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Forest amenity values and the rotation age decision: a Nordic perspective

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There is a great variety and complexity in multiple-use forest management problems. From the perspective of a welfare maximizing social planner, the information requirements for a complete solution to multiple-use problems are usually insurmountable. Based on the framework proposed by Hartman (Hartman, R. 1976. The harvesting decision when a standing forest has value. – Econ. Inq. 14: 52–58.), this paper addresses the harvesting decision by a land owner who considers specific non-timber amenities as well as timber production in the management of a single stand. Relevant empirical evidence was reviewed and standing forest goods and services for Nordic conditions were identified for two stylised cases, a southern stand with beech and, for comparison, a northern stand with Norway spruce. Production relationships and shadow values for the non-timber goods and services were also investigated with the review of the existing literature. The review was synthesised as a qualitative description of the development of timber and non-timber values during a forest rotation, and solutions to the harvesting decision problem in different situations. The findings were used to show how the choice of tree species and rotation age may influence the value of a forest stand in a multifunctional setting. It was found that the values vary considerably throughout a rotation, and that these dynamics need to be taken into account when evaluating multiple-use forestry decisions. Some amenity values tended to increase the economically optimal rotation age, whereas others tended to decrease it, as compared to consideration of only timber production.

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The determination of the optimal harvest age of a single forest stand is a classical problem in forest economics. The first economic solution to the problem was introduced by Faustmann (1849), who considered the optimal rotation when timber has a value. It has become increasingly apparent in recent decades that the flow of values from the standing forest, in terms of non-timber goods and services, needs to be included as well. The presence of standing forest amenities in combination with the absence of market prices reflecting their value to society implies that forestry decisions based solely on timber production may be socio-economically inefficient (Hanley et al. 1997). The relevant solution to the harvesting decision problem, therefore, requires consideration of the relevant decision criteria as well as the objectives of the decision maker.

An early multiple-use extension of the Faustmann approach was provided by Hartman (1976), who included an amenity value function in the optimisation problem. In his paper, it was shown that the presence of non-timber goods and services provided by a standing forest may have important impacts on when the stand should be harvested. Optimisation models which only consider the timber value are likely to provide incorrect information about the harvest timing when the forest stand also provides a significant flow of non-timber amenities. A number of multiple-use extensions of the Hartman model have been suggested in the literature, including ecological services: biodiversity (Juutinen 2008), carbon sequestration (van Kooten et al. 1995, Stainback and Alavalapati 2002), carbon sequestration and biodiversity (Caparrós and Jacquemont 2003), forage and water production (Strange et al. 1999), back-country hiking (Englin 1990), trout catch, wildlife diversity, visual aesthetics, soil movement, deer harvest, moose harvest and water yield (Calish et al. 1978), and resin tapping (Wang et al. 2006).

A complete solution to the Hartman problem from the perspective of a welfare maximizing social planner would require that all relevant standing forest amenities are accounted for simultaneously. Most studies have treated one or two non-timber amenities at a time, sometimes including stand interdependencies (Koskela and Ollikainen 2001, Koskela et al. 2007).

The present study approaches the Hartman problem from the perspective of the Nordic countries. The focus is on two stylised forest stands. The first is a beech stand representing the southern region, i.e. Denmark and southernmost Sweden, where beech forests exist. The second is a spruce stand representing the northern region, i.e. the remaining parts of the Nordic countries, where Norway spruce is a dominating tree species. The analysis considers a small unit of forest land, i.e. a stand, where the trees are harvested simultaneously (except for seed trees left when a stand is regenerated naturally), and real timber prices are assumed to be constant over time. It is assumed that there is no interdependency between stands. The analysis is based on a review, synthesis and extension of earlier research.

The aims of the study are threefold: to identify relevant standing forest amenities in the Nordic countries, to identify production and shadow value relationships for these goods and services and their change during the rotation of a forest stand, and to investigate solution properties to the harvesting decision problem when considering non-timber values in different situations.

The paper continues with a short overview of the development of multiple-use forestry in the Nordic countries. This is followed by outlining the general economic theory underlying the harvesting decision when considering values of timber as well as non-timber goods and services. Next, non-timber forest amenities, production and value relationships are identified for the two stylised cases of a southern beech stand and a northern spruce stand in the Nordic countries. The information is synthesised in a qualitative description of the development of non-timber values during a forest rotation. Finally, the paper discusses and concludes solutions to the harvesting decision problem when considering non-timber values in different situations.

Background

The management paradigm should be seen as dynamic and a result of historical contingencies and patterns. Forest planning and management has been an important discipline in ensuring a non-declining supply of timber and fuel wood, with an emphasis on silvicultural techniques, forest mensuration and harvest prognosis. Today, issues related to other forest outputs, e.g. recreation, biodiversity and sustainability, are also taken into account (Ekelund and Hamilton 2001, Danish Forest and Nature Agency 2002).

