Assessments of Diameter Growth and Optimal Rotation Length for Even-aged Spruce Sites in Estonia

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Abstract

Optimal rotation length of even-aged spruce forests is under discussion in Estonia. Thus far no single criteria is accepted to determine the rotation length. Moreover, the rotation length is affected by a repertoire of stand-level variables. A previous estimate of optimal rotation length was assessed through simulation of stand development by static and dynamic model components. However, such results depend on the model components added to the system that predicts the development. Here we investigate the cumulative diameter growth of Norway spruce in twelve stands throughout Estonia. Our analyses are based on actual tree-ring growth data, measured and rigorously validated to generate mean radial increment for each of the studied stands. Using the tree-ring data, we are not only able to estimate the time it takes for a tree to attain certain diameter that allows regulatory felling, but also to determine the optimal rotation length based on the assumption that the observed radial growth rate is a longtime variate that is specific to a given site. The interrelationship between the diameter growth and rotation length was used when estimating the optimal rotation length for each stand, that is, the lower the diameter growth the longer the optimal rotation length. Cumulative diameter growth showed a relatively rapid increase to a phase of maximum growth increment, with a subsequent decrease towards a phase of considerably slower growth. It appeared that the regulatory felling age of spruce stands yields a near-maximum sum of diameter growth in a variety of Estonian spruce stands. In specific circumstances, such as diverging regulatory and optimal cutting age, a reduction of rotation length may be justified.

Keywords: Norway spruce, felling age, diameter growth, growth increment, saw logs.

Introduction

Forest management planning is typically aimed towards different functions and values. Owing to multiple objectives and constraints, there is usually no single solution to universally resolve all management concerns (Korjus 2014). Obtaining the most profitable economic value can be seen as one, but not the only forest management motive (van Kooten et al. 1995, Tahvonen 1999, Posavec et al. 2011, Piekutin and Skręta 2012, Põllumäe et al. 2014). Nevertheless, the felling age of different tree species has for long been a subject of discussion in forestry literature (Chang 1984, Tahvonen 1999, Brazee and Dwivedi 2015). Trees of different species have different growth rates in different forest site conditions, and the felling age is inherently related to parameters quantifying these conditions. The official felling ages are determined for the main forest tree species in Estonia under the Estonian Forest Law (Forest Act 2006, Metsaseadus 2006) and in appropriate regulations. For Norway spruce (*Picea abies* (L.) Karsten) the felling age is reached at tree age of 80 years at breast height or at trunk diameter at breast height (DBH) of 26 cm, whichever is reached first on sites possessing 1A, 1 and 2 quality class (Metsa majandamise… 2007). Since 2014, the actual cutting age of a forest plot is calculated from corresponding measures for different tree species, weighted by the proportion of the species (Forest Act 2006, Lamp 2014, Metsaseadus 2006). Modelling by using the Finnish stand simulator MOTTI (Hynynen et al. 2005; Salminen et al. 2005) was recently used to show that optimal rotation length for a spruce stand was 53 years (Korjus et al. 2011). As acknowledged by those authors, further studies and alternative approaches, preferably using actual data on growth and yield data from Estonia, are needed before large scale application of their results on rotation lengths are implemented. Our study is based on the premise that tree-ring data may well serve a feasible alternative for estimating the rotation length. In fact, tree-ring analyses provide non-destructive and retrospective biomonitoring tools for producing growth data with annual accuracy (Spiecker 2002). An additional factor increasing the favourability of tree rings for analyses of the felling age is that the sample trees are commonly cored at breast height (1.3 metres above the root collar) (Laas et al. 2011). Thus, the tree-ring based estimates of diameter growth can be readily compared with the regulatory felling age, which is determined from a trunk diameter at the same height. The principle of sustainable forest management designates that biodiversity, ecological, economic and social functions of forest are maintained, the forest management thus ensuring the productivity levels in the future (Sustainable… 2016). Combining this principle of sustainability with the dendrochronological principle of uniformitarianism (Kaennel and Schweingruber 1995: 374), it is possible to further estimate the diameter increment over a series of consecutive rotations. Calculating the highest possible number of rotations, each of the rotations achieving the mean DBH of 26 cm, over a long period of time, we are finally able to compare the site-specific estimates of optimal rotation length with the regulated rotation length in Estonia. In this study we did not aim to deal with the other aspects of sustainable management of forests, including biodiversity, regeneration capacity, vitality and relevant ecological, economic and social functions (Schuck et al. 2002, Hansson et al. 2012).

The main objective of this paper is to demonstrate how the elevation of cutting age (and rotation length) would change the DBH during a course of rotations. Secondly, we aimed to study the optimal cutting age of even-aged spruce forests. Thirdly, the results were compared with the regulatory cutting age as officially determined under the Estonian Forest Law.

