and the effect of an assumed higher price level on the cost-effectiveness was investigated. The result showed evident changes in the cost-effective criterion but that change had no impact on the ranking of CWD-increasing measures.

6.4 Paper IV

CWD is very important for biodiversity in forests but conservation measures to increase CWD must be performed cost-efficiently. Least-cost combinations of CWD-increasing measures were estimated in a Norway spruce-dominated forest estate in central Sweden. More precisely, using combinations of six different measures was investigated; retention of living trees at final cutting, artificial creation of high stumps during thinning operations and at final cutting, manual scarification just after final cutting to avoid destruction of CWD, prolongation of rotation, retention of snags at final cutting and complying with the FSC-standard impacts in the amount of CWD and net present value at the estate level. The results revealed that an optimal combination of CWD-increasing measures and forest stands could increase the volume of CWD by 322 per cent with a decrease in present value of only 10 per cent. The optimal combination of conservation measures depends on the desired increase in CWD. When comparing the results of Paper IV with the prescriptions of the FSC-standard the analysis thus showed that huge improvements in the cost-efficiency of biodiversity-oriented forestry are possible.

References

Amacher, G.S., Ollikainen, M. & Koskela, E. (2009). *Economics of forest resources*. MIT Press, Cambridge, Massachusetts.

Andersson, G., Brunberg, T. & Westerling, S. (1990). Defining productivity standards for mechanized scarification. *The Forestry Research Institute of Sweden*. Report 1990.2. Stockholm.

Anonymous. (1974). Skogsbruket och miljön – en policyförklaring. Domänverket, Skogsstyrelsen, Skogsindustriernas samarbetsutskott, Sveriges Skogsägarföreningars Riksförbund. Stockholm. 27 ss [In Swedish].

Baumol, W.J. & Oates, W.E. (1988). *The theory of environmental policy*. Cambridge University Press, Cambridge.

Bergstrand, K.G. (1986). *Basic data for productivity targets in motor-manual cleaning*. The Forestry Research Institute of Sweden. Report 1986.2. Stockholm.

Brunberg, T. (1995). *Basic data for productivity norms for single-grip harvesters in final felling.* The Forestry Research Institute of Sweden. Report no 7, 1995. Uppsala.

Brunberg, T. (1997). *Basic data for productivity norms for single-grip harvesters in thinning.* The Forestry Research Institute of Sweden. Report no 8, 1997. Uppsala.

Brunberg, T. (2004). *Productivity- norm data for forwarders*. The Forestry Research Institute of Sweden. Report no 3, 2004. Uppsala.

Coutu, F.H. & Ellertsen, B.W. (1960). *Farm forestry planning through linear programming*. Tennessee Valley Authority, Division of Forestry Relations, Report No. 236-60.

Dahlberg, A. & Stokland, J.N. (2004). *Vedlevande arters krav på substrat*. Jönköping: Swedish Forest Agency. Report No. 7. [In Swedish, English abstract].

Draper, N.R. & Smith, H. (1981). *Applied regression analysis*. Wiley series in probability and mathematical statistics. John Wiley and Sons, Inc. New York.

Ekvall, H. (1986). *PLAN-20. Ett skogligt värderings- och planeringssystem*. Sveriges Lantbruksuniversitet, Institutionen för skogsekonomi, Arbetsrapport 54. Umeå [In Swedish].

Ekvall, H. (1990). *PLAN-30. Kalkyl Värde Plan. - en skogsekonomisk idé under utveckling*. Sveriges Lantbruksuniversitet, Institutionen för skogsekonomi, Rapport 94, Umeå [In Swedish].

Ekvall, H. (2001). *Plan33 – Ett verktyg för ekonomisk analys av skogsbruksföretagets virkesproduktion*. Licentiate thesis, Report No. 123. Dept. of Forest Economics, Swedish University of Agricultural Sciences, Umeå [In Swedish, English abstract].

Elfving, B. (2010). *Growth modelling in the Heureka system*. Faculty of Forestry. Swedish University of Agricultural Sciences, Umeå.

Faustmann, M. (1849). Berechnung des Werthes, welchen Waldboden, sowie noch nicht haubare Holzbestände für die Waldwirthschaft besitzen [Calculation of the Value which Forest Land and Immature Stands Possess for Forestry]. *Allgemeine Forst- und Jagd-Zeitung*. 15 Dezember 1849: 27 - 55.

Fridman, J. & Walheim, M. (2000). Amount, structure and dynamics of dead wood on managed forestland in Sweden. *Forest Ecology and Management* 131, 23-26.

