Transitioning monocultures to complex forest stands in Central Europe: principles and practice

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1 Introduction

The structure of forest stands is situated in the continuum between maximum uniformity like that of even-aged monocultures and maximum heterogeneity, as that of selection forests and other types of close-to-nature forests. During stand development, the structure may change in either direction along this continuum. It can be visualized through the age–height trajectories of the individual trees (Fig. 1). The pattern of these age–height trajectories reflects the synchrony or asynchrony of the tree development and cohort development. While all trees develop similarly in even-aged and mono-layered monocultures (a), they grow increasingly diverse in even-aged mixed-species stands (b), uneven-aged, two-layered mixed-species stands (c) and multi-aged and multi-layered mixed-species stands (d) that have no cohort structure. In the latter, we commonly find a broad spectrum of various trajectories, and a continuous ingrowth and dropout of individual trees.

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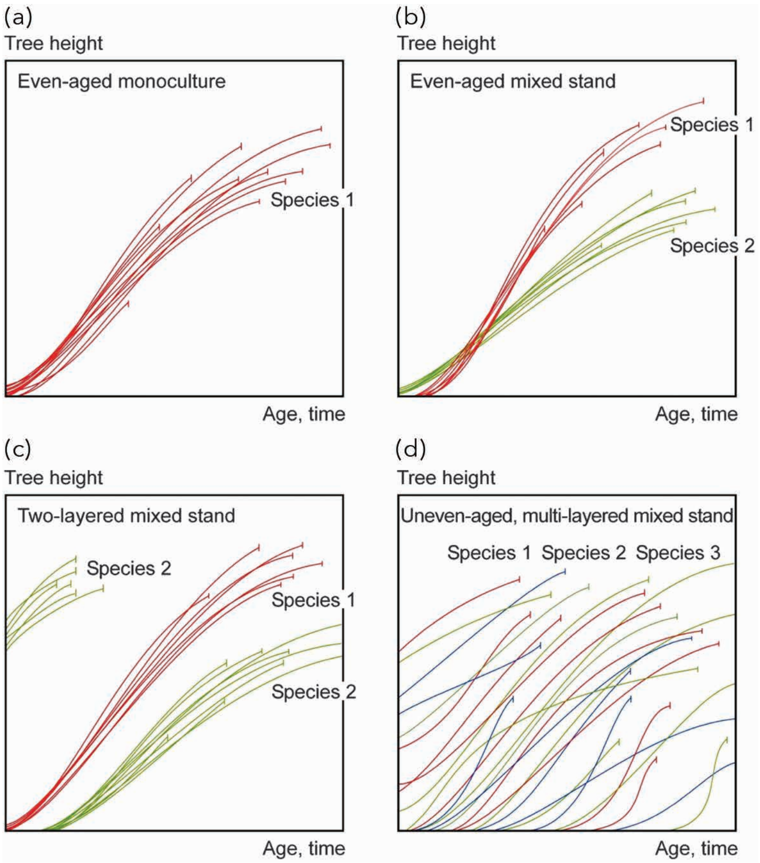

Figure 1 The four most important structural types of forest stands visualized through the age–height trajectories of the trees. (a) Even-aged and mono-layered monocultures with one cohort of trees, (b) even-aged mixed-species stands with two similarly growing cohorts of trees, (c) uneven-aged, two-layered mixed-species stands with two differently growing cohorts of trees, (d) multi-aged and multi-layered mixed-species stands without cohort structure but with a broad spectrum of trajectories, continuous ingrowth and dropout (curves with T-shaped ends) of individual trees.

This book chapter deals with the transformation of even-aged monocultures (a) into more complex forest stands (b–d). The main focus will be on the transformation of even-aged monocultures to multi-aged and multi-layered mixed-species stands, as this kind of transformation comprises all kinds of silvicultural, technical and planning challenges that emerge also in less extreme transitions, for example from (a) to (b) or (a) to (c).

In densely populated Central Europe, forests are expected to provide a lot: forest resources, forest ecosystem health and vitality, productive functions, biological diversity, protective functions and socio-economic services (MCPFE, 1993). This requires an integrative approach to forest management. Heterogeneous mixed-species stands are of special interest as they fulfil many ecosystem services better than monocultures. Therefore, homogeneous forest stands currently are frequently transformed into more heterogeneous stands. Consequently, selection forests and other kinds of close-to-nature forests are gaining ground.