The concept of multiple-use is deeply integrated into forest policies, management and planning. In multiple-use forestry the production of timber output is important, as well as non-timber outputs which are considered important from a societal point of view. This mix of outputs, e.g. recreation, hunting, berry-picking and clean drinking water, is formulated to meet a certain set of objectives. The current state of multiple-use forestry in the Nordic countries results from a long historical development. Some of the first forestry acts aimed at putting an end to forest destruction, and implementing sound forest management principles. In the 19th and 20th centuries, the forestry acts in the Nordic countries elaborated the principles of sound management and the emphasis was on the production of timber (Ekelund and Hamilton 2001, Danish Forest and Nature Agency 2002). During the second half of the 20th century emphasis shifted more towards multiple-use forestry, considering timber values as well as values of landscape amenity, natural history, culture, environmental protection and outdoor recreation (Ekelund and Hamilton 2001, Danish Forest and Nature Agency 2002).

In the most recent decades forest policy has developed rapidly in the Nordic countries. Recognising that timber production still has a great value, the value of non-timber amenities from a societal point of view may in some regions play an even more important role (Bojö 1985, Kriström 1990). Moreover, the value of non-timber forest products may also change over time (Eliasson 1994). Use values like recreation were at a relatively early stage reflected in forest policies in the Nordic countries, while existence values of e.g. biodiversity have become more in focus in the last decades (Boman et al. 2008). This development reflects societal concerns regarding what has recently become known as ecosystem service production (De Groot et al. 2002, Fisher et al. 2009). While markets are being developed for some of these environmental goods and services (Mantau et al. 2001a, b) others remain non-marketed. This calls for thoroughly considered decisions of the forest manager dealing with a system involving both marketed and non-marketed goods and services, several goals, joint production potential, long-term and, in some cases, irreversible implications.

Theory

The basic theory behind finding the economically optimal rotation age was developed by Faustmann (1849). Only considering revenues from final harvesting and regeneration costs, the present value of a perpetual series of rotations can be formulated as

$$V(T) = \frac{R(T)e^{-rT} - S_0}{1 - e^{-rT}} \quad (1)$$

where R is the net revenue earned by harvesting a stand at age T, S_0 is the cost of establishment of a new stand and r is the interest rate. This is called the soil expectation value (Klemperer 1996, Aronsson and Löfgren 2002). In order to maximise $V(T)$, the first order condition is derived:

$$V'(T) = 0 \Rightarrow R'(T) = r(R(T) + V(T)) \quad (2)$$

The second order condition is that V"(T)<0. This means that it is optimal to continue the rotation until the value increment equals the interest on the value of the standing trees plus the interest on the value of the land (Klemperer 1996, Aronsson and Löfgren 2002).

Hartman (1976) developed the framework further by including a flow of amenity values, *a(t)*, i.e. non-timber values, that occur throughout the whole rotation. Denoting the present value of the flow of amenity values *A*, gives:

$$A(T) = \frac{\int_0^T a(t)e^{-rt}dt}{1-e^{-rT}} \quad (3)$$

Assuming additivity, the total value of the forest is *W(T)=V(T)+A(T)*. The first order condition of the maximisation problem is:

$$W'(T) = 0 \Rightarrow R'(T) = r(R(T) + W(T)) - a(T) \quad (4)$$

It is seen that the difference between the Faustmann solution (eq. 2) and the Hartman solution (eq. 4) lies in the amenity value term *A(T)* and that this value is now also included in the value of the land *W(T)*. By comparison, it follows that if *a(t)* is a monotonically increasing (decreasing) function of stand age, then the optimal Hartman rotation is longer (shorter) than the Faustmann rotation (Bowes and Krutilla 1985, Hite et al. 1987). On the other hand, if *a(t)* is constant with respect to stand age, the Hartman rotation coincides with the Faustmann rotation (Bowes and Krutilla 1985).

Hartman (1976) derived the optimality criteria for this and showed that the rotation age will be shorter than if only considering one rotation. Jonsson and Jonsson (1992) compared the Hartman and Faustmann models and also showed that if *a'(t)*>0, i.e. amenity values are increasing with age, the rotation period will be longer than in the Faustmann case. Koskela et al. (2007) analysed the case of biodiversity values and found empirical evidence that including these values tends to increase rotation age.

In the present paper the possible components (non-timber values) of *a(t)* are described, and the empirical indications from the literature on functional forms for *a(t)* are analysed. It is assumed that the total value of a forest stand, *W*, is a function of both *V(T)* and several components of *A(T)*, which is used to reach the qualitative results regarding the optimal rotation.

The values from a multifunctional forest stand are assumed to depend on stand age. The value, *w*, of a stand is defined as

$$w(t) = R(t) + Re(t) + Be(t) + Ga(t) + Co(t) + Bi(t) + Wa(t) \quad (5)$$

where *R(t)* is the commercial value of timber production, *Re(t)* is the non-consumptive composite recreational value derived from public access, hunting and berry-picking, *Be(t)* is the biomass value of berries, *Ga(t)* is the biomass value of game meat, *Co(t)* is the value of sequestered carbon, *Bi(t)* is the value of biodiversity and *Wa(t)* is the value of water supply functions. Timber and non-timber values occur jointly, and the value components are interlinked by their dependence on stand age even if *w* is an additive function. The main focus of the paper is the general case where there is some degree of joint production of several of the components. This is the case for many Nordic forests, although some instances involve the more special case where all components are not present but where one or a few are maximized (e.g. biodiversity reserves without timber production and without public access).

