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Cost efficiency of measures to increase the amount of coarse woody debris in managed Norway spruce forests

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Abstract

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, coarse woody debris (CWD) is an important substrate for red-listed species. In this study, we analyse cost efficiency of five management measures taken in Swedish forestry, which aim at increasing CWD in managed forests: retention of living trees at harvest, artificial creation of high stumps, manual scarification at clearcuts to avoid destruction of CWD, prolongation of the rotation period, and retention of naturally dying trees. For Norway spruce (*Picea abies*) stands in different parts of Sweden, we calculated the present value and predicted the amount of CWD that will be present if the same management method is used over a long time. To retain reasonable amounts of naturally dying trees was always inexpensive, 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 to increase the amount of CWD. Prolonging the rotation period was the most expensive way to increase CWD. We conclude 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.

Key terms: Dead wood, forestry, FSC, Green tree retention, *Picea abies*

Introduction

Modern forestry changes and destroys the habitat for many forest-living organisms. In order to preserve biodiversity, forests are set aside as reserves, however, especially during the last decade this approach has been combined with changes of the silvicultural methods, which aim at increasing the habitat quality for forest species in managed forests (*e.g.* Larsson & Danell, 2001; Putz *et al*., 2001). Forest certification has accelerated this development, at least in temperate areas, as it makes it possible to identify products from sustainable forestry, which potentially gives a greater market access and higher prices (Gullison, 2003). Sweden and Finland are examples of countries where the current strategy to a large extent is based on improvements of forest habitats in managed forests by changed silvicultural methods (Raivio *et al*., 2001).

Coarse woody debris (CWD) is a key feature for preservation of threatened organisms in boreal forests (*e.g.* Berg *et al*., 1994; Harmon *et al*., 1986; Jonsell *et al*., 1998; Siitonen, 2001). This is because a large proportion of the species in boreal forests are saproxylic (Hanski and Hammond, 1995; Siitonen, 2001), *i.e.* they depend directly on dead wood or on other saproxylic species during some part of their life cycle (Speight, 1989). Forest management in Fennoscandia has decreased the volume of coarse woody debris (CWD) to 2 – 30% (normally <10%) of the quantity found in old-growth boreal forests (Fridman and Walheim, 2000; Siitonen, 2001). Many saproxylic organisms suffer from the decrease in habitat due to modern forestry (Kouki *et al*., 2001). Some species occur mainly in the core of unmanaged forest areas (Moen & Jonsson, 2003; Berglund & Jonsson, 2003), and they may be impossible to preserve by changing the silviculture practice on managed forestland. However, there are also many red-listed species that colonise logs and artificially created high stumps both in closed forest and on clearcuts (Lindhe, 2004). Therefore, a change of management may be an efficient complement to old-growth protection, especially for the preservation of species associated with young succesional stages (Kouki *et al.*, 2001).

The importance of CWD for biodiversity preservation is acknowledged by the Swedish government; according to Swedish governmental goals, the quantity of CWD should increase (Anon., 2001). Changes in the silvicultural practices used in managed forest landscapes, brought about by adaptations to the FSC standard (Anon., 2000), will, at least in the long run, make it possible to considerably increase the amount of CWD (Ranius and Kindvall, 2004). To maintain CWD, trees (dead or alive) must be left in the forests. Because the wood in the trees constitutes the economically most important resource in the forest, there is an obvious potential conflict between increasing the amount of CWD and the economics of silviculture. Therefore, it is important that environmental considerations are performed in a cost efficient manner. A cost efficient environmental practice means that a given cost spent on the environment improves the environmental quality as much as possible, or that the cost for a given level of environmental quality is as low as possible (Baumol and Oates, 1988). Carlén *et al*. (1999) estimated effects on biodiversity at final logging by ranking consideration measures according to how they believed that animals were affected. They found that many measures entailed no negative effect, or even a positive effect, on the net revenue of final logging, indicating potentially large unexploited improvements in cost efficiency.