Materials and Methods

Tree-ring material for this investigation were collected from twelve spruce forest stands over Estonia (Figure 1, Table 1, Helama et al. 2016). The stands were chosen because of the age maturity of the trees and higher quality classes (1 and 2). The stands represent a small number of forest site types for comparability (Lõhmus 2004). From each stand, at least ten dominant or co-dominant healthy trees were sampled with increment borer at breast height (1.3 metres from the root collar). Widths of consecutive tree rings were measured under light-microscope to the nearest 1/100 mm using the Lintab measuring system

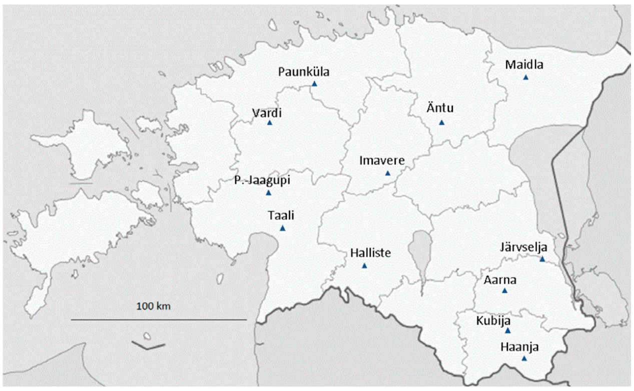


Figure 1. Location of the spruce sample sites in Estonia

Table 1. Rotation age (years at breast height) and corresponding diameter at breast height Ø (in brackets, cm) determined according to the Estonian law (regulatory), for logs (Ø = 18 cm) and based on sum of diameters (maximum ΣØ) for analysed Norway spruce stands in Estonia

Site name and type (Lõhmus 2004)		Regulatory cutting age (Ø)	Ø = 18	maximum ΣØ	ΣØ > 95% maximum ΣØ	ΣØ > 90% maximum ΣØ
Aarna	*Myrtillus*	53 (26)	43	34 (19)	24-60 (14-29)	20-78 (12-34)
Äntu	*Hepatica*	67 (26)	56	77 (30)	50-129 (20-46)	39-149 (15-50)
Haanja	*Oxalis*	59 (26)	45	24 (14)	18-42 (11-21)	14-62 (9-27)
Halliste	*Hepatica*	53 (26)	44	52 (26)	27-75 (15-34)	20-95 (11-39)
Imavere	*Hepatica*	69 (26)	55	36 (16)	24-83 (11-30)	17-127 (8-42)
Järvselja	*Myrtillus*	56 (26)	50	87 (40)	54-…* (25-…*)	45 (21-…*)
Kubija	*Myrtillus*	78 (26)	66	111 (37)	68-…* (23-…*)	55-…* (18-…*)
Maidla	*Myrtillus*	80 (14)	118	97 (16)	34-127 (6-20)	26-217 (5-32)
Paunküla	*Hepatica*	52 (26)	41	38 (22)	23-48 (14-25)	19-…* (12-…*)
Pärnu-Jaagupi	*Hepatica*	41 (26)	36	34 (23)	23-46 (16-28)	19-57 (14-32)
Taali	*Aegopodium*	80 (26)	53	24 (12)	17-40 (10-17)	14-50 (8-20)
Vardi	*Hepatica*	39 (26)	32	22 (19)	15-32 (14-23)	13-42 (12-27)

*Not established

(Rinntech 2006). Ring-width series were analysed in TSAP-Win (Rinntech 2006) and Cofecha (Holmes 1983) programs in order to identify possible measurement errors and missing rings (Grissino-Mayer 2001). Subsequent to this process of dendrochronological cross-dating, the synchronised ring-width series of each sample plot were arranged according to their cambial age, that is, aligned according to the pith ends of the ring series, preceded by ten years (Figure 2, a) during which the spruces were expected to reach the breast height. Here the calculations are exemplified by the data from Pärnu-Jaagupi stand.

This estimate of 10 years is supported by the forestry literature. As shown by Möls and Pihu (2004), young spruces in Estonia attain height of about 1.3 m (i.e. the sampling height) in 10 years. This age is similar in other countries as well, e.g. 15 years in north-eastern Poland (Bruchwald and Michalak 1984). We note that the estimate of 10 years is rather conservative, as the advance regeneration of spruce after clearcutting may attain the height of 1.3 metres even earlier due to site quality differences (Metslaid et al. 2005). The resulting mean ring-width series (Figure 2, b) approximate the ageing curve of spruce diameter growth in each of the studied stands. In a few cases, an outlier or a distinctively longer tree-ring series with deviating tree-ring growth patterns was eliminated from the assemblage before averaging. Diameter growth was attained as a cumulative sum of mean ring-widths of the ageing curve, multiplied by two (opposite radii), for incremental cambial ages. The resulting graph shows the trunk diameter increment as a mean of sample trees in each stand (Figure 2, c).

This approach allows us to calculate a total diameter growth in a thousand years timespan for any possible rotation length (Figure 2, d). Along with the regulatory felling age of 80 years at breast height (arrow A), and with the regulatory felling when the DBH of 26 cm is reached (arrow B), the two horizontal dashed lines show the 95% (higher line) and 90% from the maximum sum of trunk diameters. The rationale of the latter percentage is that the error of diameter measurement must not exceed 10% (Metsa ja puidu mõõtmise… 2013). As a result, the rotation length, with which the maximal diameter growth is attained, can be shown (here in a two hundred years section, Figure 2, e). The respective felling age, with which the maximal diameter growth is reached at a site, can be determined (arrow C).