In Section 2 of this chapter, even-aged and selection forests are introduced as borderline cases of the continuum from most homogeneous to most heterogeneous forest stands. In the former, the management and sustainability unit is represented by the normal series of age classes; in the latter, it is the selection forest itself, as it contains trees of all development stages.

In Section 3, advantages and disadvantages of the transformation from monocultures to more complex forest stands will be discussed; of special interest are the reasons for the ongoing transformation of monocultures.

In Section 4, the theoretical concept of transformation based on the development of the standing stock and the re-shaping of the tree diameter distribution in the transformation phase will be introduced. Important prerequisites, risks and criteria for a transformation will be also discussed.

Section 5 provides an example of a successful transformation. We will also show how monocultures of Norway spruce in the pre-alpine lowlands of South Germany may be transformed into a selection forest.

In Section 6, we display a scenario analysis with stand simulation models for developing guidelines for the transformation of even-aged forests to selection forest stands. Growth models can simulate the dynamics of stands they have been parameterized for – and more. When based on general rules and relationships, they can also simulate the behaviour of stands and treatment options for which there currently exist only few stands or experimental plots.

Section 7 introduces the theory of selection forest management. This section also deals with the regulation and maintenance of a successfully achieved selection forest structure, the thinning based on diameter class or target diameter and the deviation from the guideline curve and steady-state diameter distribution.

Selection forests that have been successfully managed for centuries will be introduced in Section 8 as model examples for the main principles, rules and guidelines. Their characteristic tree number–tree diameter guidelines, standing volume levels and stand density–productivity relationships will be introduced.

In Section 9, we will discuss the notion that, in view of climate change, mixed-species stands offer a special risk distribution, growth stability and adaptation to drought stress. However, here, establishment, silvicultural treatment and sustainable multifunctional utilization still require better knowledge. While research so far has focused mainly on mono-specific stands, there is still a lack of empirical knowledge and models for heterogeneous forest stands.

2 Even-aged monoculture forests versus selection forests

2.1 The concept of an even-aged and selection forest

Due to clearings in medieval times, overexploitation in the area of industrialization, and the devastation caused by the two world wars (Pretzsch et al., 2008), artificial regeneration from scratch and resulting even-aged and mono-specific stands (Fig. 1a) have been a focus of forest science and practice since the beginning of systematic forestry initiated through von Carlowitz (1713) and von Cotta (1821, 1828). Under natural conditions, that is in the absence of this strong human influence, uneven-aged stands with more species (Fig. 1b–d) would dominate in Central Europe. In contrast, even-aged stands, for example resulting from large-scale disturbances due to forest fires, beetle damage or storm in boreal or alpine forest areas, would play a minor role. This is a problem because forest science has, so far, focused mainly on even-aged mono-specific stands, which would play only a minor role under natural conditions; while mostly neglecting uneven-aged mixed stands. For instance, for even-aged mono-specific forests, the normal forest with the age class set-up has been invented and become the backbone of sustainable forest management in the last two centuries (Gadow, 2005; Hundeshagen 1823–45; Speidel, 1972). However, analogous scientific knowledge of the structure and functioning of more heterogeneous uneven-aged mixed stands and tools for their sustainable management are underdeveloped (Pretzsch, 2009).

Age-class forests consist of a mosaic of individual stands which are relatively homogeneous at the stand level, but strongly vary in age, species or stand structure between stands (Fig. 2a). Selection forests, on the other hand, are diverse in species and structure at the stand level; but this diverse structure remains similar on larger areas and over longer times periods (Fig. 2b). Thus, the diversity in age-class forests is low at the individual stand level but high at the forest unit or management block level. In the selection forest, the diversity is high locally but remains similar in space and time.