To analyse the cost efficiency of different management strategies, which allow long-term persistence of the fauna and flora dependent on CWD, empirical data as well as models of economics, dead wood dynamics and population dynamics of species associated with CWD are required. One previous attempt has considered costs and tree mortality (Wikström and Eriksson, 2000), while a case study on a saproxylic liverwort has demonstrated that it is possible to also include dead wood dynamics and assumptions regarding organism population dynamics (Kruys and Wikström, 2001). In this study, we use information available for Norway spruce (*Picea abies* L. Karst.) forests in Sweden. Norway spruce and Scots pine (*Pinus sylvestris* L.) are the dominant tree species in Fennoscandia. About 1,200 species are associated with dead Norway spruce trees in Sweden, of which more than 300 are red-listed (Dahlberg and Stokland, 2004). However, most saproxylic species may be found on more than one tree species; only 30 species are regarded as specialists on Norway spruce (Dahlberg and Stokland, 2004). We predict the opportunity cost and amount of CWD in stands subject to different management regimes. The opportunity cost of an action to increase CWD is the difference between the maximum present value that can be obtained from the stand, and the present value obtained with a management regime adopted in order to increase the amount of CWD. We compared five different management measures (retention of living trees at harvest, artificial creation of high stumps, manual scarification at clearcuts to avoid destruction of CWD, prolongation of the rotation period, and retention of naturally dying trees) that may be performed in order to preserve biodiversity associated with CWD. We estimated how much CWD are generated and what the economic consequences are for a landowner when different measures are taken to increase the amount of CWD. We compared forest stands in three different parts of Sweden, in order to analyse to what extent the same measures are the most cost efficient everywhere. If there are differences, it suggests that there should not be one single management recommended for all Norway spruce forests in Sweden, but the recommendations should be differentiated regionally.

2. Methods

For each of the management scenarios analysed, two kinds of data were obtained as output: monetary cost and amount of CWD. We used three models, one that deals with the development of the forest stand, one that deals with the economic outcome (Ekvall, 2001), and one that deals with CWD (Ranius *et al*., 2003).

Stand characteristics and development

We compared three hypothetical Norway spruce (*Picea abies*) stands in the southern (Kronoberg county), middle (Gävleborg county) and northern (mountainous part of Västerbotten county) parts of Sweden (Table 1). They were assumed to be even-aged stands with 100% Norway spruce, on moist soil, with bilberry as the dominating plant species in the field layer. The stands were assigned characteristics that are near the average values for each area (Table 1).

We predicted forest growth in each of the stands by using a growth model applied in 'The Stand Method' ('Beståndsmetoden'), which is a flexible growth model for forest valuation developed by the National Land Survey of Sweden (Anon., 1988). With age, site index and tree density as input variables, the model predicts timber volume increment and average diameter and height of the trees. The forest growth function used in The Stand Method is based on the more general Chapman-Richards function (Richards, 1959). We parameterized the model for Norway spruce, using information from the National Land Survey of Sweden.

Calculation of CWD amounts

We predicted the average amount of CWD over entire rotation periods. It was assumed that at the start of the rotation period, the management practice had already been in use long enough for the CWD to be unaffected by any previous management. Thus, in this study we only consider the amount of CWD that will be formed in the long run, but we do not analyze how CWD increases after a change in management. With all measures, a large proportion of the increase in CWD takes place immediately after the time of decision. For two methods (manual scarification, retention of naturally dying trees), the whole increase takes place at that time, while for the other (creation of high stumps, retention of living trees at harvest, prolongation of the rotation period), measures the increase takes place over a longer period.

We simulated the dynamics of Norway spruce CWD in a managed stand using a model similar to that presented by Ranius *et al*. (2003). This model predicts amounts of CWD that are good estimates of the amounts actually observed in managed forests in Sweden (Ranius *et al*., 2003). CWD is defined as dead wood, both snags and downed logs, with a diameter larger than 10 cm. To simulate CWD dynamics, we used information on forest growth (see Methods: Stand characteristics and growth), data on tree mortality, and a model that describes the decay process of CWD.

Based on field data from The Swedish National Forest Inventory, tree mortality (% of stems dying per year) was assumed to be 0.09% / year in younger stands, 0.21% / year in stands of an age up to the recommended cutting age, and 0.36% / year in stands older than the recommended cutting age (Ranius *et al.*, 2003). Mortality of retained trees, especially of a storm sensitive tree species such as Norway spruce, will normally be very high immediately after cutting if they grow in small groups left on clearcuts (Esseen, 1994). It is difficult to estimate this mortality, because it has a huge variability in space and time. In Esseen's (1994) study, the mortality was 30 – 98% during a five-year period after cutting, with a higher mortality in smaller (1 ha) patches compared to larger (0.0625 ha). Therefore, in our simulations we assumed that this one-time mortality was 50%. After that, the mortality was the same as in stands older than recommended cutting age (*i.e.* 0.36% / year).