For the timber industry the logs of certain dimensions (assortments) are required. The acknowledged minimum sawlog diameter in Estonia starts from 16 or 18 cm (Jänes 2004, Metsa- ja puidu mõõtmise… 2013). High quality logs are sold for the highest price among all wood assortments, as small dimension logs with diameter 12-(16)18 cm earn lower price (ibid.). The biggest log diameter is not prescribed by law, but a standard circular saw frame can process up to 40 cm diameter logs (Soovik 2013), while pre-peelers of log can treat up to 35 cm diameter timber (Ritsu 2014). Very large diameter logs occur seldom in Estonia and they have a specific use only. Therefore the cutting ages, according to the diameter limits of small (12-18 cm) and conventional log (18-35 cm) sized sawlogs, are shown in the graphs of the diameter sums (Figure 3).

Assessments of diameter growth and optimal rotation length were derived for each of the 12 stands (Figure 3). Site-specifically, the rotation length (see the horizontal axis shown in Figure 3) is contrasted by the respective sum of trunk diameter (see the vertical axis in Figure 3) expecting a maximal number of successive clearcuts during an arbitrary period of 1000 years. In so doing, the rotation begins with a 10-year renewal period with subsequent calculations carried out on the basis of breast height measurements (Apuhtin and Jõgiste 2005). This metric, i.e. cumulative diameter increment, was used as it describes the diameter growth of trees from tree-ring data.

Alongside the log dimensions, quality of round-wood depends on a number of other features, e.g. number of knots, presence or absence of rot, curvature etc. According to the values of these parameters, round-wood is divided into various quality classes (Uus and Jänes 1998). Here we pay attention on a quality parameter measured by the density of tree rings. Quality classes of spruce round-wood state that in the 1st quality class there must be at least 20 tree rings in the first 6 cm section of radius from the pith, while the 2nd and 3rd quality class wood can contain at least 12 tree rings in the innermost 6 cm of the radius (ibid.). Density of tree rings is related to wood density, that in turn plays a role in wood strength and solidity (Saarman 1998, Trendelenburg 1955).

Results

A hypothetical felling age for which the maximal diameter growth is attained during any given interval of time (here, 1000 years) is given for each stand. For most of the stands, the cumulative diameter reaches its maximum level well before the breast height age of 80 years. Subsequent to the this maximum phase, the slowly decreasing state of diameter growth becomes obvious. The stands representing exceptions to this rule, Järvselja and Kubija, exhibit slow growth of young spruces not followed by the maximal diameter growth until much later breast height age. Yet another exception is evident for the stand of Maidla, where the long age of the trees enabled to draw out the graph line up to 234 years, where the spruces have grown slowly during most of their lifetime, and where the maximal diameter growth is less than half of that attained in the other sites. All these three stands belong to *Vaccinium myrtillus* site type characterized by poorer soil fertility conditions than *Hepatica* and *Aegopodium* site types.

The regulatory felling age of spruce, 80 years at breast height (i.e. rotation length of 90 years), postdates the maximal diameter growth in most of the stands (Table 1). Nevertheless, the felling age of 80 years is not applied, when the trees achieve a diameter of 26 cm at younger age. Our tree-ring approach enabled to point the age of the threshold (DBH > 26 cm) specifically for each stand. It is notable that the spruces reached this DBH threshold before the age threshold in altogether ten stands (for one stand, Kubija, the two thresholds are very close to each other). In the stand of Taali, both thresholds are close to each other and take place much later the maximal diameter growth had been attained. This means that the regulatory diameter threshold is reached sooner in most of the stands than the age threshold.

In most cases the difference between the ages of attaining either the diameter of 26 cm or maximal diameter growth does not play an important role: the diameters are