Review of timber and non-timber values in Nordic forest rotations

Based on existing literature, the variables in eq. (5) and their dependency on stand age will be described in the following. The focus is on empirical evidence from the Nordic countries. In some cases where literature for the Nordic countries was limited, relevant references from elsewhere were used. The results are summarised in Table 1 and Table 2, which qualitatively describe the marginal value changes over time for spruce in the north and beech in the south. In the case of beech, two types of regeneration were considered, artificial and natural, i.e. with an upper storey the first 30 yr of a rotation. Only artificial regeneration after clear-cutting was considered for spruce. An estimate of the relative size of the given variable at the start of the rotation was also made, along with a ranking of the specific amenity according to its share of *w(t)*.

R(t): the commercial value of timber production

The commercial value of timber production, *R(t)*, is undoubtedly the most analysed forest good. The value is only realised when the forest is harvested. This is contrary to many amenities, where there is a continuous value flow throughout the entire rotation. Consequently, *V(T)* denotes the present value of timber production in a perpetual series of rotations, with a rotation age of $t = T$ years. For Nordic conditions, the rotation age for spruce is typically between 60 and 140 yr, and for beech between 80 and 120 yr. The timber value is typically increasing until the stand reaches these intervals, and decreasing in the old-growth forest (Klemperer 1996).

Re(t): the non-consumptive recreational value derived from public access, hunting and berry-picking

In the Nordic countries there are large forest areas that can be used by the public for non-consumptive recreation like

Table 1. The partial derivative signs (slopes) of the value function *w(t)* in multi-functional forestry: Case North, Norway spruce.

Components of the value function *w(t)*	Stand development phase, typical silvicultural measure, age interval					
	Starting point, 0 yr	New forest, artificial regeneration, 0–10 yr	Young forest, precommercial thinning, 11–30 yr	Middle aged forest, thinning, 31–64 yr	Old forest, final felling, 65–139 yr	Old-growth forest, 140+ yr
Timber, *R(t)* (42)[a]	Low	↗	↗	↗	→ (max)	↘
Recreation, *Re(t)* (1,2,3,4,5,6,7,31)[a]	Very low	↗	↗	↗	→ (max)	↘
Game meat , *Ga(t)* (8,9,10,11,12,13,14,44,45)[a]	Low	↗	↗	↘	↗	→
Berries, *Be(t)* (15,16,17,18)[a]	Low	↗	↗	↗	→ (max)	↘
Carbon, *Co(t)* (19,20,39,46)[a]	Very low	↗	↗	↗	↗	↗
Biodiversity, *Bi(t)* (21,22,23)[a]	Medium	↘	↘	↗	↗	↗
Water, *Wa(t)* (24,25,32,33,34,35,36,37,38,40,41)[a]	Low	↗	↘	↗	↗	↗

[a]Numbers in parentheses refer to references used to arrive at partial derivative signs, and are indicated by the corresponding numbers in superscript in the reference list.

Table 2. The partial derivative signs (slopes) of the value function *w(t)* in multi-functional forestry: Case South, beech.

Components of the value function *w(t)*	Stand development phase, typical silvicultural measure, age interval					
	Starting point, natural/artificial regeneration, 0 yr	New forest, natural/artificial regeneration, 0–10 yr	Young forest, precommercial thinning, 11–30 yr	Middle aged forest, thinning, 31–79 yr	Old forest, final felling, 80–119 yr	Old-growth forest, 120+ yr
Timber, *R(t)* (42)[a]	Low	↗/↗	↗	↗	→ (max)	↘
Recreation, *Re(t)* (1,2,3,4,6,7,31)[a]	Medium/Low	↗/↗	↗	↗	→ (max)	↘
Game meat , *Ga(t)* (26,27,13,28,29,43,44,45)[a]	Medium/Medium	↗/↗	↗	↘	↗	→ (max)
Berries, *Be(t)* (30)[a]	Very low/Very low	→/→	→	→	→	↘
Carbon, *Co(t)* (19,20,39,46)[a]	Very low/Very low	↗/↗	↗	↗	↗	↗
Biodiversity, *Bi(t)* (21,22,23,47)[a]	Medium/Medium	↘/↘	↘	↗	↗	↗
Water, *Wa(t)* (24,25,32,33,34,35,36,37, 38,40,41)[a]	High/Medium	↗/↗	↘	↗	↗	↗

[a]Numbers in parentheses refer to references used to arrive at partial derivative signs, and are indicated by the corresponding numbers in superscript in the reference list.

hiking and camping, thus making such forests important from the perspective of multi-purpose forestry (Hytönen 1995). The recreational value varies considerably depending on tree species and age of the stand, i.e. features typically resulting from the timber producing forestry (Mattsson and Li 1994). Beech can be regenerated naturally as well as artificially, while the latter alternative is dominant in spruce forestry (Bjerregaard 1979, Nilsson et al. 2005, Röhrig et al. 2006), due to natural site conditions. This has implications for the recreational value. In general, a beech stand is more preferred by recreationists than a spruce stand (Jensen and Koch 1997, Aakerlund 2000), which also seems to hold true for broadleaved trees and coniferous trees in general (Mattsson and Li 1994, Bostedt and Mattsson 1995). Additionally, a newly regenerated stand is normally much less preferred by recreationists than an old one (Holgén et al. 2000). On the other hand, if the stand becomes old-growth containing dead and fallen trees the recreational value may decrease (Savolainen and Kellomäki 1984, Lindhagen 1996, Jensen and Koch 1997, Gundersen and Frivold 2008). Natural based regeneration systems seem to produce higher recreational values than artificial regeneration (Mattsson and Li 1994, Jensen and Koch 1997). The increase in the recreational value between a young and a middle aged stand seems to be larger in the case of spruce (or other coniferous trees) than in the case of beech (Mattsson and Li 1994, Lindhagen 1996, Jensen and Koch 1997), which indicates that the increase in *Re(t)* with increasing age of the stand is non-linear.

