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A silvicultural strategy for managing uneven-aged beech-dominated forests in Thuringia, Germany: a new approach to an old problem

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ABSTRACT

Maintaining a permanent forest canopy cover and eventually harvesting wood in a final harvest according to predefined dimensions is often considered as prototype for future management of deciduous forests. An uneven-aged structure is considered by the public to resemble "natural" conditions, and by forest engineers it is considered as being more resilient to disturbances. In the Hainich-Dün region of Thuringia, Germany, beech-dominated selection forests covering about 10,000 ha have been managed for almost 1000 years, initially by irregular use, but as regular selection system since about 200 years. Managing these stands remains difficult, due to the lack of yield tables and a quantification of harvest of uneven-aged stands considering differences in site conditions and handling of over-sized trees. It is the objective of the present study to develop tables of target stand volumes, increments, and harvest for different diameter ranges of uneven-aged stands according to site conditions. The present study is based on repeated grid-based inventories of about 2150 plots, which were partly re-inventoried 3 times over the past 20 years. The recommended target wood volumes vary between 296 and 388 m^3 ha^{-1}. Stand growth rates of different yield classes were estimated to range between 6.7 and 7.7 m^3 ha^{-1} yr^{-1} which is 30% lower than for age class forest. Nevertheless, the economic returns are higher. Thus, selective cutting with single tree selection remains a viable silvicultural system, but it may change over time into small-scale shelter-woods for improving growth of regeneration.

Introduction

About 10,000 ha of multilayered, uneven-aged temperate deciduous forests are managed by selection cutting in northwestern Thuringia, Germany. These forests are cooperative forest holdings that have been owned by inhabitants of rural villages since the eleventh century (Witticke and Biehl 2009). The distinct horizontal and vertical variation of canopy height and age the of these forests at small spatial scales contrasts with the generally uniform structure of more widespread age-class rotation forests with even-aged, single-layered closed canopies. Both management systems relay on natural regeneration. Due to their unique structure, these multilayered, uneven-aged forests were included in the European habitat network of "Natura 2000" sites, and shall be maintained as uneven-aged selection forests in the future.

Scientific interest in the management of selection forests emerged in the last century (e.g. Mathes 1910; Meyer 1933; Prodan 1944) and has continued into the present (Schütz 2006; Schütz et al. 2012). It is quite remarkable that land owners have managed these forests for over ~1000 yrs. and consistently harvested trees that are 150–250 yrs. old (equivalent to 4–6 generations of owners) without documented target volumes and yield classes under conditions of changing markets of large timber. However, this historical knowledge is under threat because of changes in the professional lives of the land owners, and because of anthropogenic influences on present environmental conditions, such as atmospheric nitrogen inputs. Thus, the present study has the objective of providing operational tools for management on a statistical basis by defining targets for standing volume in relation to a range of target tree dimensions and variable site conditions for this type of forest management, and estimating the associated annual wood increment and required harvest. These management tools should avoid over-aging and unintended transition into single-layered stands as well as assure a sustainable supply of large timber.

The present discussion about continuous cover forestry was not initiated by the owners but by environmental organizations and their view about "natural" and "un-natural" forest management. This is a debate not only in Germany, but a global discussion (Brang et al. 2014; O'Hara 2016). Thus, European beech (Fagus sylvatica) selection forestry has moved into the focus of forest ecology and management in Central Europe (Beck 2015; Teuffel 2015) even though it is unclear if this management system could be used beyond a regional scale. During the process of forest conversion from age-class towards continuous cover forestry

(hereafter referred to as selection forestry), and for management of existing selection forests, yield tables and harvesting plans are not available, but are needed for establishing management plans and for making operational decisions. Existing yield tables were established for age-class forestry and have limited applicability to uneven-aged stands. Thus, the actual productivity of uneven-aged stands remains largely unknown, even though quantification of the growth rates of beech selection forests at various levels of stand volume has become an important issue for sustainable forest management. The legally required 10-year management plans demand quantification of target wood volumes based on growth rates, which implicitly needs a quantitative description of the stand structure using stem density and tree volumes in different diameter-classes. The currently available target wood volumes for deciduous selection forests were established by Gerold and Biehl (1992) based on just 3 experimental plots of 1 ha each, and the volume/stem density curves were derived by expert opinion (Biehl 1991). Also the work of Schütz (2006) is based on the same limited set of observations of Gerold and Biehl (1992), while the results are applied over large properties despite high uncertainties. Gerold and Biehl (1992) and Schütz (2006) identified target volumes and diameters. Schütz (2002) and Hessenmöller et al. (2012) quantified the increment of individual trees in relation to stand density, without information on stand growth. In the past there is no recommended amount of harvest considering the existence of overaged trees from past management. This lack of information has among other factors resulted in overstocking and in changes of the uneven-aged forest structure over the past few decades. Here we attempt to revise these targets in a framework of site specific-yield tables.

In view of unintended changes in forest structures, repeated grid-based inventories of beech selection forests were carried out at a regional scale encompassing all selection forest stands in Thuringia during the past few decades (Hessenmöller et al. 2012). The results of these inventories are the basis for the present analysis which aims to derive target wood volumes and forest structures of uneven-aged stands, depending on the top height and the diameter of "target trees" to be harvested.

The structure of the forests that are managed by selective cutting is the result of development over centuries. Selection forests are naturally regenerating. Trees of all dimensions are mixed at a small spatial scale. Overtopping of regenerating and subdominant trees occurs, but management tries to confine regeneration to gaps of harvested target trees in order to minimize overtopping. By the time trees pass the threshold for harvestable wood dimension (7 cm DBH in Germany) these trees are generally not growing in the shade of remaining shelter trees. This contrasts selection forests of fir and spruce that exist in southern Germany and Switzerland (see Engler 1900; Biolley 1901; Schütz 1997; Zing et al. 1999) where tree crowns sustain over-topping for long periods of time. Thus, beech dominated selection forests represent a special case of permanent forest cover management in Germany (Schütz 2002). In contrast to the coniferous or the mixed coniferous/deciduous selection forests, beech selection forests are composed of small cohorts of trees of similar age with overlapping crowns (Figure 1). Regeneration is managed in small groups of trees growing in gaps to ensure the natural pruning of the hardwoods. In terms of classification of management systems (O'Hara 2014), the uneven-aged beech forest is a transition between a single tree-selection system (Plenterwald in the strict sense, as defined for coniferous forest) and a small-scale shelter-wood-systems. It is not a group selection, because single trees are marked and supported as future trees. Selection forestry also does not emulate a natural disturbance regime, because it regulates the diameter distribution of the whole tree population.