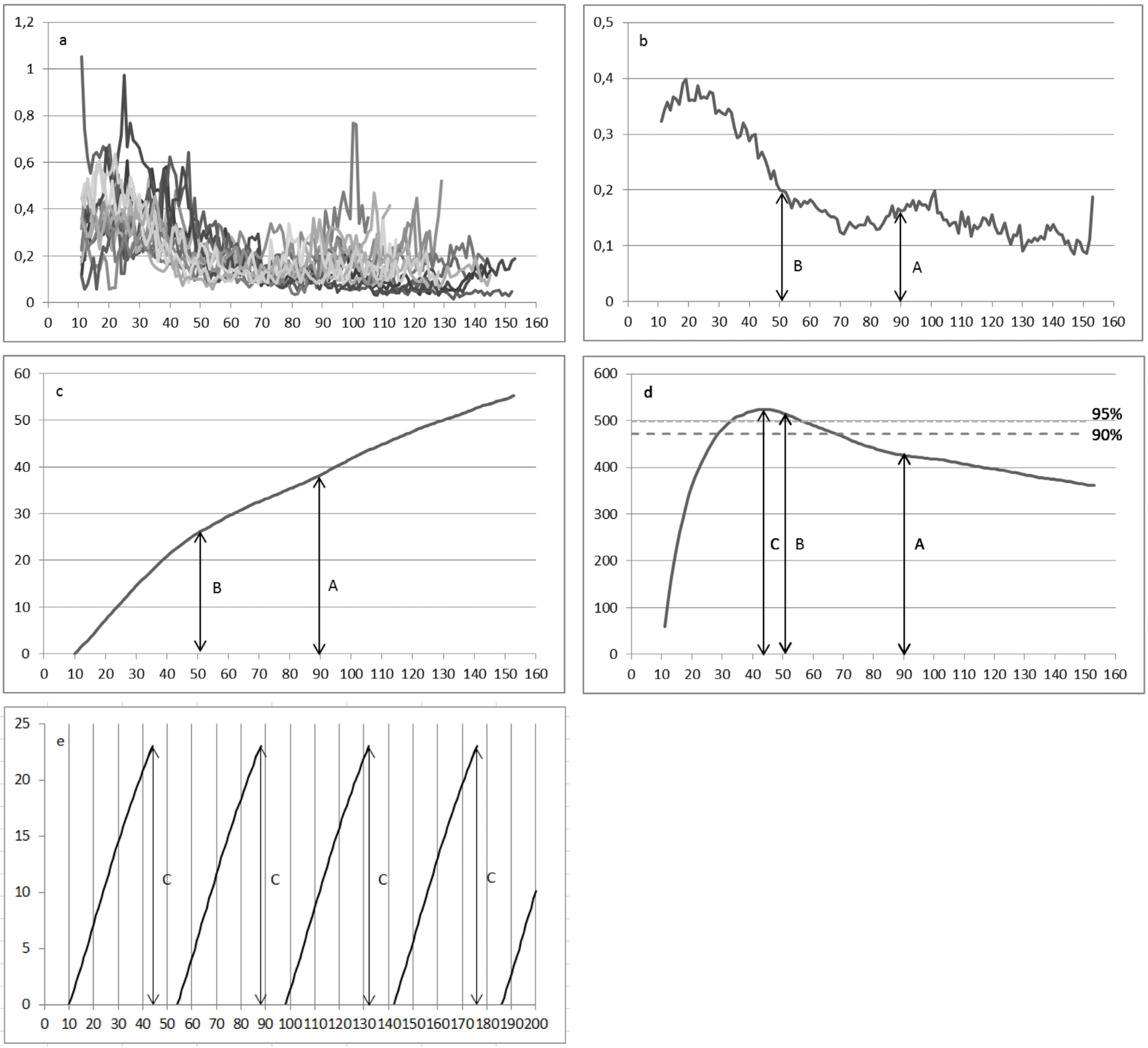


Figure 2. a – radial increment (width of tree rings, cm) of sample trees at 1.3 m height (ordinate), arranged by their cambial age (abscissa, years); b – average radial increment of the trees (ordinate, cm) according to cambial age (abscissa, years); c – cumulative tree-ring increment of a tree diameter (ordinate, cm) during its lifetime (abscissa, years); d – total sum of diameters in 1000 years (ordinate, cm) at different rotation length (abscissa, years), with 90% and 95% level from the maximum sum of diameters; e – successive cumulative tree-ring increments (ordinate, cm) shown here in a 200-year period (x-direction, years); A – cutting age of 80 years, B – tree age at diameter 26 cm plus 10 years, C – age at maximum sum of diameters in 1000 years; time period in years is plotted in *x*-direction, trunk diameter in cm is plotted in *y*-direction