The total value derived from hunting is assumed to consist of a non-consumptive recreational value, and a consumptive value represented by the value of harvested game meat (see next section). The non-consumptive recreational experience of the typical hunter is assumed to be similar to the recreational experience of any other forest recreationist, and is therefore subsumed into the general recreational value *Re(t)*. Empirical studies from Denmark and Sweden have shown that the non-consumptive value is the largest component of the total recreational value derived from hunting (Mattsson 1990, Lundhede et al. 2009). Similar to hunting, the non-consumptive recreational value from berry-picking is assumed to follow the general pattern *Re(t)* of forest recreationists. Based on the reviewed literature, it could be concluded that the recreational value is generally higher in the beech stand than in the spruce stand. For both stand types, the literature suggested that the recreational value is increasing with stand age until the stand reaches the old stage and thereafter begins to decrease. The consumptive biomass values of game meat and berries are described in the upcoming sections.

Ga(t): the biomass value of game meat

The biomass of game in the stand at different phases of the rotation represents the potential harvesting opportunities of game meat, and therefore determines the biomass value of game meat to the hunter. Forage and cover are two important factors determining the availability of game in the stand (Rose and Chapman 2003). Forage is more abundant at the early stage of the rotation, whereas cover increases as the stand matures. This affects the game species adapted to different phases of the stand age, and consequently the associated biomass values. Edenius et al. (2002) show that on a national level in Sweden, there is a positive relationship between moose harvested and the percentage of young forests (3–30 yr old). In a Norwegian study, Mysterud et al. (1999) found that roe deer selected mature spruce stands as the most preferred habitat type, whereas clear-cuts were typically least preferred, with other development stages being intermediately preferred. Looking outside the Nordic countries, this finding is also supported by Latham et al. (1996) in a study of red and roe deer population densities in 20 conifer plantations throughout central and northern Scotland. Findings by Gill et al. (1996) and Radeloff et al. (1999) suggest that beech (and oak) stands form a better habitat for roe deer than spruce stands. This conclusion was also drawn for Danish conditions by Olesen et al. (2002), who found that the density of roe deer was negatively correlated with the share of conifers in the landscape. For North American conditions, Meier et al. (1996) report that opening of the tree canopy increases the light and thus the abundance of food for white-tailed deer. Findings by Dahl (2005) suggest that mountain hares prefer young stands during the hunting season in the autumn and winter, whereas Borchtchevski et al. (2003) found that mountain hares were more abundant in a logged forest than in a pristine forest. Jansson and Pehrson (2005) found brown hares predominantly in 20–50 yr old thinning forests. The species of coniferous forest birds utilize different successional stages ranging from willow grouse in the young forest, over black grouse and hazel-hen in the young and middle aged forests, to capercaillie in the old forest (Angelstam 1994).

In Sweden, about 80% of the total harvest of game meat comes from moose and roe deer, the next most important game species in terms of meat being hare and forest birds (Mattsson 1989, 1990). These species are also the most extensively hunted in terms of hunting days (Mattsson et al. 2008). Given the previous ecological findings, it was therefore assumed that the biomass value of game meat for the spruce stand increases and peaks when the stand reaches an age of 30 yr mainly due to the increasing abundance of moose meat. Thereafter, the abundance of moose as well as the value of game meat decreases until the stand age of 50 yr. This outweighs a possible increase in the meat value of the hare population in this age interval. The meat value then increases again due to increasing abundance of roe deer and finally levels out as the stand reaches the old-growth stage.

For the southern beech forests, the situation in Denmark is probably the most relevant reference. The main harvested game species in Denmark in terms of biomass are roe deer, fallow deer and red deer (Asferg 2002). Hare is also a common game species in Denmark. Among forest birds, common wood pigeon is harvested in the greatest numbers. The greatest contribution to game biomass value in the beech case is therefore assumed to come from the three deer species. The biomass value of game meat in a beech forest is assumed to follow the same pattern as for Norway spruce as it peaks when the stand reaches an age of 30 yr, mainly due to increasing abundance of roe and red deer meat. Thereafter, the abundance of deer as well as the value of game meat decreases until the old forest phase, when the meat value increases again due to increasing abundance of undergrowth and browsing vegetation for the deer. It finally levels out as the stand reaches the old-growth stage. Based on the ecological literature reviewed, it can be concluded that the general deer habitat quality, and therefore meat value production capacity, is greater in the beech stand than in the spruce stand. As illustrated in Table 1 and 2, there is an increase in game meat value for both spruce and beech in the first years of the rotation, followed by a decrease until the mature period.