Fryk, J. (1985). *Silvicultural techniques: the final report of a Nordic Research Council on Forest Operations (NSR) research project carried out between 1981 and 1984.* The Forestry Research Institute of Sweden. Report 1985:5. Spånga.

FSC.(2000). Svensk FSC-standard för certifiering av skogsbruk. Svenska FSC-rådet. Uppsala [In Swedish].

FSC. (2009). FSC reflected in scientific and professional literature**,** *FSC Policy Series* No. 2009 - P001. Eds: Karmann, M. & Smith, A.

Gaffney, M.M. (1960). Concepts of financial maturity of timber and other assets. North Carolina State Collage, *Department of Agricultural Economics,* Information Series No. 62.

Gould, E. H. & O`Reagan, W.G. (1965). *Simulation, a step toward better forest planning*. Harvard Forest Papers, No. 13, 1965.

Hanski, I. & Hammond, P. (1995). Biodiversity in boreal forests. *Trends in Ecology and Evolution* 10, 5-6.

Hartman, R. (1976). The harvesting decision when a standing forest has value. *Economic Inquiry.* 14(1), 52-58.

Hautala, H., Jalonen, J., Laaka-Lindberg, S. & Vanha-Majamaa, I. (2004). Impacts of retention felling on coarse woody debris (CWD) in mature boreal spruce forests in Finland. *Biodiversity and Conservation* 13, 1541-1554.

Heady, E.O. (1952). *Economics of agricultural production and resource use*. Prentice-Hall, New York.

Hooke, R. & Jeeves, T.A. (1961). Direct search solution of numerical and statistical problems. *Journal of the Association for Computing Machinery (ACM)* 8 (2): 212-229.

Hyytiäinen, K., Hari P., Kokkila, T., Mäkelä, A., Tahvonen, O. & Taipale, J. (2004). Connecting process-based forest growth model to stand-level economic optimization. *Canadian Journal of Forest Research* 34, 2060-2073.

Keddy, P.A. & C.G. Drummond. (1996). Ecological properties for the evaluation, management and restoration of temperate deciduous forest ecosystems. *Ecological Applications* 6: 748-762.

Keddy, P.A. (2010). Wetland ecology: Principles and conservation (2nd edition). *Cambridge University Press,* Cambridge, 497. 225-227.

Klemperer, W.D. (1996). *Forest resource economics and finance*. McGraw-Hill, Inc. New York.

Kolda, T.G., Lewis, R.M. & Torczon, V. (2003). Optimization by Direct Search: New Perspectives on Some Classical and Modern Methods. *Siam Review* Vol. 45, No. 3, 385–482.

Kruys, N. & Wikström, P. (2001). Optimising uneven-aged management for economic efficiency and occurrence of wood-inhabiting species. In: Kruys, N., Bryophytes and fungi on dead spruce: integrating conservation with forest management planning. Dissertation. Dep. Ecology and Environmental Science, Umeå University, Umeå.

Lichtenstein, M.E. & Montgomery, C.A. (2003). Biodiversity and timber in the Coast Range of Oregon: inside the production possibility frontier. *Land Economics* 79: 56-73.

Lofroth, E. (1998). The dead wood cycle. In: Conservation biology principles for forested landscapes. Edited by J. Voller & S. Harrison. UBC Press, Vancouver, B.C. pp. 185-214.

Lorenz, K. & Lai, R. (2009). *Carbon Sequestration in Forest Ecosystems*. Springer Netherlands.

Luyssaert, S., Schulze, E.D., Börner, A., Knohl, A., Hessenmöller, D., Law, B. E., Ciais, P & Grace, J. (2008). Old-growth forests as global carbon sinks. *Nature* 455 (7210), 213-215.

von Malmborg, G. (1967). Ekonomisk planering av lantbruksföretaget [Economic planning for the combined forestry-agricultural firm]. Dissertation. *Jordbrukets Utredningsinstitut och Institutionen för skogsekonomi*, Skogshögskolan, Stockholm [In Swedish, English abstract].

von Malmborg G., Ericson, O. & Styvén, L. (1970). Ekonomisk jord- och skogsbruksplan – Metodutveckling. *Jordbrukets Utredningsinstitut,* Meddelande nr 5, Stockholm [In Swedish].

Miljödepartementet. (2001). Svenska miljömål – delmål och åtgärdsstrategier. Regeringens proposition 2000/01:130. Stockholm [In Swedish].