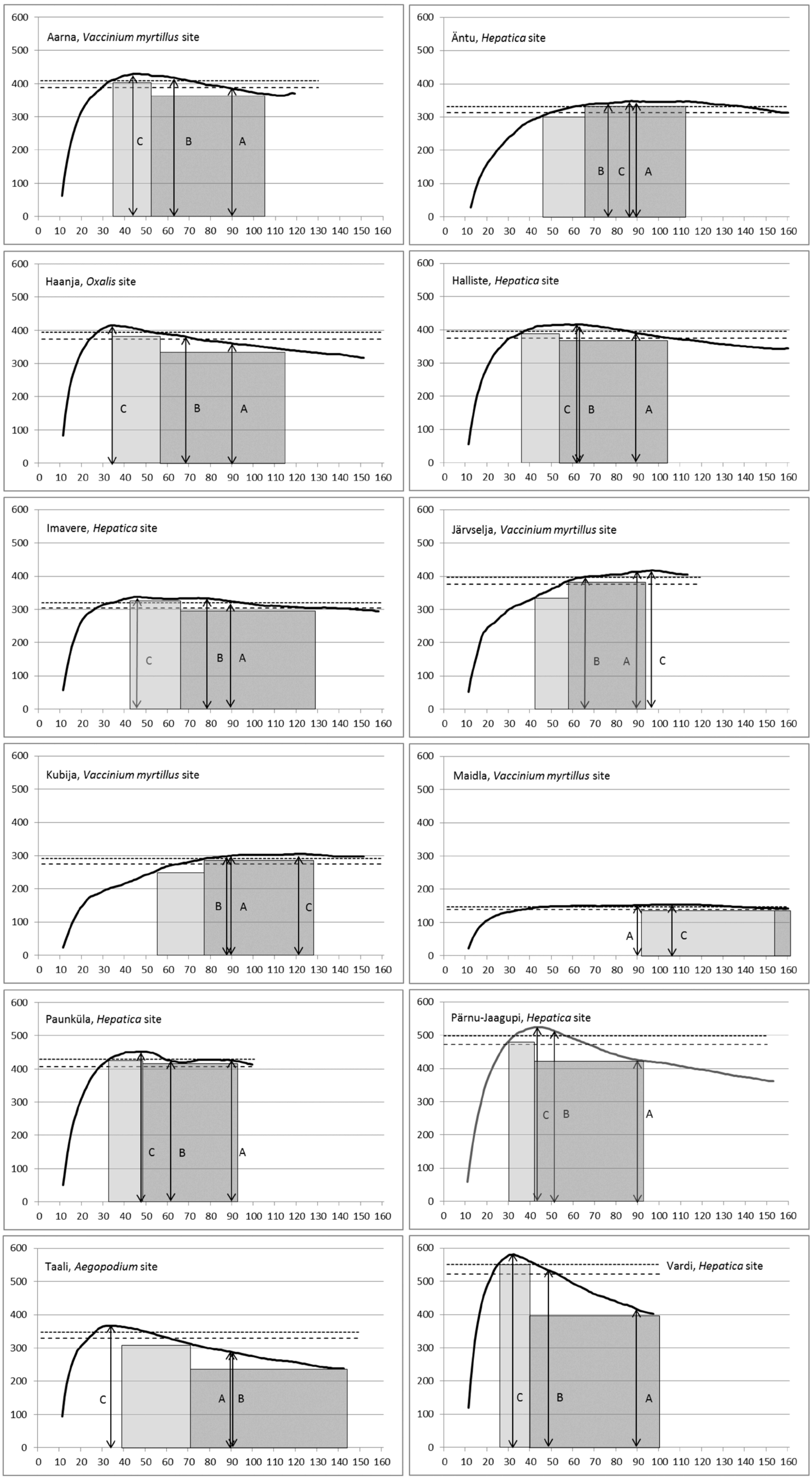


Figure 3. Total sum of diameters in 1000 years (as in Figure 2, d) in the twelve sample plots. Light grey rectangle shows the cutting age for small diameter logs, dark grey rectangle shows the cutting age for saw logs. Meanings of the capitals A, B and C are the same as in Figure 2. Length of rotation cycle in years is plotted in *x*-directiom, and respective cumulative diameter in cm is plotted in *y*-direction

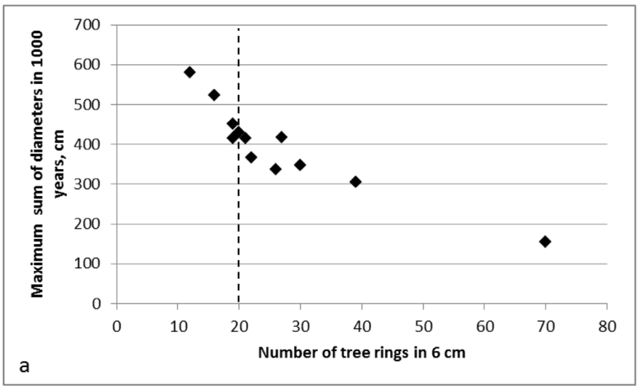
rather close to each other by any of the two criteria. For instance, in seven stands the cutting at age when the diameter of 26 has been attained would give above 95% of the maximal diameter growth (Figure 2, upper dashed line), whereas in the stand of Maidla the cutting at age 80 years would yield also above 95% of the maximal diameter growth. In three stands the cutting at 26 cm diameter age would yield above 90% of the maximal diameter growth. Thus, cutting at the age when the diameter of 26 cm is attained does not appear significantly decreasing the sum of diameters in the long time course. It is notable that in the stand of Taali, the cutting at the age of 80 years or at the age when the diameter of 26 cm is attained (here, at the age of 81 years) would mean a significant loss in the sum of diameters (Figure 2).

Alongside these estimations, there are other important parameters of round timber to be noted. The thicker sortiments of round timber are sold both as conventional logs and small dimension logs, but with higher price for logs. Taking into account the limits of measurements for small-diameter logs and conventional logs, re-calculated to the sampling height, 1.3 m, the respective tree age range between the small logs and logs are shown in Figure 2 as lighter grey and darker grey rectangles. We see that in all cases (with an exception of Maidla stand), the cutting age with 26 cm diameter falls into the determination of logs (ibid.). At the Maidla stand, by contrast, the spruces had not reached the small log measurements yet for their cutting age of 80 years. Focusing on the maximal diameter growth, the respective cutting age coincides with the log measurements in four cases (the darker grey area in Figure 2), whereas in the stand of Järvselja the maximal diameter growth had been achieved at the measurements above a normal log, by the thickness of 39 cm. The maximal diameter growth had been achieved for six stands when the spruce trees yielded small logs only (lighter grey area in Figure 2). Under the circumstances where the regulatory cutting age and age at which the maximum sum of diameters was attained yielded nearly the same diameter, it would thus be economically reasonable to let the forest stand grow to the log measurements. In the stand of Taali, the maximal diameter growth was achieved so early that the forest site did not yet produce even small logs.