Be(t): the biomass value of berries

Picking wild berries in forests has been practiced by many inhabitants in the Nordic countries since the ancient times. It seems, however, to have decreased in Sweden and Norway in recent decades (Vorkinn et al. 1997, Lindhagen and Hörnsten 2000). Still, berry-picking is considered to be important, especially in Finland (Saastamoinen et al. 2000, Kangas 2001), but having less importance in Denmark due to a more limited public access (Plum 1998).

As for most other non-timber forest amenities, the production of berries is dependent on tree species and age of the stand. According to an overview by Kellomäki (1984) focusing on northern forests dominated by coniferous trees, the production of berries is high in the beginning of the rotation period and when the forest is old. Kardell (1980) made a more detailed study concerning the same kind of forests, specifically taking into account lingonberry (cowberry), bilberry and raspberry. The former species being the most important and the latter the least important with regard to quantities collected and traded (Kardell 1980, Kangas 1999, Saastamoinen et al. 2000). Kardell's results showed an increase in the production of raspberries in the newly regenerated stand, but decreasing again after a few years. On the other hand, the production of bilberries increases very significantly from the stand being newly regenerated, and has reached the highest level when the stand is old, then tending to decrease as the stand is becoming old-growth. Lingonberries show a similar pattern in the production throughout stand ages, but not as pronounced as bilberries (Kardell 1980). The market price of lingonberries is about double as that of bilberries (Kangas 1999). Since most of the raspberries consumed do not originate from "forest-picking" but from artificial cultivation, the market value of the forest berries is very much dominated by lingonberries and bilberries. Information on berry production in beech forests in the Nordic countries is not that easy to obtain. A study from Belgium by Godefroid et al. (2005) shows that the probability of occurrence of blackberries in beech forests is between 0.6 and 0.7 from when the stand is newly regenerated until the stand is old, but is decreasing in the old-growth stand. However, this tells little about the level of production of blackberries. Furthermore, because of similar reasons as for raspberries, the market value of blackberries as well as other berries from beech forests in the Nordic countries can be assumed to be very low. It can be concluded that in general the production of berries is greater in the spruce stand than in the beech stand. The production and the value increase with increasing stand age in spruce, but not in beech, and tend to decrease in old-growth stands for both.

Co(t): the value of sequestered carbon

Forest ecosystems can be important in sequestering carbon. The amount of carbon sequestered in forest vegetation and soil can be affected by changing forest management practices, such as changing the rotation period or the frequency and size of thinning interventions in a stand. In addition to net carbon storage in timber, branches and needles, the forestry carbon cycle should, in principle, include net storage in the forest soil, forest products and emission originating from the decay of these products (Gutrich and Howard 2007). Generally, the rotation age is expected to increase when including the carbon storage value in the Faustmann model (Liski et al. 2001). Emissions from the decay of forest products will involve the release of carbon. Various approaches have been suggested to take this into account, either by specifying the release as a constant proportion of the total amount sequestered, or as a decay function of the product life after the timber is harvested (van Kooten et al. 1995, Price et al. 1997). Creedy and Wurzbacher (2001) define the proportion released as a function of stand age. This has to be subtracted from the production over the rotation. Thus, the carbon sequestration value increases over the rotation, tending to level out if the stand is kept long enough for substantial natural decay to set in.

Bi(t): the existence value of biodiversity

Biodiversity is often seen as a specific objective in multipurpose forestry and several studies point out its importance for the non-timber values of forestry. Biodiversity in forests is, to a large extent, influenced by the frequency and size of the disturbance (Barnes et al. 1998). Dead wood is often seen as playing a major role (Ranius et al. 2003, Ódor et al. 2006) for many threatened species for which conservation is an important issue. The presence of dead wood will not be explored separately here, but it is assumed that in a productive forest stand there will also be a certain amount of dead wood, as found in Sweden by Ranius et al. (2003). It is generally accepted that older stands yield higher biodiversity benefits than younger stands (Koskela et al. 2007, Brunet et al. 2010). Fritz et al. (2008) found significantly higher number of lichens and bryophytes in old stands than in young stands in Swedish beech forests, whereas Vehviläinen et al. (2008) found mixed results for different tree species and predatory arthropods in Finland, Sweden and the United Kingdom. Ranius et al. (2003) analysed coarse woody debris (CWD) for different stand characteristics as it is a key feature for preservation of many endangered species. They also found increased CWD by stand age, but most notably the lowest CWD for middle-aged stands.

Species abundance and composition may depend on the successional stage of the stand. For deciduous and coniferous stands, Harrelson and Matlack (2006) showed that species lacking obvious seed dispersal mechanisms are disproportionately uncommon in young stands, but tend to be more frequent in old stands. Bütler et al. (2004) found that the probability of the presence of three-toed woodpeckers increased from 0.10 to 0.95 when snag basal area increased from 0.3 to 0.5 m^2 ha^{-1} in central Sweden. Hence, recolonization of species in early successional stages may result in higher biodiversity compared to middle-aged stands, and lower than compared to old stands with higher contents of CWD and biodiversity adapted to late successional stages.