According to the theory of selection forestry (Mathes 1910), density management is based on the notion of a steady state in which the number of trees in a diameter class is replenished from the next lower diameter class such that the tree number of a specific diameter class remains constant despite harvest taking place mainly in the largest

Figure 1. Continuous cover beech forest near Langula (Photo taken by D. Fritzlar in 2016).

diameter classes. In reality there are deviations from this ideal situation which may change the forest structure in the long-term. Even though other views for managing selection cutting especially in multi-species stands emerged (e.g. O'Hara and Gersonde 2004; O'Hara 2014), in view of a rather conservative ownership and due to the long time it takes to implement any changes in taget wood dimension, and by the fact that the existing management type has been legally conserved by the Natura 2000 framework of the EU, there is no possibility for changing this management type, even though guidelines for harvest are missing. The existence of large oversized trees documents that the past management of these forests can be improved by adequate yield tables without changing the overall management concept.

Since crown dimensions increase with stem diameter, the number of trees decreases with increasing diameter along all tree-dimensions. Therefore, based on average conditions of a region (Goff and West 1975), the stem density-diameter curve of selection forests corresponds to a falling geometric series. Meyer (1933, based on de Liocourt 1898) and Cancino and Gadow (2002) used a negative exponential function for the mathematical description of this observation (Equation (1))

$$N = a \cdot \exp(-b \cdot \text{DBH}) \quad \text{or equivalently}$$
$$\ln(N) = \ln(a) - b \cdot \text{DBH},$$

(1)

where N describes the stem density, DBH represents the diameter at breast height, and a and b are empirically-derived parameters. Because Equation (1) is an empirical function, a functional interpretation of the parameters a and b remains difficult. The steps to derive a density-diameter curve after Meyer (1933) are documented in detail by Schütz (2002). This equation resembles the self-thinning line of Luyssaert et al. (2011). In the results section, Figure 5, it will be shown that the forests under investigation follow this assumption, in part due to the existing management.

The stand density-diameter curve describes the current state of the forest at the stand level. It also allows quantifying the number of trees per diameter class that can be removed. Removals are compensated for by ingrowth from lower diameter classes along the diameter range (Schütz 1975). The curvature of the function depends mainly on two factors: (i) the diameter increase of trees in each diameter class, which determines the ingrowth at each stage and (ii) the removal by harvest or by natural mortality from all diameter classes (Schütz 2002). Under conditions of a steady state at the stand level, it is assumed that the stem density-diameter curve, the tree height-diameter curve, and the growth rate should remain constant (Mitscherlich 1970). The amount of harvest in the largest diameter class is determined by the wood increment in the smaller diameter classes. Over- and under-usages of target trees lead to a loss of the equilibrium assuming no disturbances.

The natural disturbance regime could potentially have major implications. On the one hand, nature conservation views selection forestry as near-to-nature by creating uneven-aged stands and forming gaps. The baseline for comparisons is the un-managed forest. On the other hand, the management of selection forestry involves a regulation of the diameter-distribution along the whole diameter range by thinning. Thus, management tries to reduce the risk of disturbances of target trees. In this context it is interesting to note, that the investigated forest region did not face any major natural disturbance during the past 70 years (quantitative observations exist since about 1950). Only the complex disease of bark necrosis resulted in major salvage cuttings in the 60ties, which affected mainly old trees without affecting the canopy structure. Defoliation by *Calliteara pudibunda* in the 80ties was not as severe in selection forests as in neighboring age class forests. The storm events in early 2000, which resulted in major wind-throws in neighboring managed and un-managed forests, caused minor damage in the investigated selection forests. There is no historic record of a forest fire. Thus, we may say that selection forestry prevented this region from disturbances that took place in neighboring managed and un-managed conservation forests. This may indicate that selection forestry was more resilient to disturbances than un-managed and age-class managed stands.

The selection system is an un-natural system (see O'Hara 2016). In case of a disturbance, such as overharvesting or loss or under-harvesting of large timber, it is expected that the stands move up and down the prescribed density-diameter relation. Only in case of changes in site conditions, such as by nitrogen deposition from the atmosphere, the stands could move to higher or lower yield classes.

Maintaining a prescribed density-diameter distribution is difficult to implement in long-term operational forest management. For example, beech selection forests in the Hainich Region currently show a significant overstocking of large timber, and a stem density that appears to be too low in small and medium-size timber (Gerold and Biehl 1992; Hessenmöller et al. 2012). If this under-harvesting of large timber continues, it is expected that these stands could eventually turn into an old-growth type structure with a single canopy layer, as it is observed in the old Fagus National Park of Semenic, Romania (Turcu 2012; Schulze 2017). Harvesting all the large trees in the short term would also disturb the multi-aged structure, by creating too much regeneration and interrupting a sustainable harvest of large target trees. Thus, it turns out to be difficult to implement the steady state during practical forest operations.

It is the objective of this study to support operational forestry by defining target volumes and densities for different diameter ranges of uneven-aged beech stands according to site conditions. Target wood volumes of a specific diameter class will be derived based on the thinning line that describes the basic principles of the steady state with removals of all diameter classes by harvest. Since an objective of selection forestry is the supply of large-diameter wood, the thinning curves and the associated target wood volumes describe the upper boundary of maximum wood volumes that should not be exceeded to avoid natural tree death and over-aging, and suppressing natural regeneration. An additional boundary is set by the target diameter for final harvest. We will inspect deviations from the model-thinning curve considering the possibility that such deviations may also be a natural feature of uneven-aged deciduous forests.

Methods

Study area

The study area of the Hainich-Dün region in north-western Thuringia, Germany, is approx. 200×50 km containing different land uses (agriculture, forest and infra-structure). The regional forest cover is about 30%. Elevation ranges from 300 to 600 m above sea level. The mean annual temperature is between 6 and 8°C, and precipitation is between 600 and 750 mm. Geological parent material is limestone with a Pleistocene loess cover or a loam-clay cover from weathering of the limestone (Grüneberg et al. 2010). The main soil types in the study area include Luvisol and Stagnosol at loess-dominated sites, and Cambisol at sites dominated by residual clay from the weathering of limestone (Schöning et al. 2013). Wet deposition of nitrogen is about 20 kgN ha^{-1} y^{-1}.

The selection forests under investigation comprise the following cooperative forest ownerships: the cooperative Hainich (10.37 E, 51.13 N) consisting of the villages Langula, Großengottern and Oppershausen owning 1120 ha, the cooperative Niederdorla (10.35 E, 51.16 N) owning 640 ha, the cooperative Oberdorla (10.34 E, 51.17 N) owning 760 ha, and the cooperative Keula (10.52 E, 51.35 N) owning 650 ha. By law these forest cooperatives are required to establish 10-year management plans which document the harvestable biomass based on growth rates, and the owner must maintain this type of management as part of the EU-Natura 2000 directive.