Considerations towards an economically optimal cutting age could be attempted by assessing how the cutting age to produce log-size timber coincides with the regulatory cutting age for these forest sites. Guided by the maximum sum of diameters during a number of rotations, the optimal cutting age, compared with the regulatory cutting age, would be as follows (Figure 3). In 7 of the stands the cutting age should be decreased (by 9 to 19 years), whereas in three of the stands the regulatory cutting age is optimal. Finally, in two of the stands (Järvselja and Maidla) the cutting age should be increased.

Attention was also paid here to the relation between round-wood quality, the maximum sum of diameters, and the corresponding age of the spruces (Figure 4, a). As this work is based on tree rings, we chose the parameter of ring widths as an indicator of round-wood quality: the higher the number of tree rings counted in the 6 cm section of radius around the pith, the improved the quality of the timber (Uus and Jänes 1998). Figure 4 shows that the maximum sum of diameters is clearly inversely related to this quality indicator. In the case of these 12 spruce stands, 8 of them yield round-wood of the 1st quality class and 4 sites of the 2nd quality class. Accordingly, an increase in wood quality come with a decrease in sum of diameters, i.e. in quantity.

Figure 4, b shows the estimates of tree ages at maximum sum of diameters in relation to the number of tree rings in that 6 cm section around the pith. It becomes evident that spruce sites of higher quality has to be cut in older age, in order to attain the maximum amount of wood. This relation is not linear, because the maximum



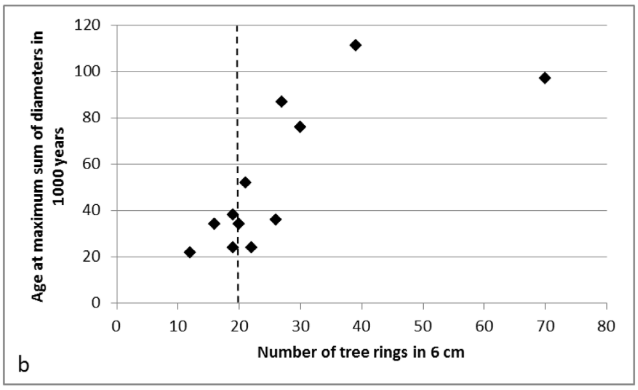


Figure 4. a – relationship of the number of tree rings in the innermost 6 cm of the radius of round-wood with the maximum sum of diameters in 1000 years, b – relationship of the number of tree rings in the innermost 6 cm of the radius of round-wood with the corresponding cutting age of spruces. The vertical dashed line marks the threshold value of the number of tree rings for the 1st quality class of round-wood

sum of diameters may remain stable during a decade or even a longer period of time; therefore, the optimal cutting age may also vary without any remarkable change in the sum of diameters. Nevertheless, these graphs once again demonstrate the well-known controversy of quality and quantity. In the forestry, various cutting ages may result in nearly the same sum of diameters. The choice of the cutting age depends also on the requirements that are set to the quality of the round-wood.

Discussion

Does the application of regulatory cutting age result in optimal diameter growth? From the presented figures it is possible to comprehend that following the regulatory cutting age the diameter sum exceeds 95% of the maximum in altogether nine plots. Only in two stands (Paunküla and Vardi) the diameter sum appears to exceed 90% of the maximum, and in an only one stand (Taali) the diameter sum is much less than expected. Therefore, it seems that in most cases the regulatory cutting age is justified respectively achieving the maximum sum of diameters, although the maximal diameter growth could be somewhat optimised by an earlier cutting age.

In addition to the maximal diameter growth, it is economically substantial that the diameters of the harvested trees consist mostly of logs (pole stand) because of their higher price in the wood market. For instance, in September 2014 the price for spruce log (without VAT) was 71.31 €/cubic meter in Foundation Private Forest Centre (PFC) and 73.33 €/cubic meter in Estonian Timbertrade Center (ETC), while the prices for spruce small log (without VAT) were 66.58 and 68.93 €/cubic meter, respectively (Hepner 2016), i.e. 93-94% of the log price. Accordingly, our Figure 3 illustrates the span of the small log and log diameters as light grey and grey rectangles, respectively to the cutting age. Eventually, the value of the timber sortiment depends on the demand in the market (Malinen et al. 2006, Posavec et al. 2011).