A number of environmental valuation studies show that the value to the public of species preservation is significant (Loomis and Gonzalez-Caban 1998, Hailu et al. 2000, Jacobsen et al. 2008). Based on these studies it is assumed, for both the spruce and beech examples, that the value of biodiversity is higher in the old than the young stand, and generally decreasing from the early regenerated stand towards the middle-aged stand, and increasing towards the old-growth stand (Bütler et al. 2004, Brunet et al. 2010).

Wa(t): the value of water supply and quality

Forest ecosystems are important providers of clean drinking water, in particular when located close to larger cities where the demand and scarcity of water may be high. A number of studies show that the choice of tree species and forest management regimes may affect the water yield. Outside the Nordic countries, Bosch and Hewlett (1982) investigated 94 catchment experiments and concluded that thinning and clear felling can be used as management tools to increase the water yield from a stand. Similar results were found by Whitehead and Kelliher (1991) and Fahey (1994), and by Holstener-Jørgensen (1959, 1961, 1967) for Danish forest stands. The water yield peaks just after final timber felling and regeneration, when the loss caused by interception of the growing stand and vegetation is low. After the peak, the water yield decreases as a function of increasing timber volume, transpiration and interception of the stand. Shiklomanov and Krestovsky (1988) generalised the functional form of water yield during a rotation. The water yield increases by ca 60% immediately after clear felling, and decreases for the following 40 yr, when it starts increasing again. This pattern is very similar to the predictions in Kuczera (1985).

Forests and forestry affect different dimensions of water quality. Creedy and Wurzbacher (2001) investigated the water benefits in terms of water yield provided by an Australian ash forest. These water benefits were found to be decreasing until about 30 yr of age, increasing thereafter, and finally stabilizing at the maximum value when the forest reached > 200 yr of age. Rothe and Mellert (2004) studied nitrate concentrations in water samples from spruce and beech stands in Germany, finding a clear age-related pattern for spruce stands. In young stands (<40 yr of age) nitrate concentrations were negligible, but higher in older stands. Nitrate concentrations in beech stands were found to be lower than in spruce stands and independent of age. Moreover, concentrations were higher in clear-cut areas than in areas treated with e.g. group selection or single tree selection. Hansen et al. (2007) suggested that nitrate leaching from forests on former arable land is decreasing during the stand establishment phase (up to 20 yr of age), increasing thereafter and stabilizing above 40 yr of age. They also found a greater leakage from oak than from spruce stands. For Swedish coniferous stands, Akselsson et al. (2007) found an increased leakage of nitrogen up to two years after final harvest, with greater leakage after clear-cutting than in a shelterwood stand. They also found higher concentrations of some other nutrients in groundwater from clear-cuttings than in shelterwood stands. Taken together, these findings suggest that water yield and water quality in terms of nitrate concentrations, to a certain extent move in opposite directions during the rotation. The joint effect on water value is therefore assumed to be increasing during the first ten years (because of increasing water supply until year 10 and a nitrate leakage that peaks already after 2 yr), decreasing during the next 20 yr (due to decreasing water yields when the new stand establishes and increasing nitrate), and increasing thereafter (due to increasing water yields and a stabilised nitrated level after 40 yr). A similar pattern, but at a higher value level, was assumed for artificial regeneration of beech due to lower nitrate leakage from a beech stand. An even higher value level was assumed for natural regeneration of beech, due to lower nitrate leakage without clear-cutting.

Discussion

The previous sections have investigated the production and values of different forest goods and services in a Nordic context, and how they change over the life-time of a stand. Since the values of forest goods and services may be uncertain (Conrad 1997, van Kooten et al. 2001), a simplified approach is applied that captures value changes over the rotation period and value weights of forest goods and services. The different value changes over the rotation are compared and an example of a weighting of the values is given.

Relative changes in value over time

Figure 1 shows the value of each amenity relative to its maximum, for the example of a beech stand with artificial regeneration. Owing to a lack of more precise information, changes are described in a schematic way. A decrease corresponds to half the previous value and an increase to double the previous value. This decrease or increase may be indicated over two periods if the literature provides evidence for it, thus the value in between is an interpolation. Furthermore, each amenity is seen independently from the others. The optimal rotation age with respect to timber production alone is found when the stand reaches its old phase, and the farther the stand deviates from that rotation age, the higher the economic losses. All the other goods and services have output flows during the rotation. It is evident that the carbon sequestration value is continuously increasing over the rotation, and so too is the biodiversity value from when the stand is middle aged and onwards. Thus, managing the forest with considerations for these additional services would tend to increase rotation age as compared to the management based only on timber production. The value of berry production is constant throughout the rotation and will therefore not affect the decision of when to harvest. Recreational value is also found to increase as the stand age increases, though it does not continue once the forest reaches the old-growth phase. Thus, if the objective of the forest management is recreation, the rotation age may be similar to that of when only timber production is considered.

At a young stand age, the value of water is high and increasing, followed by a decrease, and then increasing again. The value function depends, however, on both the quality and the quantity of water. Depending on the local importance of each of these factors (i.e. which of them is the most scarce), the dynamics of the value function over time may vary considerably. There may be situations where two or more different rotation ages could lead to the same water value, since the value function may exhibit multiple maxima. A similar pattern can be found for the value of game meat.