Dying trees were assumed to have a diameter that was 7.6% smaller than the mean of the living trees (Ranius *et al*., 2003). Based on the stem diameter (in m) at a height of 1.3 meter (*d*), a volume (*V)* for each tree (in m^3) was calculated by equation (1), which has been developed based on data presented by Sillerström (1985).

$$V = 11d^2 - 0.7d \qquad (1)$$

Because the decomposition goes faster in a warmer climate, the residence times changes from the south to north of Sweden. We assumed the residence time to be 50 years in Kronoberg, 70 years in Gävleborg and 120 years in Västerbotten (based on Hofgaard, 1993; Hytteborn & Packham, 1987; Ranius *et al.*, 2004). For Kronoberg, residence times for each decay class were multiplied by 50/70, and for Västerbotten by 120/70. We assumed that the volume of a CWD stem was equal to the volume of the living stem when in class 1-3, 80% when in class 4-5, and 60% when in class 6-8.

As a measure of the CWD, we used the amount that is present if the same management regime prevails over such a long time that there is no effect of any former management regime. Thus, the forest was simulated over 400-500 years with a constant management regime over time, but output data were only considered from the last rotation period. This was done to avoid any effect of how much CWD that was present at the starting point. The amount of CWD varied over the rotation period, and an average value was calculated. The main difference from the model presented in Ranius *et al.*, 2003, was that there was no stochasticity when annual mortality was calculated. We simulated 100 replicates (= identical 5-ha stands) to achieve results that were stable between simulation runs.

Modelling monetary costs

We planned the management of the stand and calculated the opportunity costs using ‘Plan33’, which is a Visual Basic computer program for economic forest management (Ekvall, 2001). When we planned the management of the stand, we used present value maximization. The decision on timing for final clearcutting and the number, type (*e.g.* size of felled trees in relation to those retained), timing and intensity of the thinnings was based on the Faustmann rule, through an iterative search for a global present value maximum (see Appendix 1 for an economic-theoretic account of the use of the Faustmann model for defining opportunity cost measures). The search algorithm used in Plan33 was based on the Hooke and Jeeves’s (1961) direct search algorithm. The optimization routines were similar to those used in the Stand Management Assistant (SMA) software (described by Valsta, 1992a; b), but parameterized for Swedish conditions. The number of thinnings was restricted to a maximum of five. Moreover, the stem diameter must exceed 8 cm before the first thinning and the time between thinnings was at least 4 years. The thinnings were allowed to have an intensity of between 1% and 50% of the standing volume per thinning, and the minimum volume removed in a thinning was 30 m^3/ha. Each individual thinning must be profitable to be suggested in Plan33.

All economic calculations were based on the price lists for 2002 from Mellanskog (Table 2). Mellanskog is a cooperative society of non-industrial forest owners, and one of the most important intermediaries in the Swedish timber market. In the calculation of costs of management measures, we assumed that the most common methods in Swedish forestry were used (Table 3). This means that felling, cutting, pruning, and stacking is conducted using a harvester. Transport from the felling site to the logging road is conducted with a forwarder. Manual felling was assumed to be conducted only when the number of trees to be cut was low. Regeneration is conducted using traditional methods and includes soil scarification, planting, regrowth control and pre-commercial thinning (Table 4). These measures were assumed to take place at the time recommended by Mellanskog (Table 5). Mellanskog also provided estimates of time consumption for silvicultural activities. The price of spruce pulpwood was 240 SEK/m^3. To transport pulpwood with timber truck by ASG, one of the largest transport agents in Sweden, costs 0.25 SEK/m^3 km, while transports of saw timber cost 0.30 SEK/m^3 km.

The opportunity cost of a measure to increase CWD is the difference between the maximum present value that can be obtained from the stand and the present value obtained as a result of undertaking the measure (Appendix 1). The present values are discounted to the time when the decision to undertake the measure is made. To exemplify, for extension of the rotation period this decision is made at the time of the profit-maximizing clearcut, while the decision to conduct manual scarification is taken after the harvest. We used this present value measure because in any forest estate, stands of different ages exist simultaneously. Therefore, changes of the management measures at certain ages of the stand can always be conducted somewhere, but not everywhere, in the forest. Therefore, this is a reasonable replication of the decision problem faced by a private forest owner who is expected increase the total amount of CWD at an estate.

Management practices

We considered five management measures (Table 6) that may be used to increase the amount of CWD. For each of these, we analysed one to three different levels of intensity. If possible, one of the levels corresponded to recommendations by the Forest Stewardship Council (FSC). For each level, the present value and CWD volume were compared with a reference case where no action was taken to increase CWD. In the reference case, forest management was conducted with the sole purpose of maximizing present value. The management regime (rotation period and time and intensity of thinnings) was adapted to maximize the present value without action to increase the amount of CWD, and was not changed when the measures to increase CWD were analysed.