In this chapter, we introduce stands of N. spruce, silver fir and European beech as model examples for selection forests, since they already represent the dominating selection forests in Europe, and the ongoing transformation activities will further increase their importance in the future. In selection forests, tree species and age cohorts, which grow separately in age-class, are combined within one stand. For instance, N. spruces, silver firs and E. beeches of different sizes and ages can occur in close neighbourhood in selection forests (Fig. 2b). Due to their shade tolerance and ability to sit and wait in the understorey for

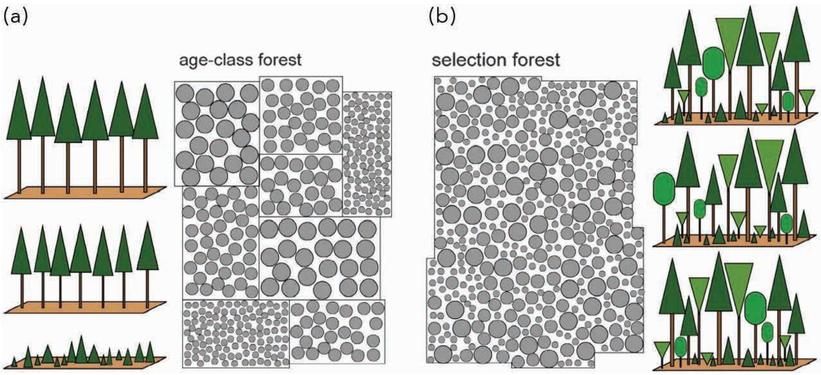

Figure 2 Stand structure in (a) even-aged normal forest and (b) selection forest. The age-class forest (a) consists of a spatial mosaic of stands with varying age, tree composition and structure. The selection forest (b) has a wider range of species and structural diversity at the stand level, but retains a similar structure across space and time.

decades, silver fir and E. beech play a key role in selection forests (Pretzsch, 1985). Selection forests may also consist of pure beech (Dittmar, 1990), spruce (Reisch, 1950; Indermühle, 1978) or pine (Guldin et al., 2017; Yamahata, 1965), as long as the standing volume is kept sufficiently low. Selection forests appear as unmanaged old growth forests. They look similar to the plenter phase of the cycle of old growth forests. Nonetheless, they are highly artificial systems (Mayer, 1984). To keep them in a steady state, they require continuous silvicultural management (Schütz, 1989, 1997).

At the stand level, these two approaches, that is age-class forest and selection forest, result in very different annual volume growth courses. Figure 3 shows the annual growth for age-class forest stands (Fig. 3a), the selection forest (Fig. 3d) and several intermediate approaches (Fig. 3b and c). In age-class forests (Fig. 3a), the current volume increment follows a uni-modal curve over time and decreases to zero at the time of the transition to the next forest generation. In the selection forest (Fig. 3d), the combination of trees of many age classes, sizes and species results in a relatively steady course of current volume increment, as the stand area is continuously covered at a high level of stand density and growth.

2.2 Age-class forest versus selection forest as a management unit

Before introducing the concept and techniques of transforming monocultures to heterogeneous mixed stands, we will briefly outline the basic principles of the silvicultural system age-class forest versus selection forest. As shown in Fig. 4a (from left to right), a management unit of an age-class forest consists