Beech was used as an example, but it follows from Table 1 and Table 2 that many of the goods and services tend to vary in the same way over the rotation for spruce and beech, the exception being berries. The absolute value levels also differ between amenities (as indicated by the starting points in Table 1 and 2), which highlights the importance of value weights.

Assigning value weights to goods and services

Figure 1 illustrates the relative value for each amenity as compared to the maximum obtainable value, but in order to find the optimal rotation age it is necessary to look at the slopes of the different curves as well as their absolute

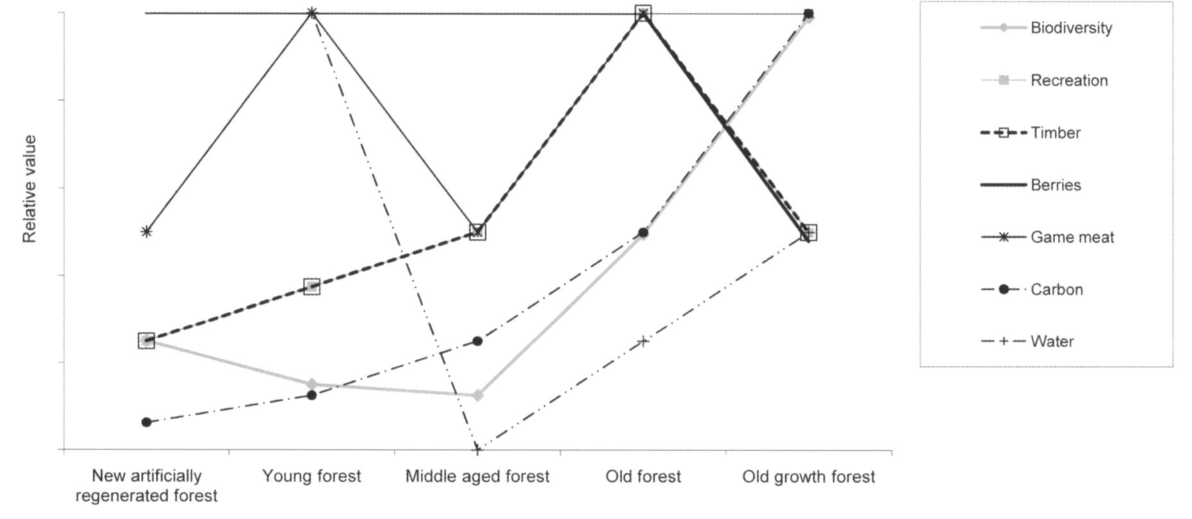

Figure 1. Relative value of each amenity, for the example of a beech stand with artificial regeneration. The value is depicted in relation to the value at the time during the rotation when it is at its maximum.

positions. Table 3 displays estimates of the different values for a typical beech stand, originating from various literature sources. The proportion of each amenity value out of the total value of all amenities can be assigned as a weight to the relative value from Fig. 1. This value-weighted comparison is illustrated in Fig. 2. This should not be seen as an exact result but rather as an illustration of how such a weighting could be done. At young ages, water is the most valuable amenity, whereas biodiversity and carbon sequestration services become more valuable later in the rotation. Recreation is also more valuable later in the rotation, although less valuable in old-growth stands. It should be emphasised that many of the estimates from Table 3 are uncertain. Norman et al. (2010) find recreational values that are up to 10 times higher than the estimates used here.

The weights used in Table 3 and Fig. 2 are based on production as seen from societal interests at large. Depending on the ownership of a forest and the stakeholders involved, the weights of the goods and services may vary. It is noteworthy that rotation ages in the Nordic countries are normally longer than the economic optimal according to the Faustmann criterion. One reason may well be that forest managers more or less explicitly (often by legal requirements) take non-timber goods and services such as biodiversity into account. It is also important to look at these aspects not only within stands, as done in the above section, but also between stands and at landscape level. The quantity and quality of drinking water in urbanized regions can be affected significantly by land use, choice of tree species and rotation age. A study by Hansen et al. (2008) on the water balance in eight Danish forests shows that 75% of the precipitation is evapotranspired in spruce stands, while in oak and beech stands it accounts for 58% and 65%, respectively. Therefore, it is important to discuss the value weights of amenities and the implications for stand, forest or landscape level decisions. In addition, it is important to decide whether these amenities should be provided from specific or uniformly distributed areas.

Conclusions

This paper has compared existing knowledge of a variety of goods and services from forests in a Nordic context. The evidence has been used qualitatively to show how the choice of tree species and rotation age may influence the value of a forest stand in a multifunctional setting. It was found that the values vary considerably (and often in a non-linear way) throughout a rotation, and that these dynamics need to be taken into account when evaluating multiple-use forestry decisions. Some amenity values tend to increase the economically optimal rotation age, whereas others tend to decrease it. Including services like biodiversity and carbon sequestration would tend to favour longer rotation ages, as compared to consideration of only timber production. Conversely, water production may favour shorter rotations. For some areas, an increase in total value might be obtained by converting spruce forests to beech forests owing to the amenity values of biodiversity, recreation, water and game. This, however, is not the case for the value of berries. Transferring these stand-level observations to the forest level raises the question of whether joint production on all areas is preferable or whether some specialisation of production would be preferable.