Forest inventory

The study uses grid-based forest inventories of about 2150 plots with 1000 m^2 areas per plot, 1120 of these plots were re-inventoried 3 times over the past 20 years (see Supplement 1).

Single tree data

The height data of the Hainich cooperative originate from the inventories in winter 2004 and winter 2014. A total of 11,784 tree heights were measured of beech (*Fagus sylvatica*), 1498 measurements of ash (*Fraxinus excelsior*), 846 of sycamore (*Acer pseudoplatanus*), 269 of Norway maple (*Acer platanoides*), 231 of hornbeam (*Carpinus betulus*), 74 of lime (*Tilia cordata, T. platyphyllos*) and 76 oak trees (*Quercus robur, Q. petraea*). Breast height diameters (DBH) were converted from circumference measurements using a tape to the nearest 0.1 cm. This involved 12,997 DBH measurements of beech, 758 measurements of ash, 416 of sycamore, 74 of lime, 76 oak trees, and 156 measurements of Norway maple.

Diameter distribution model and target stock values

The harvestable wood volume per diameter class was determined under the assumption that a balanced curve of average diameter versus stand density is maintained at regional scale and that the increment at stand level is constant (Schütz 2002). We will inspect deviations from this assumption.

The procedure of statistical model is depicted in Figure 2 showing the different kinds of data inputs, the computations and the model results.

According to Equation (2a), the stem volume of an individual tree (V) is a function of its basal area, which is determined by the tree DBH$_{tree}$, tree height (H_{tree}) and a form factor (f), which reduces the volume of a cylinder to the appropriate cone-shaped volume of a tree:

$$V = \frac{\pi}{4} \mathrm{DBH}_{tree}^2 \cdot H_{tree} \cdot f. \tag{2a}$$

In the specific case of beech, the volume is estimated with the modified volume function according to Wenk (Döbbeler et al. 2006) with the input variables DBH in cm and H in m only (Equation (2b)).

$$V = e^{(-10.34 + 2.024 \cdot \log(\mathrm{DBH}_{tree}) + 1.035 \cdot \log(H))}. \tag{2b}$$

The estimated volume is the (merchantable) over-bark wood volume over 7 cm in diameter.

Under natural conditions, i.e. without harvest, it is expected that a regenerating stand would develop following a negative exponential track (Goff and West 1975) according to Equation (3):

$$N = a \cdot \mathrm{DBHstand}^{(-4/3)}, \tag{3}$$

where N describes the stand density, and DBH$_{stand}$ is the average DBH of trees on an inventory plot. The parameter a is a scaling factor that is related to site and stand characteristics (Pretzsch and Biber 2005). The constant $-4/3$ is derived from the $-3/2$ power law by Yoda et al. (1963) assuming that the metabolic rate of individual plants scales to the 3/4th power of body mass (Pretzsch and Mette 2008). We use this equation to describe effects of thinning by management (see Equation (10a,b)).

In addition to stand density, we try to estimate the required growing space of beech crowns and optimize stand density while avoiding overtopping. The growing space or projected canopy area A_p describes the cumulative projected crown area of a tree which increases linearly with basal area g (Equation (4)). In this study, we use Equation (4) to derive the maximum projected area (A_p) under the conditions of a selection forest.

$$A_p = s_0 \cdot g_i + s_1, \tag{4}$$

where g$_i$ describes the basal area g of tree i, and s_0, s_1 are model parameters.

Based on DBH Equation (4) changes into:.

$$A_p = s_0 \cdot \frac{\pi}{4} \cdot \mathrm{DBH}_{tree}^2 + s_1, \tag{5}$$

DBH$_{tree}$ is the diameter of a specific tree.

The average diameter- stand density-curve is limited by the target diameter, DBH$_{max}$, at which trees are supposed to be ultimately harvested. In managed forests, these individuals are selected as "target trees" at an early age on the basis of operational forestry decisions. Target trees shall be harvested at a prescribed diameter (e.g. Abetz 1976; Klädtke 1990; Abetz and Klädtke 2002). No commercial thinning takes place below 15 cm DBH in *Fagus sylvatica* because high competition
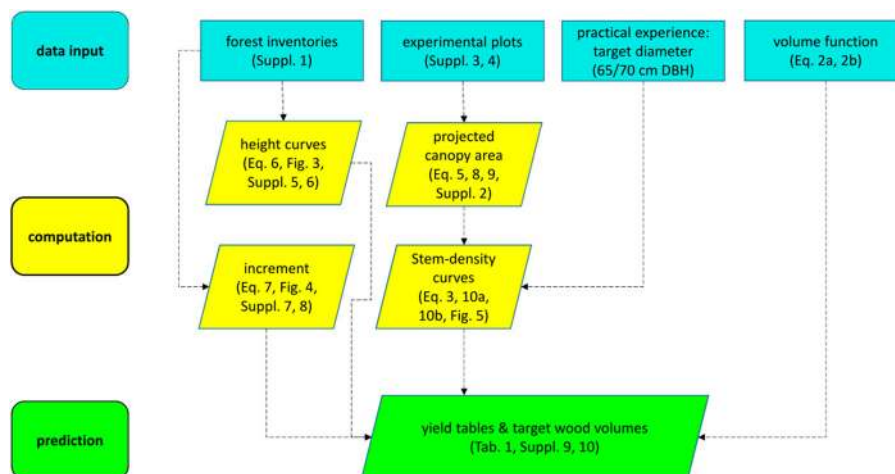
Figure 2. Data inputs, computations and model results for predicting stand volumes and yield tables.

between individual trees is required to achieve de-branching of individuals. Only poorly formed individuals are removed during taming. Commercial thinning takes place for diameters >15 cm (6 till 8 m branch-free length of shaft) to reach the prescribed diameter distribution. Thinning and promotion of target trees takes place across all commercial stem diameter classes.

For the calculation of stand wood volume from single tree volume (Equation (2b)) and the density-diameter-curve (Equation (3)), the site conditions for the development of the tree height have to be considered. Tree height is also affected by stand density, but it is eventually limited by local water and nutrient availability.

For assessing tree height in relation to diameter of individual trees, the tree height model of Chapman-Richards is used (Equation (6), Richards 1959):

$$H = H_{max}(1 - e^{(-h_1 \cdot \text{DBH}_{tree})})^{h_2}. \tag{6}$$

Equation 6 allows the description of a sigmoid asymptotic height curve in relation to DBH. The parameters h_1 and h_2 are shape parameters; H_{max} is the tree top height, which is approached in this study by a DBH of 100 cm. H_{max} is the basis to determine the site index.