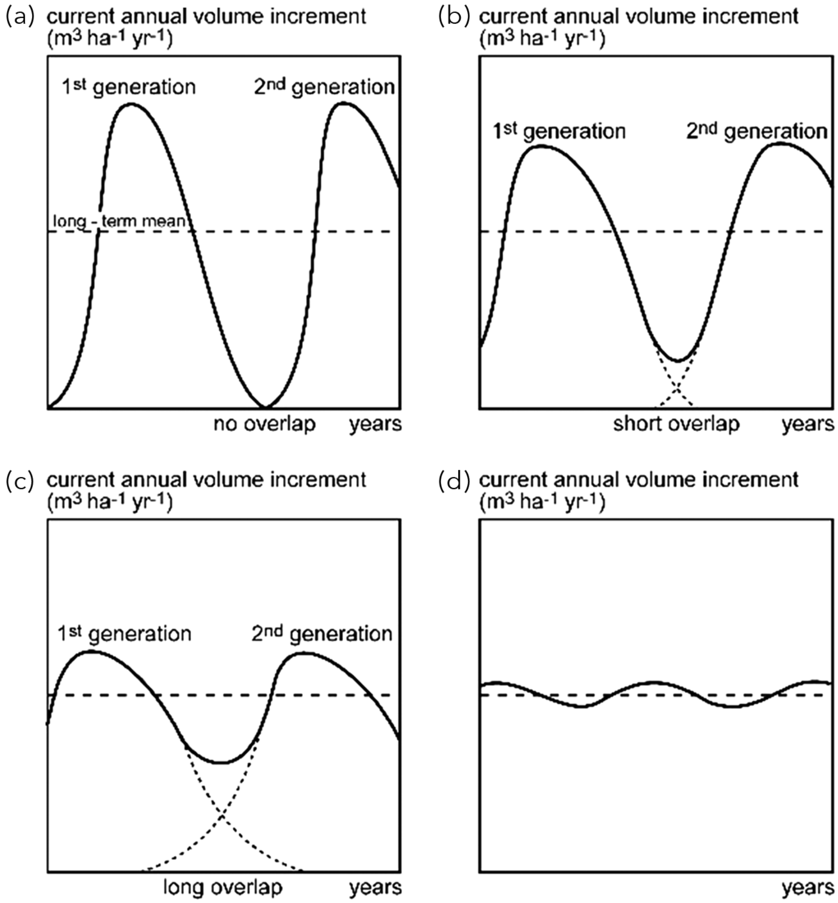

Figure 3 Schematic representation of the current volume increment for four different silvicultural concepts. (a) Clearcut system without generation overlap, (b) short overlap, (c) long generation overlap between successive stand generations and (d) selection forest system. The longer the overlap between trees or cohorts of different ages and sizes, the steadier the course of current volume increment. Source: adapted from Assmann (1970, p. 473).

of even-aged stands of different ages. In the ideal form of a normal forest, all age classes have the same share of the total management block area. In an alternating sequence, mature stands in the rotation age are harvested and replaced by regeneration. The normal even distribution of stand area over age class results in a mosaic of clearings and even-aged regeneration and stands of different ages. This results in a rather constant average standing stock and growth over the whole management unit. Summed up, the uni-modal tree number–diameter distributions of all stands of the management unit would

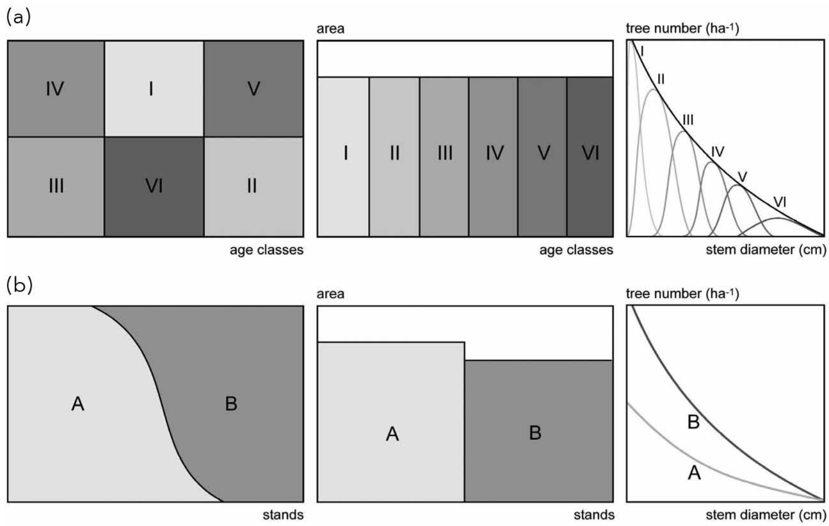

Figure 4 Schematic representation of (a) a management block with age-class forest stands and (b) selection forest stands. The division of the management block in stands, the area share of the stands of the management block and the resulting diameter distributions (from left to right).

yield an exponentially decreasing tree number–stem diameter distribution (Assmann, 1970). In contrast to the selection forest, this exponential tree number–stem diameter distribution results from merging different stands.

As a matter of form and order, selection forests are also divided into separate stands (Fig. 4b, from left to right). However, they do not represent different age classes. Rather, all stands are uneven-aged, mixed and multi-layered. Here, each stand has an exponential tree number–stem diameter distribution. Summing up all distributions of an entire management unit results in an exponential tree number–stem diameter distribution similar to the age-class forest. However, here the overall exponential distribution does not result from a combination of individual stands with different ages, but rather from individual stands, which all have exponentially shaped tree number–stem diameter distributions.