For each individual stand the aim, in principle, is to maximise the production of all amenities. But when including multiple stands, one needs to consider under which circumstances is multiple-use in each stand superior to specialisation of one particular use in a given stand. Another issue is the resulting change in the optimal rotation decision. Vincent and Binkley (1993) showed that domi-

Table 3. Example of assigning weights to the different goods and services.

Service	Total annual value (Euro) ha^{-1}	Source	Important assumptions	Proportion of total value
Biodiversity	376	Danmarks statistik et al. 2002, Jacobsen et al. pers. comm.	Stated preference study, improvements for biodiversity in all forests in Denmark	0.29
Recreation	198	SCB 2001, Zandersen et al. 2007	Lower estimate from Denmark, almost equal to average result from Sweden	0.15
Timber	99	SCB 2001	All forests in Sweden	0.08
Berries	0	–	Very low value, assumed (almost) zero	0.00
Hunting	67	Meilby et al. 2006	Forests in eastern Denmark	0.05
Carbon	293	Danmarks statistik et al. 2002, European climate exchange 2009	Broadleaved forest in Denmark, and a carbon price of 15 Euro ton^{-1}	0.23
Water	247	Bastrup-Birk et al. 2003, Lundhede and Hasler 2005, Statistikbanken 2009	Broadleaved forest in eastern Denmark, value is based on a stated preference study and statistics on amount of consumption	0.19

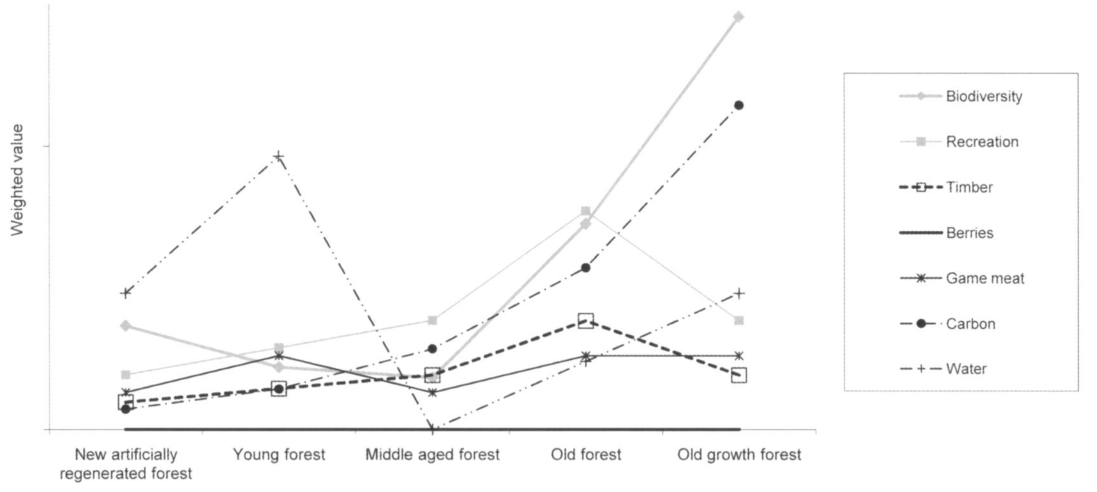

Figure 2. Example of assigning weights to the relative values from Fig. 1, for the example of a beech stand with artificial regeneration. The used weights are from Table 3.

nant use (specialisation) can be superior to multiple-use even when the stands in a forest are identical, if timber and non-timber production are not equally responsive to management efforts. Zhang (2005) revisited the Vincent and Binkley paper arguing that while their results may be correct, their reasoning is not. Constraints on input factors (including time), cross-spatial interaction at forest level or ownership-level (Swallow et al. 1997, Boscolo and Vincent 2003), changes in technology and relative prices, and ecological and economic thresholds of production and management are additional reasons that warrant specialisation.

Cross-spatial interactions between neighbouring stands are well known. Timber harvest may negatively affect the habitat for biodiversity hosted in adjacent stands, or recreational possibilities. An important question on stand level, regional or national level is to what extent production of timber and ecosystem services should become specialized. Zhang (2005) concludes that for some areas timber production has a comparative advantage, while in others, providing environmental outputs has comparative advantages. In areas between these two extremes, joint production may be more efficient. Boscolo and Vincent (2003) and McCarney et al. (2008) show how uniform management across stands may be superior for the joint production of timber and carbon sequestration, while specialized management might often be superior for the joint production of timber and biodiversity. Similar patterns could be expected in a Nordic context with differences in production potential between sites, e.g. it may be optimal to produce timber and sequester carbon on rich soils, and berries and biodiversity on poor soils. In order to model this, the responses of each good or service to soil quality and management decisions would need to be quantified. Moreover, there is a need to quantify not only the biophysical response but also the value response. This is an important and challenging task for future research.

A lack of knowledge on amenity values and their relations to stand characteristics may be part of the reason why sufficient levels of ecosystem services are not always obtained. This is an important aspect of future applied research as it could help decision makers determine the implications of different policies. The current review may be helpful in facilitating conceptual discussions between researchers from different disciplines, stakeholders and decision makers. This may, in turn, help to reach a mutual understanding about the trade-offs involved in multiple-use forestry. The contribution of this paper is therefore mainly pedagogical, while explicit solutions to the harvesting problem in multiple use forestry remains important for future research.

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