The management measures were analysed considering three stands (Table 1) using a discount rate of 3%. To analyse how sensitive our results are to the assumed discount rate, for Gävleborg all management measures were also analysed using a 2% and a 4% discount rate.

The five management measures are described below:

(1) *Retention of living trees at harvest*

When the FSC standard (Anon., 2000) is applied, living trees covering at least 5% of the stand are normally retained at cutting, both as individual trees and in small groups of trees. In retained areas, the volume of standing trees per hectare is lower than the average (Ola Kårén, pers. comm.), and therefore we assumed that the retained area has a site index and a timber volume per hectare equal to 75% of the average value for the stand. Tree retention at harvest reduces the present value because the area is lost for timber production. Moreover, costs increase on the remaining area since setup costs per hectare associated with felling machines increase when the area becomes smaller.

(2) *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 (Anon., 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. High stumps are created from trees of all quality classes, but lower quality classes are over-represented (Kårén, pers. comm.). Asthere is no data available on their quality, we assumed that the high stumps always are created from wood of timber quality class 4 (for definitions of quality classes, see Table 4), while for harvested trees, the wood at the base of the tree may belong to the quality class 1, 3 or 4. Creating high stumps reduces present value because the timber value in the stump is lost, and the cutting costs increase since machines have to avoid the high stumps.

(3) *Manual scarification of the clearcut*

At final cutting and plantation, machines are used which destroy CWD. According to the FSC standard (Anon., 2000), forestry operations should take care to preserve the CWD and, if possible, scarification should be avoided. A recent study in Finland shows that 58% of the younger CWD, and 88% of the older CWD is destroyed at final cutting if scarification is carried out, while with no scarification the loss is 15% (Hataula *et al*., 2004). We compared two different methods (by hand and with machines) of scarification before plantation. Scarification by hand reduces the present value of forestry since it is more expensive than using machines, but we assume that only 15% of the CWD is lost when this method is used.

(4) *Prolongation of rotation period*

We compared three levels of prolonged rotation time with rotation times that are economically optimal (see Appendix 1). Prolonged rotation time increases the amount of CWD because the period when the living trees are large enough to possibly generate CWD becomes longer, and destruction of CWD due to cutting occurs at longer intervals. An extension of the rotation time reduces the present value of forestry mainly through the discounting effect, *i.e.* the forest owner must wait longer for the revenues of the clearcut.

(5) *Retention of newly formed CWD in a year with high natural mortality*

If large quantities of spruce CWD are generated, for instance by wind-throw or snow breakage, the risk for bark beetle outbreaks may increase (Shroeder and Lindelöw, 2002). For this reason, but also because newly dead spruce trees have a commercial value (Törlind, 1998), newly formed CWD is usually removed by the forest manager if the amounts are large.

When we analysed this measure, we assumed that the forest was different compared to the other scenarios; here we assumed that at a particular age (always midway between the last thinning and the cutting), the mortality is exceptionally high, while for all other scenarios the tree mortality was held constant and no newly formed CWD was removed. Therefore, the results from this conservation measure are not directly comparable to the other measures. We compared a scenario with all CWD generated at the year with high mortality retained, with a scenario with CWD from this year removed. Leaving naturally dying trees reduces the present value both because the timber in the trees is lost and because it increases of future cuts, since machines have to avoid it. According to FSC, the forester is not allowed to remove all trees; a few representative dead trees per hectare must be retained (Anon., 2000).

3. Results

Management regime and volume of CWD

The rotation period that maximized present value was between 70 and 130 years, with a shorter period for more productive stands (Table 7). When the present value was maximized, the predicted amount of CWD was highest in the south (Kronoberg), and lowest in the north (Västerbotten, Table 8). Different discount rates generate different management regimes (Table 7). With a lower discount rate, more CWD was generated (Table 8).

A comparison between measures prescribed by the FSC-standards in Sweden showed that, for instance, retaining 5% of the area gave a much larger increase of CWD than creating three high stumps per hectare (Table 8). If the tree mortality is occasionally high and many of the dead trees are retained, it can lead to a considerable increase in CWD volume (Table 9). However, retaining just 1 m^3/ha of newly formed CWD on a single occasion, as prescribed by FSC, gave a small increase in the volume of CWD (Table 9).

Cost efficiency

When no occasions of high natural mortality take place, the most cost efficient way to increase CWD in all regions was to artificially create high stumps at thinning operations and final cutting (Fig. 1). Using manual scarification and retaining trees at cutting were intermediate with regards to the opportunity cost to increase CWD, while increasing the rotation period was the most expensive method.