In Estonia, minimal diameter of a conventional log can be determined using different criteria (18 or 16 cm - Jänes 2004, 24 cm – Meier 2008, 18 cm - Laas et al. 2011: 350). Considering the 18 cm criterion to differentiate between small-diameter log and saw log, the diameter is measured at the distance of 10 cm from the top end of a log either outside or inside the bark, according to agreement (ibid.). Usually, log diameters are calculated excluding the bark. Our corer samples have been taken at breast height, that is 1.3 m from the root collar. Taking into account the stump height ca. 30 cm, our corer samples are located at approximately 1 metre from the butt end of log. This may cause some discrepancy. The standard conifer log length starts from 310 cm (and goes longer with a 30 cm step). Determining the minimal log diameter 18 cm as measured at 10 cm lower from the top end of the 310 cm log, the distance between the diameter measurement and our increment measurement translates into 2 metres. The respective diameter of that log at our sampling height then becomes (18 + 2 + 2 =) 22 cm, in the premise of butt log taper with 2 cm diameter decrease per a metre (Laas et al. 2011: 824, Vaus 2005). Therefore, we may consider the minimum diameter of log starting from 22 cm at breast height (DBH).

Are there any logical ways to consider the upper limit of conventional log diameter? Physically the limit is determined by the thickness of the forest trees growing in the study region. Practically the trees do not reach the biologically determined maximum age and corresponding thickness because of the forest management. There are only 14 spruce trees known in Estonia with DBH exceeding 95 cm (300 cm circumference, Puss 1997), and the diameter of the thickest of them actually comprises of several individual stems. It is also notable that extremely voluminous logs have only specific usage as they are difficult to process and need a special sawing machinery. Considering this, it is reasonable to limit the conventional log diameter to ca 35 cm. This measure would stand for DBH of ca. 39 cm, in the premise of butt log taper with 2 cm diameter decrease per one metre. Using these considerations, we can calculate the DBH limits for small-diameter logs: given that the top diameter of small log starts from 12 cm, the minimal DBH of small log should be 14 cm (the respective small log and log diameter limits are shown as quadrangles in Figure 2).

It is useful to have a look at the criterion for cutting age that had to be applied in these forest sites according to Estonian forest law. According to the law, regeneration cutting (including clear cutting and shelterwood cutting) had to be carried out either at the diameter of 26 cm or at the tree age of 80 years (Figure 2, c), which ever achieved first. This consideration is valid for monoculture spruce stands, as for mixed stands the cutting age is calculated from the composition of the stand (Forest Act 2006, Metsaseadus 2006). The case of monoculture stand was considered in this study. In Maidla plot, the diameter of 26 cm was not achieved until the 150 years, as shown in the graph. The extraordinarily slow radial increment of these spruces can probably be explained by excessive moisture of the site. In nine out of twelve cases, the maximum diameter growth is achieved even earlier than the diameter of 26 cm. The difference to reach either this diameter and the maximum diameter growth can be several decades, thus exceeding the length of an age class (20 years) in altogether six cases. Again, the site of Maidla appeared an exceptional case, with a difference of 77 years between the age the diameter of 26 cm (at age 174 years, out of the graph) and the maximal diameter growth (at age 97 years) was attained. At this stand, the cutting age of 80 years should be applied according to the law.

Our results can be compared with a monographic treatment of Scots pine in Estonia (Kurm 2014). Comparison between spruce and pine shows that the net revenue maturity age of Scots pine in more fertile site types does arrive earlier than the regulatory minimum cutting age (Kaimre 2014). Similarly, Piekutin and Skręta (2012) stated that for Scots pine stands of higher site index the rotation age is lower than that of poorer sites. And as Korjus et al. (2011) have demonstrated, the economically optimal rotation length for Norway spruce stand could be as low as 53 years, although the same authors admit the risks in practical application of short rotations.

Therefore, it is obvious that in most cases the regulatory cutting age of spruces growing in these sites falls well into the criteria of log size and/or tree age, with an exception of the stand of Maidla. In most cases, however, the decrease of cutting age would increase the diameter growth (Figure 3). It is also likely that shorter cutting age would diminish possible damage by root rot, as this disease appears mainly in the older age of spruces (Korjus et al. 2011) or by windthrows as this hazard is especially destructive for old and weakened stands (Beinhofer and Knoke 2007).

On the other hand, carrying out the cutting later and with thicker logs, also yields longer logs. Again, the stand of Maidla contained such slow-growing spruces that even with a very prolonged cutting age (say, the age of 140 years), the log size is at the limit of achievement but at a very low diameter sum level, as compared with other sites under this investigation. It is possible to see that in altogether nine stands the maximal diameter growth of 300-400 cm may be reached, while in the Maidla stand this is reached to ca. 150 cm only and to more than 500 cm in the stands of Pärnu-Jaagupi and Vardi (both *Hepatica* site type). Previous studies have evidenced that stand productivity depends greatly on thinnings and intermediate fellings in young age of trees (Kairiūkštis and Juodvalkis 2005). The differences in maximal diameter growth may be due to different management of these stands during the lifetime of trees.

The effects of neither self-thinning nor sanitary cuts here were studied too. It is obvious that with regards to the maximum diameter sum over a number of rotations the fact of self-thinning is an argument for earlier cutting age. If the self-thinning period coincides with the start of the regulatory cutting age, it is reasonable to cut at earlier term. It is postulated that sanitary cuts do not increase the general production of timber during a rotation cycle, but higher quality and thicker sortiments are achieved at the clearcut (Laas et al. 2011). Therefore, self-thinning and sanitary cuts are not excluded in these calculations, but they do not affect the maximum diameter sum over rotations.