Target diameter

In this study, 65 and 70 cm DBH are defined as "target diameters" for individual trees to be eventually harvested. This target diameter is a subjective decision made by the land owner based on present market conditions. Beyond 70 cm an economic devaluation takes place due to colored red heartwood (Wernsdörfer et al. 2005) and increasing stem rot. It should be noted that the target diameter was >80 cm in the past (Schütz 2006), and it decreased over time as a result of the economic demands of the wood industries. Commercial thinning must take place also at lower diameters, even though the commercial value decreases with DBH. The aim of the management is to market the most valuable trees at the diameter class 6 (DBH 60–69 cm) and 7 (DBH 70–79 cm) in stem lengths

of up to 8 m. The regulation of stand density at lower DBH results in wood suitable for industrial use only. Alternatively the trees harvested remain on site and contribute to the dead wood store.

Statistical treatment

Quantile regressions to estimate the parameters of the tree height – DBH relationship (Equation (6)) and the increment functions (Equation (7)) were calibrated using the quantreg v4.27 package (Koenker 2008) for R (R Core Team 2015). The height quantiles were used to form three distinct yield classes.

Increment of single trees

The diameter increment of single trees over 10 years (I_{d10}) was determined by Equation (7) (Korsun 1935). The model parameters i_0, i_1, i_2 were fitted to the repeated inventories data measured in the Hainich cooperative in the periods 1994–2004 and 2004–2014:

$$I_{d10} = e^{(i_0 + i_1 \cdot \log(\text{DBH}_{tree}) + i_2 \cdot \log(\text{DBH}_{tree})^2)}, \tag{7}$$

where DBH_{tree} represents the single tree diameter, and i_0, i_1, i_2 are model parameters.

The inventory based determination of increments contains high uncertainties due to the fact that trees are harvested or lost at unknown times over a 10 year period, and grow across borders of the nested concentric rings of the inventory plots. Also, it remains unclear if he negative exponential curve of density over diameter holds at different special scales (Goff and West 1975).

Determination of the single-tree projected canopy area

The parameter estimation of the single-tree projected canopy area function (Equation (5), parameter s_0, s_1) is based on data of the 13 plots of 1 ha (Fischer et al. 2010, Suppl. 2).

Results

Single tree projected canopy area model:

The allometric function to estimate the projected canopy area of a single tree in m^2 is related to DBH in cm (Equation (8)). This function includes trees with diameters exceeding the target dimensions:

$$A_p = 248.4339\left(\frac{\pi}{4}\right)\left(\frac{DBH_{tree}}{100}\right)^2 + 10.32311. \qquad (8)$$

The parameter values $s_0 = 248.4339$ and $s_1 = 10.32311$ (Equation (5)) were estimated based on the calibration function of projected areas independent of the tree species, since *Fagus sylvatica* represents >90% of the wood volume and stand density on the 1-ha plots (Suppl. 2, 3).

In managed beech forest the crowns of dominant trees of each DBH-class may overlap, but do not overtop (Gerold 2016), in part due to thinning of subdominant trees to promote target trees. Therefore, for simplification, we assume no overtopping of crowns for trees >7 cm DBH which is the threshold for stems. Thus, the parameter a of the density-diameter curve (Equation (3)) was estimated by linear optimization (Equation (8)) assuming full coverage of the land area by tree crowns (no gaps). We are aware that overtopping occurs in multi-aged stands mainly at DBH below 7 cm. Thus, our optimization is an approximation for tree cover of the main canopy, which is constrained by the maximum size of trees at which diameter they are to be harvested. Lower diameter crown area may be underestimated. Depending on the desired target diameter Equation (3)

takes the following form for estimating stand density (Equations (9a,9b)):

$$N = 473.91 \cdot DBH^{(-4/3)} \quad DBH_{max} = 65\,cm, \qquad (9a)$$

$$N = 436.47 \cdot DBH^{(-4/3)} \quad DBH_{max} = 70\,cm, \qquad (9b)$$

where $N =$ tree density (stems ha^{-1}) and $DBH =$ diameter class (cm).

The assessment of parameter a led in both cases ($DBH_{max} = 65$ or 70 cm) to a complete cover.

In stands with a target diameter of 65 cm, the tree density is estimated to be 409 stems ha^{-1} (see Table 1) which is equivalent to a basal area of 23.3 m^2 ha^{-1}. In stands with a target diameter of 70 cm, the tree density is 384 stems ha^{-1} with a basal area of 24.3 m^2 ha^{-1} (Table 1). The predicted basal areas are higher than the values of Schütz (2006) who suggested 22 m^2 ha^{-1} based on target diameters of >80 cm and being independent of site quality.

Tree height model

A tree height model (Equation (6)) was estimated for the 0.25, 0.50 and 0.75 quantiles of the measured heights of beech (Suppl. 5, 6). For volume estimates we used the height model of *Fagus* only because *Fagus* represents over 90% of the stand wood volume. The Quantile curves are the basis for identifying the following yield classes (see Figure 3):

Yield class A: 0.75 quantile with >34 m height at target tree diameter 65 cm DBH
Yield class B: 0.50 quantile with 32–34 m height at target tree diameter 65 cm DBH

Table 1. Target volumes, increments, canopy top heights, stand density and basal area for two target diameters and three yield classes. According to Prodan (1944) three classes of diameter are distinguished: small (7–24 cm DBH), medium (25–49 cm DBH), large (50 cm+).

	DBH-class (cm)	Target Diameter 65 cm for 3 yield classes			Target Diameter 70 cm for 3 yield classes		
		A	B	C	A	B	C
Target Volume (m^3/ha)	7–24	38	33	29	35	31	27
	25–49	156	143	130	144	132	120
	>50	158	147	137	198	185	173
	Total	352	323	296	377	348	320
Wood Increment (m^{3}ha^{-1} 10y^{-1})	7–24	17	16	14	16	14	13
	25–49	37	34	32	34	32	29
	>50	23	22	21	27	26	25
	Total	77	72	67	77	72	67
Top Height (m)	7–24	24	22	19	24	22	19
	25–49	33	31	29	33	31	29
	>50	36	34	31	36	34	32
	Main canopy	34+	32–34	32-	34+	23–34	32-
Density (stems/ha)	7–24		272			250	
	25–49		102			94	
	>50		35			40	
	Total canopy		409			384	
Basal Area (m^2/ha)	7–24		4			4	
	25–49		9			10	
	>50		11			9	
	Total stand		24			24	
Number stems harvested (stems/10y)	7–24		132			116	
	25–49		22			23	
	>50		5			6	