Selection forests of Norway spruce (*Picea abies* L.), silver fir (*Abies alba* Mill.) and European beech (*Fagus sylvatica* L.) are model examples of this silvicultural system. Under ideal conditions, they display an exponentially decreasing tree number with an increasing stem diameter (Fig. 4b); and each of the three tree species continuously contributes to all canopy layers from the understorey to the medium and upper layer. Because of this, the canopy space is extensively filled with assimilating leaf mass. Tree removal in the upper or medium layer cause gaps, while also improving light conditions and promoting growth in the layers below. This may balance the growth losses in the upper canopy. Consequently, multi-layered structure removals here do not generally cause growth losses as in the mono-layered forest. In the latter, thinning causes gaps that need a considerable time to be closed and exploited by neighbours in order to balance the losses of the removed trees. A continuous removal of trees of all diameter classes may keep the exponential diameter distribution and guarantee a continuous growth rate and steady state of structure and productivity (Fig. 3d).

3 The transition from monocultures to more complex forest stands

Complex forest stands, such as selection forests, often fulfil the various forest ecosystem functions and services better than age-class forest stands. The criteria for ecological, economic and social sustainable forest management (MCPFE, 1993) include the care for (1) forest resources, (2) forest ecosystem health and vitality, (3) productive functions, (4) biological diversity, (5) protective functions and (6) socio-economic functions. The primary reasons for the transition to close-to-nature forests are their advantageous stability, resilience, biodiversity and protective functions (cf. Table 1). The mechanical stability, drought resilience and risk distribution concerning (a) biotic disturbances represent special demands for forests under climate change and increase with structural

Table 1 Examples for limitations and benefits of a transition from monocultures to complex forest stands

Advantages	Disadvantages
Ecology	
Reduced risk, resilience and resistance in view of damage	Structural homogeneity at the regional level
Structure and habitat diversity at the stand level	No open space areas, genetic depletion
High carbon sink	Risk of windthrow in the transition phase
Economy	
Risk distribution, no planting costs	Challenging harvest techniques and high harvest costs
Low tending costs, focus on high volume	Lower wood quality
Stems, continuous cut and income	Restriction of tree-species cultivation, higher expenses for inventory and planning
Socio-economy	
Amenity and attraction of tall trees	Forest structure dark and humdrum for visitors
Permanent cut and employment of wood workers	Monotonous species assemblage
Low road damage by harvest	More difficult hunting and browsing control

and species diversity. Structural diversity can increase biodiversity, which in turn may improve risk resilience. Continuous forest cover reduces erosion and humus loss. Therefore, selection forests or other complex forest types are of special interest for state and community forests, which should provide a wide range of forest services for the public.

For smaller forest properties, selection forests have the special additional advantage of permanent cut and wood supply on the entire forest area. A normal age-class forest would be impossible due to the limited area, that is regular harvest would need to be interrupted for longer time periods. The selection forest is a kind of 'Dauerwald' ('permanent' forest), that is, the area is continuously under forest cover and forest management concerning regeneration, tending, thinning and threshold diameter felling. This results in a continuous wood supply and income based on silvicultural interference over the entire management block area.

In medium and advanced stand ages species diversity and structural heterogeneity can significantly increase the stand productivity; this is mainly due to better canopy space filling and light use by trees in different layers (Pedro et al., 2015; Zeller et al., 2018; Zeller and Pretzsch, 2019).

The advantages of more complex forest stands, for example their higher stability against various disturbances and their superiority regarding many ecosystem services, attract attention (Bauhus et al., 2017, Bravo-Oviedo et al., 2018). Thus, at present there is a tendency towards transformation of age-class monocultures to continuous covered forestry worldwide (Vitkova and Dhubháin, 2013). This generates interest in methods of inventorying, characterizing and modelling (del Río et al., 2016; Gadow et al., 2012; Pretzsch, 1985, 1996) heterogeneous stands and in concepts and guidelines (Pretzsch and Zenner, 2017) for transforming age-class monocultures to more complex stands.

In the continuum between maximum uniformity like that of even-aged monocultures and maximum heterogeneity, selection forests represent a very natural variant (Schütz, 1989, 1997). However, there are many other silvicultural concepts which extend the overlap between successive stand generations in order to avoid clearcut and mono-specific and mono-cohort forest stands (Brockway et al., 2007; Guldin, 2007; O'Hara, 2002). Most of the concepts mimic small-scale natural disturbances (O'Hara and Ramage, 2013) or aim at leaving retention trees (Gustafsson et al., 2012; Lindenmayer et al., 2012) for a continuous forest coverage. The worldwide tendency of close-to-nature silviculture is for example represented by Pommerening (2006) in Great Britain, (Brockway et al., 2007), Guldin (2007) and Nyland (1998, 2003) in the United States, Coates (2002) and Weetman (2005) in Canada, Scott et al. (2015) in Australia, and Seydack (1995, 2000) in South Africa. In the following, we sketch the specific Central European approach of transitioning monocultures to complex forest stands.