As a final part of this discussion, we wish to pay attention to the limitations of the method developed in this study. First, the assessment of the maximal diameter growth is based on statistical determination of the age-dependent growth trend. In our study, this growth trend was computed separately for each of the forest stands. Thus, the resulting growth trend comprises data of site-specific growth variability. Radial growth variability of any tree is, however, simultaneously influenced by factors exogenous to the particular site (Cook 1987); the tree growth is also controlled by climate variability (Fritts 1976). Yet, the influence of the different factors may occur on timescales longer than the lifespan of the sampled trees. For example, the development of climatic change is a long-term process, with its initiation somewhere around the mid-19th century, with a supposed continuation of climate change impacts over the 21st century (Kont et al. 2002). As a consequence, the calculated growth trends of sample trees, with their limited lifespan, may not fully represent the fluctuation of past and future growing conditions in the same site. While the calculated growth trends do exhibit the general features of age-dependent growth characteristics, there is a possibility that the future conditions will result in altered growth variability, growth trends, and thus the value of time-dependent assessments of maximal diameter growth may be limited.

Alternative methods can be used to analyse the relations of radial growth, the maximum diameter sum, and the optimal cutting age. In fact, one possibility not applied in this study, but suggested previously in dendroclimatic literature would proceed through signal-free estimation of age-dependent growth trends (Melvin and Briffa 2014). In such an approach, the site-specific growth trends would not be determined simply as average curves of age-dependent radial growth. Instead, the dendroclimatic signal, represented by the resulting tree-ring chronology, is removed from the measurement data of tree-ring width series, after which the determination of growth trends could, at least theoretically, be carried out with tree-ring data that are not expected to contain the influence of time-dependent growth characteristics, such as the influence of ameliorated and/or deteriorated climatic disturbance (Melvin and Briffa 2008). Therefore, the development of the method applied in this study could be continued in the future by applying the suggested methodology of signal-free estimation of growth trends.

Second, the assessment of the maximal diameter growth was carried out here for tree-ring data originating from forest sites of which initial phases of stand development were not monitored. That is to say that it may not be possible to state whether the examined data from the studied sites represents spruce radial growth from sheltered or unsheltered site conditions and how the stands may or may not have been stratified during the development after regeneration of the studied trees. At the same time, it is well known that the radial growth of spruce is particularly well shaped, especially in the case of the age-dependent growth trend, by the varying stages of stand development (Mikola 1950). That is, the most reasonable way of determining the radial growth trends, with subsequent assessments of maximal diameter growth, would likely proceed by separating the age-dependent growth data into different categories depending on the way the particular stands had developed into their current stage. As mentioned above, this was not a research target possible to attain through this study, but such approach remains an interesting prospect for more detailed estimation of spruce radial growth in Estonia.

The premises of spruce stand and with clearcut managements have been applied in this study, leaving the duration of 10 years between the clearcut and the next generation to reach the breast height. By using such a simple model, it is assumed that all trees reach the cutting age and no intermediate cuts are carried out. The model does not take into consideration possible changes of the number of trees in a forest site nor the impact of recent and future climate change (Nilson et al. 1999). All calculations have been calculated merely for a linear sequence of an average tree growth. Also, height increment of trees and hence the volume increment has not been taken into consideration. Therefore, the diameter sums may not have full practical meaning for calculating the wood volume or roundwood value, but they serve for relative comparison of conventional log and small log outcome in the case of different felling ages, with the limitations described above. As Eastaugh et al. (2013) state: „The choice of modelling approach is usually a compromise between precision and generality." We have followed this concept by keeping the number of variables as low as possible to avoid the decrease of precision by cumulated errors of variables. In this model we see the effect of increasing cutting age to the cumulative diameter of trunks in a long time period. Alongside, the cutting ages respective to small log and log diameter limits are also shown. Generally, drawing these outcomes was possible due to sampling overgrown forest stands that exceeded the regulatory cutting age.

Conclusions

The cumulative sum of diameters of spruce trunks in a linear sequence at different cutting ages has demonstrated a great variability between the 12 forest stands with different forest site types. Among these sites, a *Hepatica* site (the stand of Vardi) yielded the highest sum of diameters, while a *Myrtillus* site (the stand of Maidla) showed the lowest sum of diameters. The general character of the obtained graphs showed that during the first few decades of growth the diameter sum increases rapidly, and after a maximal level it gradually decreases. In most cases the regulatory cutting age, based on minimal log diameter of 26 cm (DBH), falls well into the log size and simultaneously produces over 95% of the maximum sum of diameters. We conclude that such cases the regulatory cutting age (especially based on DBH of 26 cm) is rational. Nevertheless, in some cases, the cutting age could be lower, to achieve the maximum sum of diameters. The exceptions are distinguished either when very high growth rates are found in young age or when very low growth rate dominates throughout the lifetime of the trees. Eventually, the decisions for reasonable cutting age should relate to the quality of the forest site and the specific requirements for the round-wood production.

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