Note: The recommended harvest equals increment under conditions of a growth equilibrium. The table does not contain the volume of the excess number of large trees (50–65 cm) and of the over-dimensioned old trees from past management (>70 cm), which need to be successively harvested over time (see Figure 8).
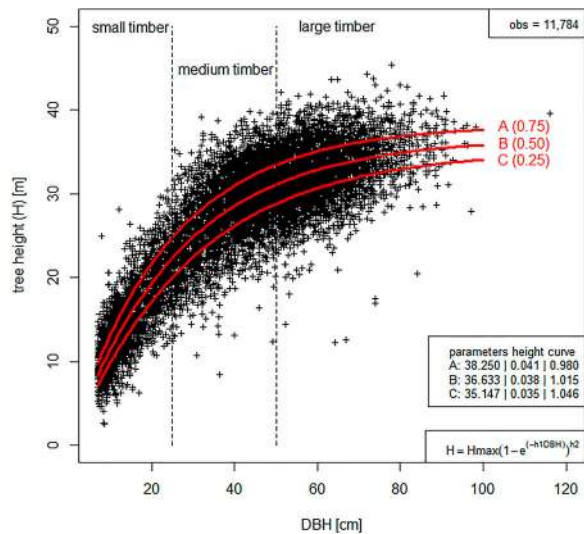
Figure 3. Tree height as related to breast height diameter (DBH). The red lines represent the 0.25 (25% above and 75% below the line), the 0.5 and the 0.75 quantile of the height distribution.

Yield class C: 0.25 quantile with <32 m height at target tree diameter 65 cm DBH.

Diameter increment model

The 10-year diameter increment of individual trees was classified by the 0.10 (model *incr10*), 0.25 (model *incr25*), 0.50 (model *incr50*), 0.75 (model *incr75*) and 0.90 (model *incr90*) quantiles of the diameter increment versus DBH distribution based on the data for *Fagus* (Figure 4). The model *incr90* describes the highest diameter increment and model *incr10* the lowest diameter increment for a given range of DBH (Suppl. 7). Data for other tree species are summarized in Supplement 8. The DBH increment reaches a maximum at age 30 to 40, and there is a constant or slightly decreasing rate of DBH increment with further increasing age. If height would
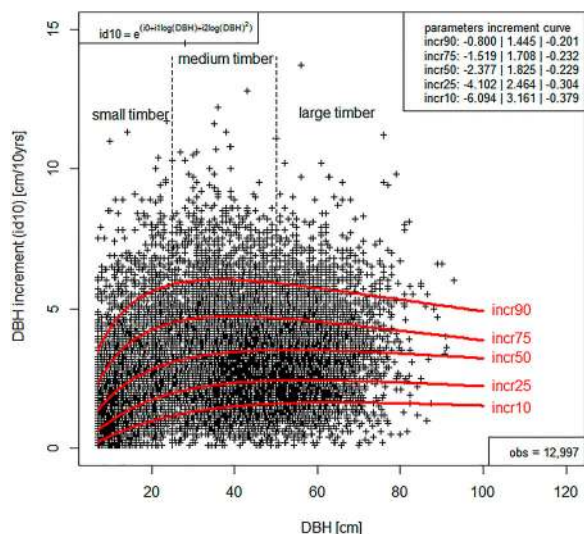
be included in addition to diameter, the peak of growth at young age would be even more pronounced (see also Figure 7).

Target stand-level wood volume values

The quantification of the targeted stand-level wood volume, which describes the stand wood volume at the equilibrium diameter distribution for different height-based yield classes, was derived in two steps: (1) the estimation of the stem density-diameter curve (see Equations (9a and 9b)), and (2) the estimation of the stand wood volumes considering the yield classes A, B and C (Equation (2b) and Equation (6), Suppl. 5).

Based on the initial assumption that the ratio of stand density and DBH remains constant, basal area is independent of the removal (Assmann 1957), but dependent on the targeted stem-diameter curve (Figure 5). The observed stand density showed a strong decrease in small timber, remained almost constant in medium sized timber, and declineed with final harvest. At all sites, there were oversized trees which may reach a DBH of 100 cm.

The projected crown areas as related to DBH decreases but show a hump at a DBH between 50 and 70 cm, while small to medium sized timber covers a lower crown area (Figure 6). This deviation from the anticipated equilibrium line of Biehl (1991) is mainly due to past management and the existence of over-sized trees.

The DBH increment model of individual trees (Equation (7), Table 1) allows the estimation of stand growth rates for different harvestable wood volumes (Figure 7(a)). Stand growth increased with DBH and reached a maximum at 50–60 cm DBH when also canopy area reached a maximum (Figure 6). Beyond 60 cm DBH stand growth rates decreased with stand density. The difference in increment between the two target diameter models (DBH$_{max}$ = 65 versus 70 cm) was very small (Table 1). Integrating the increments over the

Figure 4. Diameter increment at breast height diameter (incr) as related to breast height diameter for 5 quantile classes.
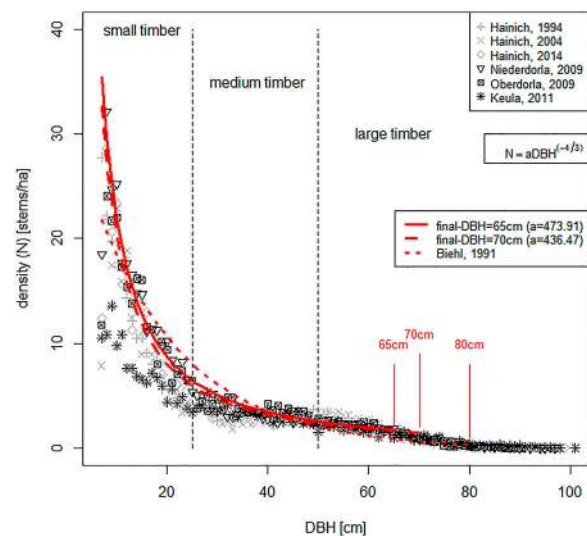

Figure 5. Stand density (*N*) as related to breast height diameter (DBH) based on data from 6 different forest cooperatives using selection cutting. The red lines are the predicted stem curves for 65/70 cm final-DBH.
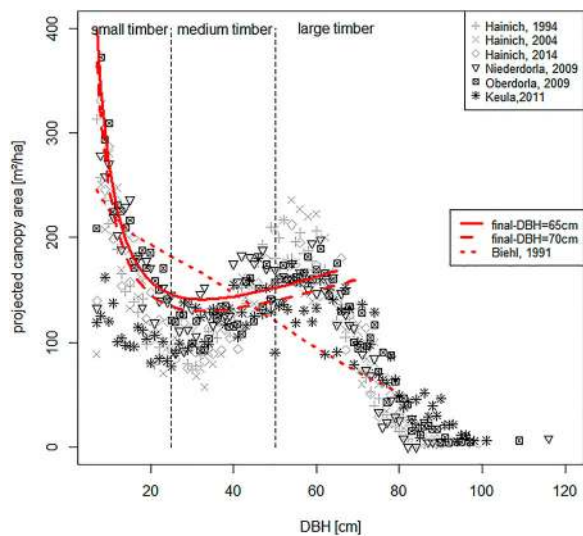
Figure 6. Projected canopy area as related to breast height diameter (DBH) based on data from 4 different forest cooperatives using selection cutting. The red lines are the optimized projected crown areas for different harvestable target dimensions.

diameter range shows (Figure 7(b)) that about 10% of the total increment occurs in the oversized trees, but this affects indirectly the growth of all diameter classes.