The results differed between the three parts of Sweden. When occasions of high natural mortality, *e.g.* wind-throws, occurred in Västerbotten and Gävleborg, a cost-efficient way to increase CWD was to retain these trees (Fig. 2). The cost was in most cases negative, implying that it was cheaper to leave naturally dying trees than to remove them. In Kronoberg, retaining naturally dying trees was also a rather cost efficient measure but it was more expensive than to artificially create high stumps. In Västerbotten, the cost of using manual scarification was only marginally lower than artificially creating high stumps, but in Gävleborg and Kronoberg it was almost as high as retaining living trees.

The cost efficency differed only marginally between different discount rates (Table 8 and 9). Therefore, only the results from a discount rate of 3% are presented in Fig. 1 and 2.

4. Discussion

Cost efficiency

The cost efficiency of measures to increase CWD differed somewhat between geographic regions, whereas varying the discount rate only had minor effects on cost efficiency (Table 8 and 9, Fig. 1 and 2). In all regions, creating high stumps was cost efficient. Important reasons for this are that all dead wood that is not harvested due to this management measure becomes CWD and almost no area has to be excluded from production. In the northernmost county Västerbotten, manual scarification was almost as cost efficient as creating high stumps, whereas in other regions it was less cost efficient. The reason for this difference between regions is that the rate of decay is lower in the north, which implies that the destruction of CWD by machines used at soil scarification will affect the amount of CWD over a longer time in the north compared to the south.

At years with high natural mortality, a way to cost efficiently increase CWD is to retain naturally dying trees (Fig. 2). In Västerbotten and Gävleborg it was always profitable to retain such trees, whereas in Kronoberg, there was a small cost associated with retaining dying trees. In our calculations, we have not taken into account the potential cost associated with an increased risk for attacks by bark beetles, mainly *Ips typographus*, which develop in newly dead spruce trees (Shroeder and Lindelöw, 2002). According to the Swedish forestry act (Anonymous, 1994), up to 5m^3/ha newly formed conifer CWD may be retained. If this amount of CWD is present at individual stands, it is not expected to substantially increase the risk for bark beetle attacks (Hedgren *et al.*, 2003). Thus, leaving reasonable amounts of dead trees is indeed likely to be a cost efficient way to increase amounts of CWD.

All measures included in the FSC-standard were more cost efficient than increasing the rotation period, suggesting that the latter is not a valid alternative to FSC, given that the aim is to increase the volume of CWD. However, with a prolonged rotation period other forest habitats are formed (older, shaded forest stands with trees dying naturally) than with the other measures, and these habitats may be particularly valuable for some organisms.

There were differences between the FSC measures both concerning their contribution to CWD and their cost efficiency. The measure that always created the largest amounts of CWD was retention of 5% of the forestland. Creating three high stumps at thinning and final cutting, and leaving 1m^3 of storm felled trees only lead to small increases in CWD. According to the FSC regulations, the forest manager is not allowed to remove any recently dead trees, unless the volume of newly formed CWD is larger than 3m^3/ha. This seems to be sound both economically and for biodiversity conservation. The FSC-standard prescribes limitation of the use of soil scarification and that care should be taken at harvesting, but it is not forbidden to use soil scarification machines. Therefore, the change of scarification method that we have modelled represents a larger change than normal when the FSC-standard is adopted.

To make FSC more cost efficient, in all regions more newly formed CWD should be retained in years with high mortality, in combination with creation of a larger number of high stumps. Manual soil scarification should also be considered, particularly in Västerbotten. However, to increase the amount of CWD is no end in itself; the aim is to improve the habitat for saproxylic organisms. To increase the total amount of CWD, which this study is focused on, is then an important task, but it is also important to improve the diversity of dead wood in the managed forests (Similä *et al*., 2003;

Jonsell & Weslien, 2003). Thus, it is not desirable to only use the most cost efficient measure, but in every forest landscape many different measures should be combined. This is because employing a multitude of conservation measures will produce substrate suitable for different species. For instance, creating high stumps provides abundant standing CWD which is used by certain beetles (Lindhe, 2004), whereas avoiding soil scarification with machines mainly increase the amounts of downed CWD in late decay stages, which benefits cryptogams (Kruys *et al*., 1999). Therefore, adopting several different measures to increase CWD in managed forests as prescribed by FSC today is a good concept, even though we still do not know to whether the levels in the FSC-regulations are sufficient for survival of any threatened species or not.