Mönkkönen, M., Reunanen, P., Kotiaho, J.S., Juutinen, A., Tikkanen O.-P. & Kouki, J. (2011). Cost-effective strategies to conserve boreal forest biodiversity and long-term landscape-level maintenance of habitats. *European Journal of Forest Research* 130:717-727.

National Land Survey of Sweden. (1988). *Beståndsmetoden för skogsvärdering*. Rapport 1988:1-3. Gävle [In Swedish].

National Land Survey of Sweden. (2002). Riktlinjer för skogsvärdering - Användare av beståndsmetoden. PM Beståndsmetoden. Gävle [In Swedish].

Newman, D.H., Gilbert, C.B. & Hyde, W.F. (1985). The optimal forest rotation with evolving prices. *Land Economics*, Vol 61, No 4. 347-353.

Nilsson, G. (1976). Stamfördelningar [Diameter distributions]. The Forestry Research Institute of Sweden (former: Logging Research Foundation). Report 1976.2. Stockholm [In Swedish, English abstract].

Nilsson, N-E. (1978). Produktionsmall för tidsfördelning av framtida slutavverkningar och gallringar, för medelförrådsberäkningar mm. SOU 1978:7. Skog för framtid. Bilaga 4 [In Swedish, English abstract].

Ohlin, B. (1921). Till frågan om skogarnas omloppstid. *Ekonomisk Tidskrift,* no 12, Stockholm [In Swedish].

PEFC. (2010). Fakta om certifiering av skogsbruk. PEFC och FSC- standarder för uthålligt och ansvarsfullt skogsbruk. (2010-04-15). http://pefc.se/wp-content/uploads/2010/11/ fakta_ om_certifiering_av_skogsbruk_100415.pdf [2013-09-15]. [In Swedish].

Pressler, M.R. (1860). Aus der Holzzuwachslehre. *Allgemeine Forst- und Jagt-Zeitung,* vol 36, 173 - 191.

Ranius, T., Kindvall, O., Kruys, N. &, Jonsson, B.G., (2003). Modelling dead wood in Norway spruce stands subject to different management regimes. *Forest Ecology and Management* 182, 13-29.

Richards, F.J. (1959). A flexible growth function for empirical use. *Journal of Experimental Botany* 1959, 10, 29.

Samuelson, P.A. (1980). *Economics*. Eleventh Edition. McGraw-Hill.

Siitonen, J. (2001). Forest management, coarse woody debris and saproxylic organisms: Fennoscandian boreal forests as an example. *Ecological Bulletins* 49, 11-41.

Speight, M.C.D. (1989). *Saproxylic invertebrates and their conservation*. Council of Europe, Strasbourg.

Stevens, V. (1997). The ecological role of coarse woody debris: an overview of the ecological importance of CWD in B.C. forests, Working Paper 30/1997, Victoria, B.C.: Research Branch, B.C. Ministry of Forests.

Sweden Statistics (2001). Intäkter och kostnader i jord- och skogsbruket (JEU) efter typgrupp/storleksklass och intäkts-/kostnadsslag. År 1996 - 2001. SCB. Örebro [In Swedish].

Swedish Forest Agency. (1948). Kungl.skogsstyrelsens anvisningar rörande tillämpningen av skogsvårdslagen den 21 maj 1948 (SFS 1948:237). Stockholm [In Swedish].

Swedish Forest Agency. (1994). *Skogsvårdslagen, Handbok*. Jönköping [In Swedish].

Swedish Forest Agency. (2008). *Rekommendationer vid uttag av avverkningsrester och askåterföring.* Meddelande 2-2008. Swedish Forest Agency. Jönköping [In Swedish].

Swedish Forest Agency. (2012). *Swedish statistical yearbook of forestry*. Jönköping.

Swedish Tax Agency. (2004). *Tax Statistical Yearbook of Sweden 2004*. Stockholm.

Tikkanen, O-P., Matero, J., Mönkkönen, M., Juutinen, A. & Kouki, J. (2012). To thin or not to thin: bio-economic analysis of two alternative practices to increase amount of coarse woody debris in managed forests. *European Journal of Forest Research 131*: 1411-1422.

United Nations. (2013). Population and vital statistics report. *Statistical Papers.* Department of Economic and Social Affairs. Series A Vol. LXV.

Valsta, L.T. (1992a). An optimization model for Norway Spruce management based on individual tree growth models. *Act Forestalia Fennica* 232, 1-20.

Valsta, L.T. (1992b). A scenario approach to stochastic anticipatory optimization in stand management. *Forest Science* 38, 430-447.