The total stand growth increased from 67 m³ ha⁻¹ for yield class C over 10 years to 77 m³ ha⁻¹ and 10 years for yield class A (Table 1). The increment, averaging 7.2 ± 0.4 m³ ha⁻¹ yr⁻¹, can be harvested without changing the stand structure. This is equivalent to 5–6 large stems ha⁻¹ every 10 years, which is one stem every 40–50 m. To maintain stand structure, additional 140–150 stems of smaller dimensions also have to be harvested per hectare and decade.

The targeted stand volumes are dependent on stand density-diameter curves (Equation (9a, 9b)) and on the yield classes (A, B, C). Generally, recommended stand wood volumes increase with the yield class, which implicitly

depends on tree height. Thus, for instance, at a target DBH of 65 cm, wood volumes of 296 m³ ha⁻¹ are recommended at yield class C, and of 352 m³ ha⁻¹ at yield class A (Table 1).

The amount of wood that should be harvested in the future is not only determined by the increment, but also by the over-aged and over-dimensioned trees of past management. This is shown in Figure 8 where the solid line indicates a harvest equal to increment for different growth levels and yield classes. The large volume of trees that are over-aged since management during the period of the GDR, and that are over-dimensioned since the period of Schütz (2006), affect present and future harvest. At yield class A the harvest should be up to twice the increment in order to obtain the anticipated forest structure within one planning period of the management plan. Such high harvest would result in a change of the forest structure in the following decades. Therefore, the period of handling the past management will probably take 3 or 4 decades. This also demonstrates that the management of selection forestry is rather conservative and not easily adjustable to changes in markets (e.g. a change in target dimensions) or to environmental changes (e.g. changes in growth rates), but the legacy is mainly due to failures in past management.

Discussion

Target dimensions

This study presents targets for stand based wood volumes, basal areas and stem densities at full canopy cover for uneven-aged deciduous forest stands as estimated using a strong experimental and statistical basis of repeated and detailed inventories as realized on long-term plots and covering 10,000 ha. This baseline is needed in order to determine the wood increment and the stem number to be harvested without disturbing the stand structure at regional scale. The derived growth and yield tables (Table 1) are based on
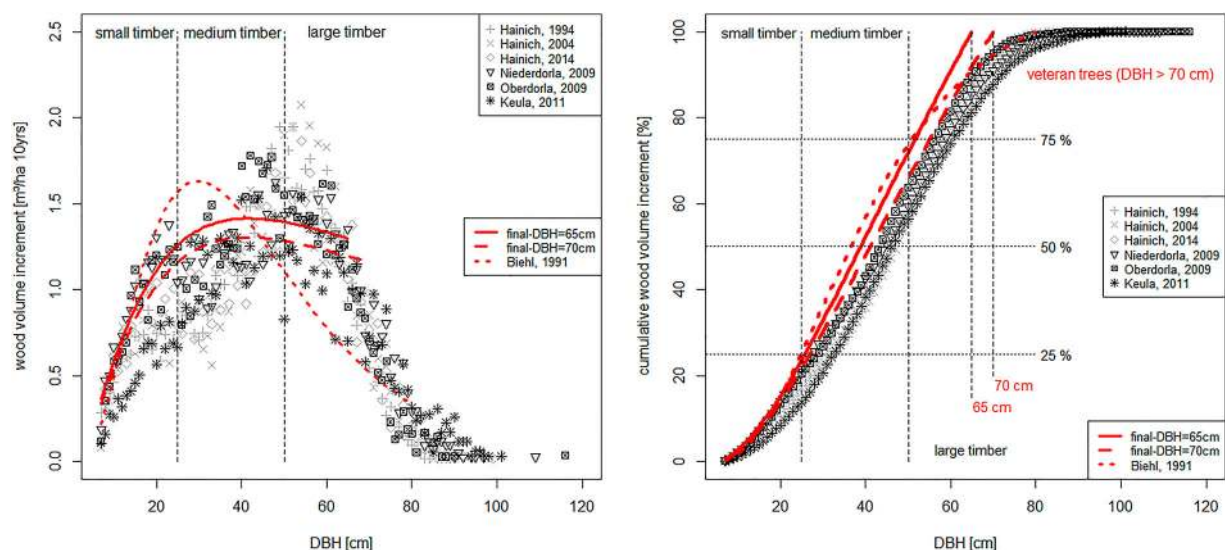

Figure 7. (a) Wood volume increment as related to DBH for various forest cooperatives using selection cutting. The red lines indicate optimal growth distribution at a sustainable diameter distribution for three target diameters. (b) Cumulative wood volume increment for various forest cooperatives using selection cutting and for the three target diameters (Figure 7(a)).
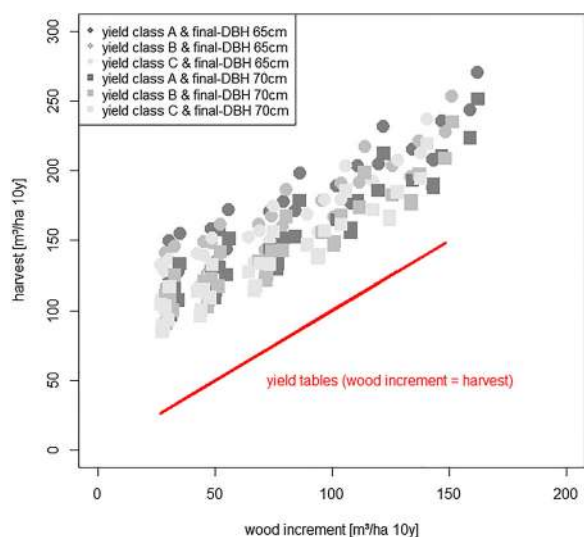
Figure 8. The relation between harvest and increment for yield class A, B, And C and two target diameters for final harvest (65 and 70 cm). The solid red line indicates the potential harvest assuming the total increment is used (1 : 1 line). The data are based on the DBH-increment model of Figure 4 and the inventory data of Figure 5, representing the variation in increment of each yield class. The clusters represent (from low to high increments) the .1 (incr 10 of Figure 4), the .25, .5, .75 and the .9 percentile of the data cloud of Figure 4, and assuming that all trees of excess diameter (over-aged and oversized trees from historical management) are harvested within the next 10-year management plan.

target diameters of 65 and 70 cm DBH representing maximum values which should not be exceeded under present market conditions for economic reasons. The target diameter has decreased over time from 80 cm to 65 cm with major consequences on the diameter distribution until present, such as the existence of oversized and overaged trees. The yield tables are based on self-thinning at lower diameters (<15 cm) because wood between 7 and 15 cm has no commercial use and natural debranching is necessary for achieving high quality large timber. Commercial thinning starts at a DBH of >15cm, and aims to maintain the diameter-density relationship that is designed to promote target trees for the production of large timber. Annual stand growth and its use to approach the anticipated curves of density versus DBH varies depending on the yield class between 6.7 m^3 ha^{-1} yr^{-1} (yield class C) and 7.7 m^3 ha^{-1} yr^{-1} (yield class A). The target diameter of 65 cm versus 70 cm has only a small effect on total volumes and increments, but affects the diameter distribution.