4 The concept of transformation

4.1 Regulation of the standing stock and diameter distribution during the transformation process

The challenge of the transformation process is expressed for example by the development of the standing volume stock (Fig. 5). In the age-class forest the standing volume stock accumulates continuously during stand development and is not reduced until close to the rotation age, when regeneration is established naturally or artificially (Fig. 5a). Moreover, the standing stock is either reduced abruptly through clear cut; or continuously in the final years of the rotation, as represented by the decreasing saw tooth curve in Fig. 5a. During or after this removal, regeneration is established to create the next-stand generation (see Fig. 3).

In contrast, the transformation of even-aged monocultures to selection forests requires a much earlier stand volume reduction (Fig. 5b). Commencing at the age of approximately 50 years, the main stand volume is continuously reduced to promote naturally or artificially established regeneration in the understorey. Meanwhile, the total stand volume is restocked by the cohorts ingrowing from the understorey to the main stand during a long period of generation overlap. Repeated and spatially separated opening up of the main

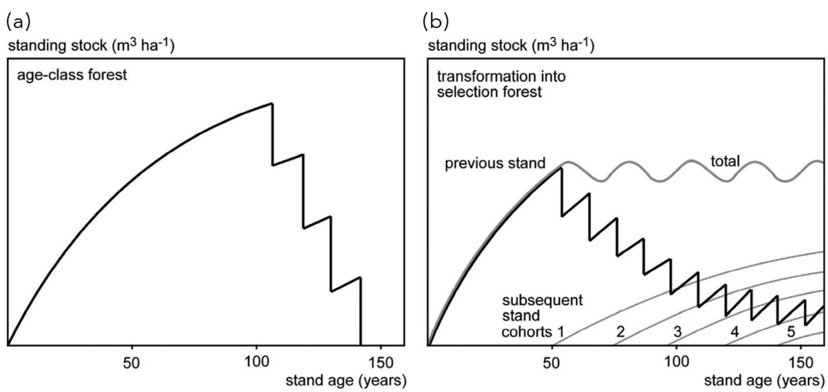

Figure 5 Regulation of the standing stock in the transition phase from an age-class forest to a selection forest structure. (a) In age-class forests, the standing stock continuously accumulates with increasing age and is reduced in advanced stand age upon approaching the rotation age. (b) For transition to selection forest or other kind of continuous covered forest stands, the standing stock starting at middle age is continuously reduced so that cohort of natural or artificial regeneration can develop under the main stand. The standing stock of the initial stand and the cohorts (here n = 1 . . . 5) of the subsequent stand together is maintained in a steady state (wavy line) as trees are removed (decreasing sawtooth line) and growing in (increasing volume of ingrowing cohorts) continuously.

stand, and planting or natural regeneration efforts, allow the next generation to develop in several cohorts (see Fig. 5b, n = 1 . . . 5). Thus, an understorey diverse in structure and age gradually grows into the remaining main stand and generates an uneven-aged and multi-layered continuously covered forest, for example a selection forest. The successful establishment of the regeneration requires a reduction of the standing stock significantly below the usual density in the final phase of age-class forests; otherwise, the regeneration will be out-shaded and vanish over time.

The process of transformation can be demonstrated in more detail through the development of the tree number–stem diameter distribution (Fig. 6). Starting with the approximately bell-shaped distribution typical of mature even-aged mono-specific stands (t = 0), the naturally or artificially established cohorts in the understorey continuously widen the left branch and extend the range of the diameter distribution to the left, while the distribution of the main stand develops to the right. Consequently, after several decades of transformation activities, the even-aged mono-specific stand will be converted to an uneven-aged multi-species stand with an exponential decrease of tree number with diameter (Fig. 6, from left to right).