Validation of the model and generality of the results

Because this study aims at predicting the cost efficiency in idealized stands using the same management regime over a long time, it is impossible to validate the outcome by comparing with field data. However, the CWD model that we used in the simulations has previously been validated by comparing the outcome with the current amount of CWD in Swedish managed forests (Ranius *et al*., 2003).

The amount of CWD predicted in this study is within the magnitude achieved from recent field inventories in Sweden (average: 6.1m^3/ha, Fridman and Walheim, 2000). However, these inventories show that the amount of CWD is highest in the northwest of Sweden and lowest in the south, while we obtained the opposite pattern in this study (Table 8). This is because in the south of Sweden, newly formed CWD has often been removed (Törlind, 1998), while in the north-west of Sweden there are still many forests that never have been managed using modern forestry methods. As our study aims at predicting the situation in a forest where the management practice have been adopted to maximize present value for a long time, we did not take such differences in management regimes into account.

In this study, we have analysed cost efficiency at the stand level. Raising the perspective to the forest estate level would generate different answers to the question of cost efficiency. A forest estate contains stands differing in tree species composition and site index. Studying different measures to increase the amount of CWD in such a complex context would not generate one single ranking of measures, but rather an optimal mix of measures, which would depend on tree species, site index and economic variables such as the distance to the logging road. The general trend in this study would be found also at the estate level, however, it would be clearer that it is a combination of measures, rather than one single measure, that is the most cost efficient way to increase the amount of CWD.

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Appendix 1. Economic theory

Each of the changes in silvicultural measures that increase the amount of CWD may be thought of as a small social project. The relevant cost then becomes a measure of what is forgone as a result of undertaking this project, that is, the opportunity cost of the project. At the forest stand level, the opportunity cost of an action to increase CWD is the difference between the maximum present value that can be obtained from the stand, based on the optimal choice of rotation period, regeneration method, etc., and the present value obtained as a result of undertaking the project. The optimal choice of rotation period to maximize present value is determined by the Faustmann model (Faustmann, 1849). Setting the Faustmann model in modern capital theoretical terms, assuming a perfect capital market and that all future prices are known, the present value, J, of a forest stand from an infinite number of rotations can be defined as:

$$J = \frac{(p - c_h) f(T) - c_p}{e^{rT} - 1} - c_p \tag{1}$$

where p is the real timber price per unit of volume, c_h is the real harvesting costs per unit of volume, $f(t)$ is the growth function for timber for a certain forest stand as a function of time t, and time T is the age of the stand when it is clearfelled. c_p is the cost of regeneration, while r is the discount rate (e.g. Hanley *et al*., 1997). In our calculations we used a more complicated version of equation (1).

The timber volume is assumed to increase with time, hence $f'(T) > 0$, according to a curve with the classic sigmoid shape. Differentiating (1) with respect to *T* and setting equal to zero gives:

$$(p - c_h) f'(T) = r(p - c_h) f(T) + r\frac{(p - c_h) f(T) - c_p}{e^{rT} - 1} \qquad (2)$$

which is the classic Faustmann formula. It implies that a forest stand should be harvested when the rate of return of the forest stand equals the interest of the value of the stand plus the interest of the value of the forestland.

The amount of CWD may be increased in several ways, and the effect on cost may differ between different management measures. The opportunity cost, *C*, of an action that increases the amount of CWD at the expense of an increase in the harvesting costs, c_h, can, by modifying equation (1), be defined as:

$$C = \frac{(p - c_h^0) f(T^0) - c_p}{e^{rT^0} - 1} - \frac{(p - c_h^1) f(T^0) - c_p}{e^{rT^0} - 1} \qquad (3)$$

where c_h^0 and c_h^1 are the harvesting costs before and after the action to increase CWD.

If the management action involves leaving part of the standing volume at the time of the clearcut, either as a proportion of the stand area or in the form of high stumps, the opportunity cost can be defined as:

$$C = \frac{(p - c_h) f(T^0) - c_p}{e^{rT^0} - 1} - \frac{(p - c_h)\left[f(T^0) - V\right] - c_p}{e^{rT^0} - 1} \qquad (4)$$

where V is the amount of timber volume left standing. This management action may lead to increased harvesting costs, in which case equation (3) and (4) must be combined.

The management action may also involve prolonging the rotation period beyond the rotation period dictated by equation (2). In this case the opportunity cost can be defined as:

$$C = \frac{(p - c_h) f(T^0) - c_p}{e^{rT^0} - 1} - \frac{(p - c_h) f(kT^0) - c_p}{e^{rkT^0} - 1} \tag{5}$$

where T^0 is the optimal rotation period and k is a proportionality factor by which the rotation period is prolonged.