The target wood volumes presented in this study are higher than those recommended by Gerold and Biehl (1992), who suggested volumes between 180 and 360 m^3 ha^{-1} anticipating much larger target diameters of >80 cm. Schütz (2006) recommended 306 m^3 ha^{-1} with an annual stand growth of 7.4 m^3 ha^{-1} yr^{-1} based on the same data as Gerold and Biel (1992).

The presently observed stem density

The existing wood volume and density structure of most selection forests in Hainich-Dün differs at low DBH from the suggested guide-line curves of this study (Figure 5) Comparing the anticipated density curves (Equation (9a and b)) with the

grid-based inventory shows a higher basal area than anticipated for optimal diameter distributions at lower stem densities. This indicates an overstocking of large trees (Dittmar 1990; Hessenmöller et al. 2012). Under actual management, the existing wood volumes of the studied selection forests contain diameters that are far above the target levels. This is confirmed by the 13 experimental plots that were used to derive the projected canopy area function (Equation (9), Suppl. 3). An analysis of the projected crown areas suggests that (except for the cooperative Oberdorla) a deficit of trees at a DBH of small timber exists (Figure 6). The high wood volumes above the intended target diameter in combination with a deficit of trees at small diameter could result in a distortion of the stand structure in the long-term. In 2014, for example, the wood volume of the cooperative Hainich for DBH 65 cm and above was approximately 99 m^3 ha^{-1} or 26% of the total wood volume, and this changed the forest stands into a type of overaged age class forest. It becomes very difficult to resume the selection cutting principle under such conditions, because the gap at low DBH persists and cannot be refilled later in the growth cycle of individual trees. Thus, a future gap in harvesting emerges, unless future trees can be sufficiently promoted to fill this gap. The "rotated sigmoid shape" (Goff and West 1975) of the area contribution of different DBH classes appears to result mainly from past management and from changes on target dimensions. This management effect is enhanced by an increase of growth rate with DBH (up to 60 cm). Despite all deviations, the negative exponential distribution of stand density and diameter will remain. Whenever the over-dimensioned trees are harvested, this will result in a steeper slope and in younger stands.

Old trees

The present target volumes and increments contain a historic fraction of existing trees which cannot be harvested within a decade. These old and over-dimensioned trees are considered as "veteran trees". The excess of large timber emerged not only from the recommended high target diameters in the past (>80cm), but also in part from a special mentality of the owners, who historically used the forest as a saving account where trees were harvested only if exceptional financial resources were needed (e.g. the renovation of a house). Also, during the period of a socialistic economy in the former GDR, the selection cut forests were not included in the regular forest operations. Thus, there was a period of 60 years without proper maintenance of the steady state, which resulted in overstocking of over-aged trees of large diameter in the present. In addition, such "veteran trees" are generally heavily branched, vigorously growing trees and not suitable for sawwood. In view of the low commercial value of these trees and the relatively high harvesting cost, these trees were left on site, not considering the long-term consequences.

The carry-over effects of various management decisions in the past are apparent in the well-documented beech selection forest of Keula. For the year 1884 a wood volume of 288 m^3/ha was reported, and in 1957 the wood volume was 296 m^3 ha^{-1} based on 324 stems per hectare (Richter 1958). In 73 years, the wood volume had changed by only 3%. A

forest inventory in 2011 recorded a wood volume of 377 m³ ha⁻¹ with 262 stems per hectare (Hessenmöller et al. 2012). Thus, the wood volume had increased by 27% in 54 years (of which 32 years were under management of the former GDR), while the number of trees decreased by 21%. The central DBH of the wood volume distribution shifted from 49 to 56 cm, and the center of the stem number distribution from 26 to 30 cm. In 1963 an area of 5 ha was taken out of management at the Keula forest. This un-managed stand reached a wood volume of 775 m³ ha⁻¹ in 2008 and a stem density (≥7 cm DBH) of 232 stems ha⁻¹. The uneven-aged structure was lost within 45 years of no management. This documents the necessity of management along the whole DBH-distribution to maintain the desired forest structure.

Wood volume increment and growth rates

The estimated growth rates for the selection forests at their current diameter structure are significantly lower than the growth values for beech age-class forests. The German National Forest Inventory (BWI 3) estimates the growth of beech forests in Thuringia to be 10.2 m³ ha⁻¹ at a wood volume of 386 m³ ha⁻¹. This includes poor site conditions (Thünen Institute 2014). For the Hainich Dün region the growth of age-class forest may be as high as 14 m³ ha⁻¹ yr⁻¹. Thus, the selection system results in a loss of productivity of about 30% as compared to the age-class system.

The volume increment versus DBH distribution (Figure 7) shows an optimum at medium size trees Thus, the implicit assumption that the growth rate in different diameter classes is constant appears to be false, and it is further distorted by the selection of crop trees that receive special attention during thinning. The increment curve is also a consequence of the stand density and crown area distributions (Figures 5 and 6). Following Goff and West (1975) a period of self-thinning in the regeneration development stage follows, were a differentiation of dominance takes place, which than results in a phase where density declines due to management operations of thinning. However, in the case of the Thuringian Fagus selection forests, these developmental changes are overruled by inconsistent management in the past, and by under-harvesting of over-sized trees, when the target diameters changed. The difference between the initial assumption of constant growth and the actual growth does not change the fact that the average growth rate under selection conditions is lower than in a rotation forest. The actual growth was 6.9 m³ ha⁻¹ yr⁻¹ (cooperative Keula), 7.4 m³ ha⁻¹ yr⁻¹ (cooperative Hainich) 2004, 7.9 m³ ha⁻¹ yr⁻¹ (cooperative Niederdorla), and 8.1 m³ ha⁻¹ yr⁻¹ (cooperative Oberdorla).