This reshaping of the tree number–diameter distribution from a normal to an exponential structure requires continuous thinning from above to reduce density, mechanically stabilize and vertically structure the main stand; while cohorts of regeneration are naturally or artificially established. If the regeneration and main stand develop in a sufficiently heterogeneous temporospatial pattern, the initially bell-shaped distribution can be (permanently) transformed into an exponential structure. The exponential decrease of tree number with increasing stem diameter in Fig. 6, t = 75 still consists of bell-shaped distributions of different cohorts. Over time, this cohort structure will vanish and turn into a selection forest structure with individual trees rather than cohort mixing and distribution pattern (see Fig. 1d).

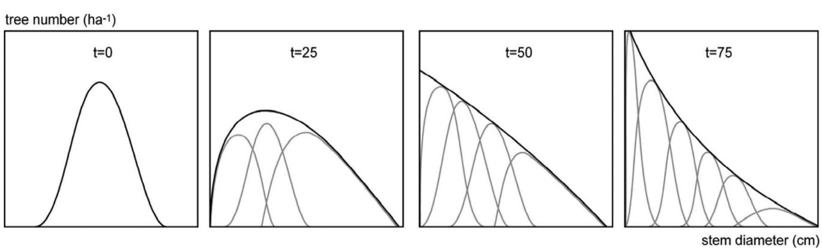

Figure 6 Schematic representation of the characteristic bell-shaped uni-modal diameter distribution of an age-class forest (t = 0) and its continuous transformation into an exponentially decreasing tree number–diameter relationship by measures of silvicultural transition from age-class to selection forest (t = 25–75).

4.2 Essential decisions and practical measures for stand transformation

Starting points for transformation are mostly 50–100-year-old mono-layered conifer stands. Whether a transformation is promising or at all possible depends on tree and stand's stability against storm, wind, ice-breakage and bark beetle attacks. In the case of relative instability, measures of transformation such as opening of the stand may cause immediate windthrow. The earlier the transformation starts, the better the stands can react by crown expansion, stem stabilization or root extension. Thus, thinning from above and underplanting at the age of 40 or 50 (years) is less risky than a later start in the mature stand development phase. In later stand development phases, gaps after thinning remain bigger, the growth reactions are slower and the individual stability is additionally lowered due to smaller crown length, higher h/d ratios and lower root–shoot allometry due to long growth in density and mono-layered conditions (Reininger, 1990).

Transformation strives for a slow and cautious opening up of the canopy in order to stabilize the main stand and locally promote the natural or artificial regeneration in an irregular and patchy pattern over the stand area. A homogeneous and whole stand level regeneration would simply replace the present mono-layered stand with another generation of mono-layered stand. The patchiness or individual-tree structure of the mixture can be generated by continuous opening up of parts of the stand, while keeping other parts closed and alive as long as possible. This may cause a broad and spatially varying pattern of growing conditions and heterogeneity in growth conditions and growth rates. As a result, the understorey does not develop homogeneously but rather in a horizontally and vertically rich structure. The main stand enables a continuous regulation of the heterogeneity but also keeps the stand productivity at a high level – even in the phase of generation overlap (Fig. 3b and c).

The probability of (successfully) keeping parts of the main stand for long-term generation overlap, regulation and structuring by shading depends on the structure of the main stand. The wider the diameter distribution, the longer the crowns of the tall and especially of the smaller trees; and the more regenerative the stems and crowns of the so far suppressed trees after thinning, the more the overlap can be prolonged. Positively contributing factors include the diameter variation of the main stand and the number of regenerative social class 3 and 4 trees. Quantitative indicators of a readiness for transformation are low h/d ratios, high crown ratios and larger variation coefficients of the diameter and height distribution.

Small-scale openings of the canopy in conifer stands caused by snow breakage, transparent tree species such as pines or larches and even locally restricted bark beetle damage in the history of the stand can have a structuring, stabilizing and natural regenerating effect. They may prepare a stand unintentionally for transformation. If a stand shows the necessary stability and structure, the transformation may be continuously developed by stock reduction to eventually 300–500 m^3 ha^{-1} underplanting and promotion of natural regeneration. The regeneration starts from the inner part of the stand and can be promoted by an individual tree or group-wise removal.