Table 1. Characteristics of stands used in simulations, followed by mean ± standard deviation for each region according to the literature. All were 5 ha, even-aged stands with 100% Norway spruce.

Stand variable	Krono berg		Gävle borg		Västerbotten (the mountainous part)	
Vegetation zone[1]		hemiboreal		south-boreal		northern boreal, sub-alpine
Site index, *i.e.* height (m) of the spruce trees when the are 100 years old[2]	32	30±3	24	24±2	16	16±2
Terrain transport distance (m), i.e. distance from the centre of the stand to the nearest road[3]	200	220±80	300	300±80	500	500±100
Transport distance to saw mill (km)[4]	30	80	40	70	60	100
Transport distance to pulp factory (km)[4]	80	80	80	80	200	110

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[1] Ahti *et al*. (1968)
[2] Fridman (1992).
[3] Anonymous (1991).
[4] Anonymous (1992). The estimates are from data pooled for larger regions (two or three counties). Standard Deviations were not available.

Table 2. Price (SEK/m^3) for saw timber of Norway spruce of different quality. Means from Mellanskog's price lists for 2002[†]. The quality classes have been defined by the Swedish National Board of Forestry (see www.virkesmatningsradet.org).

	Top diameter (cm) of the saw timber log								
Quality class*	14.0	16.0	18.0	20.0	22.0	24.0	26.0	28.0	>30.0
1	463	472	476	486	490	495	500	504	504
2	439	447	444	439	429	432	434	436	436
3	417	420	422	425	429	432	434	436	436
4	382	382	382	386	390	395	395	395	395

* *Class 1* spruce logs must be butt logs or middle logs of high quality. The sawing yield is expected to be high quality carpentry wood. This means that the log must be almost completely straight and its surface area practically free of knots.
Class 2 spruce logs must be top or middle logs with its first sound knot within 1.5 m from its thicker end. It is expected that the sawing yield from the log should contain mainly sound logs.
Class 3 spruce logs are expected to yield construction timber. Tolerance for knots is high providing strength is not compromised.
Class 4 spruce logs provide saw timber suitable for disposable packaging and other applications with low quality requirements. There is no limit on the number of knots allowed.
[†]The prices are derived from five different price lists from Mellanskog. Each of these price lists refers to a specific region and are calculated with a deduction for the transport cost to the nearest saw or pulp mill. If the transport cost of 0.30 SEK/m^3 km (for saw timber) and 0.25 SEK/m^3 km is added to these prices on the lists only small differences between the regions remain, and the average prices of these price lists are reproduced above.

Table 3. Costs of felling in Swedish forests. Data derived from functions received from Mellanskog. Indirect costs are costs for planning, marking of roads for forwarders, preparation of stacking sites, etc.

Forest management activity	Variable cost, SEK/hour	Fixed cost, SEK per stand
Manual cutting	240	–
Thinning with harvester	705	–
Clearcutting with harvester	705	–
Transport with forwarder after thinning	550	–
Transport with forwarder after clearcutting	550	–
Indirect costs for thinning	300	1000
Indirect costs for clearcutting	400	1000

Table 4. Costs for regeneration, based on data from Mellanskog.

Regeneration activity	Variable cost SEK / hour	Fixed costs, SEK / 1000 plants
Soil scarification	600	–
Planting	140	2100
Pre-commercial thinning	320	–
Regrowth control	140	–

Table 5. Timing of regeneration activities in Norway spruce forests in the simulated stands. Data from Mellanskog (years after clearcutting).

Regeneration activity	Kronoberg	Gävleborg	Västerbotten (the mountainous part)
Soil scarification	0	0	0
Planting, 2 year old plants	1	1	1
Regrowth control	6	8	9
Pre-commercial thinning	9	11	13

Table 6. Management measures taken to increase the amount of CWD. Levels of intensity analysed, and their values when no measure to increase CWD is taken. Levels corresponding to prescriptions by FSC are underlined.

Management measure	Intensity of management measure	Value when no measure to increase CWD is taken
Retention of living trees at harvest (% of the stand area)	1 5 9	0
Artificial creation of high stumps per hectare created during thinnings and at final cutting (number per hectare)	3 10 20	0
Scarification at clearcut	Only by hand around plants	No restriction
Prolongation of rotation time (% in relation to economic optimality according to Faustmann).	10 25 50	0
Retention of newly formed CWD in a year with high natural mortality. Volume of newly formed CWD (x) and volume retained (y) (m^3/ha), always one occasion per rotation period	x = 20, y = 20 x = 20, y = 1 x = 5, y = 5 x = 5, y = 1	x = 20, y = 0 x = 5, y = 0

Table 7. Rotation period and time of thinnings that optimize the present value of the stands, according to our calculations.