If the increment per tree reaches a maximum in a developmental phase of stand growth where tree individuals differentiate into dominant and subdominant individuals, the distortion of the negative exponential line as resulting from past management would be enhanced by this characteristic of the uneven-aged forest structure in deciduous forests (Goff and West 1975). This would have major consequences for management. It would not be the aim to decrease the fraction of mid-sized timber, but to actively promote growth of future target trees. However, such an approach can only be fully applied after the "veteran" trees of past management targets have been removed. Figure 8 demonstrates the problems and needs for higher harvest in order to achieve the anticipated diameter distribution in the future.

Regeneration

Current forest inventories show that there are 890 ± 2037 trees per hectare in the regeneration layer (>3 m height, <7 cm DBH). According to model I50 (Equation (7)) approximately 60 trees per hectare are needed at 7–10 cm DBH in order to maintain the number of higher diameter stems in a steady state. The required recruitment of 60 trees ha⁻¹ year⁻¹ to maintain the selection system was confirmed by Grabedünkel (2015), who estimated a required ingrowth into the DBH-class of 7–12 cm to be 54 and 59 trees ha⁻¹.

Based on the diameter increment model for beech (Suppl. 7) and Equation (7), young beech trees remain in the small timber range of 7 to 24.9 cm DBH for as long as 79 years, and in the medium timber range of 25 to 49.9 cm DBH for as long as 74 additional years (model incr50). Without any promotion of target trees, in the worst case (model incr10) a tree may remain 140 years in small timber and another 111 years in medium before it reaches a DBH of 50 cm. This is confirmed by dendrochronological studies in the selection forest Keula (Hessenmöller et al. 2012), where beech trees with an age of 110 years are still in the diameter range of small timber. The youngest beech showed an age of 26 years with a DBH of 3 cm, and the oldest beech a DBH of 87 cm at an age of 285 years. The target diameter of 65 and 70 cm were reached on average (model incr50) within 153 or 196 years respectively after they reached the DBH-limit of 7 cm. The fastest growing beech (model incr90) needs a significantly shorter period of time than average, namely 105 years or 114 years. Thus, trees are very old at the time of harvest, which would be a major disadvantage compared to the efficiency of age class forest. Assuming that consistent recruitment of young trees and the selection of future trees could result in a better increment (model incr90), it would be feasible to reduce the regeneration time to 37 years in small timber and to 42 years in medium timber. The limitation is the self-pruning phase of beech which requires a high stand density. Thus, a promotion of target trees can only take place after these trees reached a branchless height of about 8 m (crown height of 12 m).

From a silvicultural point of view, it remains important to specifically promote a few target trees in order to reach the target diameter as rapidly as possible, ideally with very good stem quality. Under such conditions, the decision concerning the target diameter to be achieved is of secondary importance because the main growth rates occur in medium sized timber. However, until now, the growth rate of target trees has not been studied in detail.

Forestry management aspects

In age class forest the rotation time of 120–160 years, and in selection forest 150–200 years. It is mainly the time for juvenile growth that is longer under selection cutting than under

age class conditions However, beyond maximizing growth there are strong incentives to maintain the selection system. It has low tending and thinning cost and the target of harvesting large trees of high commercial value is being achieved. The average harvesting cost was 17 €/m^3 for selection forest in 2014, compared to 21 €/m^3 in age class forest (BMEL 2016), at comparable average revenue of 50 €/m^3. It becomes clear that management of uneven-aged forests is more economic than that of age class operations even though management is very intense during the thinning phase, and by no means "natural".

Uneven-aged forest at a global scale

The present study is focused on uneven-aged forests with temperate deciduous tree species. We are aware that the problem of managing uneven-aged forests is presently being discussed globally (e.g. O'Hara and Gersonde 2004; Pukkala and Gadow 2012; Schütz et al. 2012; Puettmann et al. 2015; Pukkala 2016), since most forested land globally consists of uneven-aged stands. Nevertheless, a solution depends on the managed species (coniferous vs deciduous), and on the market requirements. Stocking rates of uneven-aged coniferous forests are generally higher than those of deciduous forests (Sterba and Zingg 2001) due to differences in crown structure. The market determines the target diameter, and it is interesting to note that Schütz (2006) was aiming at selling stems of *Fagus* of 80 cm, while in this study, and for the same stands, a target diameter of 60 cm offers the highest returns. For *Acer saccharum* in Canada a target diameter of only 40 cm was suggested (Hansen and Nyland 1987). This has large effects on the diameter distribution, and our study points at the difficulties in adjusting to the market demands. There is a legacy of owners, which remain in historical conditions of supply and demand. Seydack et al. (1995) defined a system which only relies on senility criteria of the stand. Trees are harvested in South African temperate rainforest only when showing obvious signs of dieback. However, this approach would not be suitable in temperate forest due to the loss in value between a target diameter and the value of wood at signs of dieback. The crown index as suggested by Donoso (2005) for coastal forests in Chile takes the important step of not only focusing on basal areas but also on vertical structure as competitive measures. Irrespective of species and market conditions, it appears important for future management that overtopping is avoided to minimize the productivity loss of uneven-aged forest compared to age class forest, and that a flexible system is used to account for variation in habitat conditions, and for the legacy of old trees and owners (Cancino and Gadow 2002) in a dynamic world of market demands. Thus, despite its many short-comings, selection cut forest is a viable solution even when considering economic aspects. This holds true especially for small enterprises which have limited work-power for intensive management.

Conclusions

Selection forests are characterized by moderate stocking of wood volumes, where the main volume increment per tree occurs at high diameters. The targets are single trees of high volume and high commercial value. The management system is based on a delicate balance of diameter distributions.

Target volumes are crucial for sustainable management of selective cutting. But the selective cutting is maintained only if frequent cuttings regulate the stand density in all dimensions. The average volume increment of selection forests is about 30% lower than the average volume increment of age class forest. The loss is mainly due to the longer period of regeneration and the abundance of small-sized trees with low growth rates.

This loss in productivity is economically equilibrated by lower cost for harvest and higher value of target trees. However, the large dimensioned trees of beech feed into a small market, i.e. it would not work if all beech forests converted to selective cutting.

Given the delicate balance of the diameter distribution and its maintenance under changing market conditions, a small scale shelterwood system may be easier to sustain than selective cutting in the future. We also think that there may be strong incentives to maintain a (modified) selection system, for cultural, historical, landscape aesthetics and recreation reasons, which all could make it worthwhile for forest owners and society to compromise economic efficiency, even though society requests these functions for free.

It emerges that selection cutting is a management system that is far from being "natural", but it is sustained by intensive management maintaining an artificial diameter distribution. This results not only in a high commercial value of harvested timber, bur surprisingly also in a higher resilience against biotic and a biotic disturbances when compared with unmanaged forest and with other management systems.

Disclosure statement

No potential conflict of interest was reported by the authors.

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