Wikström, P. & Eriksson, L-O. (2000). Solving the stand management problem under biodiversity-related considerations. *Forest Ecology and Management* 126, 361-376.

Yates, B. T. (1985). Cost-effectiveness analysis and cost-benefit analysis: An introduction. *Behavioural Assessment*, Vol 7(3), 1985, 207-234.

Appendix 1

Harvesting efficiency

Harvesting efficiency is essential in assessing harvesting costs. A model based on results from the Forest Research Institute of Sweden (Brunberg, 1995; Brunberg,1996; Brunberg, 2004) and used in Plan33looks like this:

$$\begin{aligned}\mathrm{Heff}(n) = {} & \beta_0 + \beta_1 \cdot \mathrm{Area} \cdot \mathrm{Vol} + \beta_2 \cdot \mathrm{Diam} \cdot \mathrm{Height}^2 + \\ & + \frac{\beta_3}{\mathrm{Ast}} + \beta_4 \cdot \mathrm{Cut\%} + \beta_5 \cdot \mathrm{Spruce\%} + \\ & + \beta_6 \cdot \mathrm{Decid\%} + \beta_7 \cdot (\mathrm{Surf} + \mathrm{Slp}) + \beta_8 \cdot \mathrm{Dtr}\end{aligned} \qquad (12)$$

Heff(n)	Harvesting efficiency, m^3/hour, for harvesting machine n (or manual cutting).
$\beta_0,...\beta_8$	Each machinery system has a unique set of parameter values.
Area	Area of the stand, ha.
Vol	Total volume before cut, m^3.
Diam	Mean diameter (weighed with basal area), cm.
Height	Mean height (weighed with basal area), m.
Ast	Average stem volume, m^3 (bark excluded).
Cut%	Volume percentage cut of total volume.
Spruce%	Volume percentage Norway spruce trees in the harvest, %.
Decid%	Volume percentage deciduous trees in the harvest, %.
Surf	Surface structure class of the ground (ground roughness), range: 1 - 5.
Slp	Slope class, range: 1 – 5.
Dtr	Distance from centre of stand to roadside, m.

Appendix 2

Time consumption of regeneration measures

It is essential to know the time consumption of regeneration measures in assessing regeneration costs. A model based on results from the Forest Research Institute of Sweden (Fryk, 1985; Bergstrand, 1986; Andersson et.al., 1990) and used in Plan33looks like this:

$$
\begin{aligned}
&TC(m) = \beta_0 + \frac{\beta_1}{Area} + \beta_2 \cdot XMAI^2 + \beta_3 \cdot (Surf + Slp)^2 + \\
&\qquad + \beta_4 \cdot Dtr \\
&\text{for planting add:} \\
&\qquad + \beta_5 \cdot nPl \\
&\text{for pre-commercial thinning add:} \\
&\qquad + \beta_6 \cdot Height + \beta_7 \cdot Cut\%
\end{aligned}
\qquad (13)
$$

TC(m)	Time consumption for regenerations measure m, hours/ha.
$\beta_0,...,\beta_7$	Parameters (each measure has a unique set of parameter values).
Area	Productive area of the stand, ha.
XMAI	Maximum mean annual increment, m^3/ha and year.
Surf	Surface structure class of the ground (ground roughness), range: 1 - 5.
Slp	Slope class, range: 1 – 5.
Dtr	Distance from centre of stand to roadside, m.

nPl	Number of plants/ha. The recommended number of plants in a replanting area and suitable species are prescribed in the Swedish Forest Act (Swedish Forest Agency, 1994). Number of plants is primarily dependent on site index, but regional differences and local environmental conditions play an essential part in the selection of plants.
Height	Mean height of cleaned (thinned) trees, m.
Cut%	Volume percentage cut of total volume.

Acknowledgements

Thank you to Göran Bostedt and Peichen Gong for invaluable advice and help with the thesis. Tommy Lundgren, Peter Lohmander, Ola Carlén and Bengt Kriström have provided valuable comments on this manuscript. Special thanks go to Camilla Widmark, who helped me with all administrative issues. Many thanks go to Hubert Ekvall, who assisted me with all types of computer-related problems. Finally I would like to thank Göran Bostedt, Mattias Jonsson and Thomas Ranius for a fruitful collaboration with Papers I to IV during the past ten years.

Support for this thesis came from the project "Cost-efficiency of a biodiversity-oriented forestry" financed by The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS). Additional support came from the Swedish University of Agricultural Sciences (SLU), which so graciously allowed me to make time for writing this thesis.