County	Discount rate	Stand age at cutting	Stand age at thinnings
Kronoberg	3%	70	44, 48, 52, 56
Gävleborg	2%	92	59, 63, 67, 71, 75
Gävleborg	3%	82	53, 57, 61, 65
Gävleborg	4%	83	50, 62
Västerbotten	3%	130	77, 100

Table 8. Increase of CWD (average over the rotation period assuming that the management has been the same over a long time, m^3 / ha) and cost (decrease of predicted present value at the time of decision, SEK / ha) when different measures are taken to increase the volume of CWD at even-aged Norway spruce stands in Sweden. The stands were situated in three different counties (see Table 1) and for Gävleborg, we compared three different discount rates (2%, 3% and 4%). The given values are the difference in CWD (in m^3/ha) and present value (in SEK / ha) in relation to a reference case, which implied that all newly formed CWD was taken care of (0 m^3 retained).

	Gävleborg 2%		**Gävleborg 3%**		**Gävleborg 4%**	
	CWD	Cost	CWD	Cost	CWD	Cost
reference case	*6.19*	*0*	*4.91*	*0*	*3.54*	*0*
Retention (% of area)						
1	+0.69	376	+0.59	245	+0.40	101
5	+3.66	1590	+3.24	1209	+2.20	582
9	+6.84	3089	+5.91	2010	+4.03	1057
High stumps (No./ha)						
3	+0.50	70	+0.34	45	+0.29	43
10	+1.81	234	+1.18	150	+0.93	143
20	+3.16	468	+2.45	300	+1.89	287
Scarification manually						
	+3.19	996	+3.41	915	+1.88	866
Rotation period (% extension)						
10	+1.46	1269	+1.07	1333	+089	857
25	+4.26	6795	+3.22	6232	+2.64	4620
50	+9.81	19780	+7.81	17099	+6.15	12200

	Kronoberg 3%		**Västerbotten 3%**	
	CWD	Cost	CWD	Cost
reference case	*9.73*	*0*	*3.19*	*0*
Retention (% of area)				
1	+0.93	416	+0.30	194
5	+5.20	2143	+1.61	963
9	+9.32	3845	+3.01	1731
High stumps (No./ha)				
3	+0.63	44	+0.16	33
10	+2.14	146	+0.44	109
20	+4.34	293	+0.94	216
Scarification manually				
	+3.66	1216	+1.90	509
Rotation period (% extension)				
10	+2.30	1863	+0.79	618
25	+5.87	8889	+2.17	2631
50	+13.04	25979	+5.14	6184

Table 9. Increase of CWD (average over the rotation period assuming that the management has been the same over a long time, m^3 / ha) and cost (decrease of predicted present value at the time of decision, SEK / ha) when different volumes of newly formed CWD are retained at a year with high tree mortality. The stands were situated in three different counties (see Table 1) and for Gävleborg, we compared three different discount rates (2%, 3% and 4%). The given values are the difference in CWD (in m^3/ha) and present value (in SEK / ha) in relation to a reference case, which implied that all newly formed CWD was taken care of (0 m^3 retained).

	Gävleborg 2%		**Gävleborg 3%**		**Gävleborg 4%**	
	CWD	Cost	CWD	Cost	CWD	Cost
20 m^3 wind-throw						
reference case	*6.05*	*0*	*4.48*	*0*	*3.49*	*0*
1 m^3 retained	+0.28	19	+0.33	-5	+0.44	-5
20 m^3 retained	+6.19	227	+7.00	-252	+7.23	-234
5 m^3 wind-throw						
reference case	*6.14*	*0*	*4.50*	*0*	*3.53*	*0*
1 m^3 retained	+0.21	16	+0.40	-8	+0.28	-7
5 m^3 retained	+1.51	-42	+1.75	-154	+1.78	-146

	Kronoberg 3%		**Västerbotten 3%**	
	CWD	Cost	CWD	Cost
20 m^3 wind-throw				
reference case	*6.77*	*0*	*3.60*	*0*
1 m^3 retained	+0.22	55	+0.40	-75
20 m^3 retained	+5.68	963	+7.69	-1663
5 m^3 wind-throw				
reference case	*6.78*	*0*	*3.58*	*0*
1 m^3 retained	+0.27	53	+0.43	-80
5 m^3 retained	+1.45	147	+1.92	-507