Stands that are not yet ready for transformation can be prepared, especially if they are still young (<50 years). Through repeated thinning from above, the trees of the main stand may be stabilized in their h/d ratio and crown length. Such interventions also promote regeneration. These measures widen the stem diameter and size distribution of the stand; tall trees are accelerated in their growth, while small trees are slowed down, so that the range of sizes increases. Where this preparation is successful after 10–20 years, the respective stand can be lowered in standing volume, regenerated through artificial underplanting and continuously developed towards the structure and size distribution of a selection forest.

Figure 7 summarizes the most relevant decision criteria for a transformation of age-class forest into selection forest-like stands. (1) The procedure starts with an assessment of whether the structural differentiation, variation of size structure, life expectancy, stability, crown plasticity and vitality are sufficiently high for a stand transformation. (2) If the stand is sufficiently structured, a classical selection cutting may start. This means an individual- or troop-wise removal of trees, opening of the overstorey and initiation and promotion of

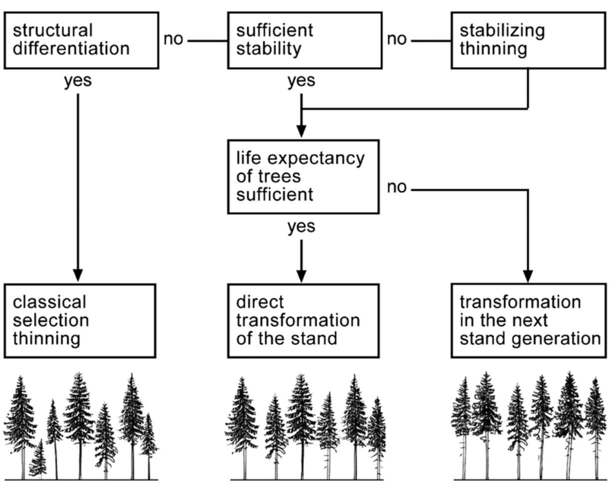

Figure 7 Decision tree for the transformation of age-class forest into continuous covered forest (according to Schütz, 1997).

the regeneration. (3) If the stand is not yet ready for transformation, its structure may be prepared through a stabilizing thinning from above. A selective cutting may further increase both stability and structure. (4) If the preparing cuts increased the stability survival and structure and the size variation of the stand, the measures of transformation, such as opening up, planting or natural regeneration or continuous fostering of the understorey can be initiated while the overstorey is continuously reduced. (5) If the chance of survival, stability and vitality of the prepared stand remain too low, the transformation cannot be achieved in this way, but instead with the subsequent stand generation. In this case, stability of the overstorey and early establishment of the regeneration should be promoted in the early stand development phase.

If a stand lacks sufficient stability and structural heterogeneity before and even after preparation, transformation in this generation should be avoided, as the risk of wind throw or storm damage and the respective financial loss is too high. In this case, harvesting the stand through classical whole stand clear cut or strip-wise clear cut and regenerating it artificially afterwards using the available pre-regeneration may be more advantageous.

5 A practical example of transformation

5.1 Developing the standing volume in the transition phase

As a representative example, we describe the transformation of even-aged Norway spruce stands on the gravel plane 20 km southeast of Munich. They belong to the municipal forest of Munich, lie 590 m a.s.l., with a mean temperature of 7.2°C and annual precipitation of 1130 mm year^{-1}. The natural tree-species combination would be European beech, sessile oak, Scots pine, silver fir and a low share of N. spruce. However, due to the building timber demand of the city of Munich, the natural forests were already replaced by spruce plantations several centuries ago, and the present ~140-year-old stands were established as plantations after clear cut. Due to the shallow soils, the alpine winds and the mono-specific character, these stands are strongly endangered by drought, windthrow and bark beetle attacks. Therefore, the stands were underplanted with 2000–3000 tree ha^{-1}, mainly fir, beech and maple several decades ago to prepare the transformation (Schmitt, 1994a,b). In 1990, we established the two experimental plots MUE 145/1 and 145/2 in these stands in order to monitor and analyse their transformation process.

On both experimental plots, the standing volume amounted to 500–600 m^3 ha^{-1} in 1990 at a stand age of 115 years. In the following 25 years, the standing volume was continuously reduced to about 250 m^3 ha^{-1} in 2014 at an age of 138 years (Fig. 8a and b). Due to the lower standing stock on MUE 145/1, the young stand is already further developed than on plot MUE 145/2,

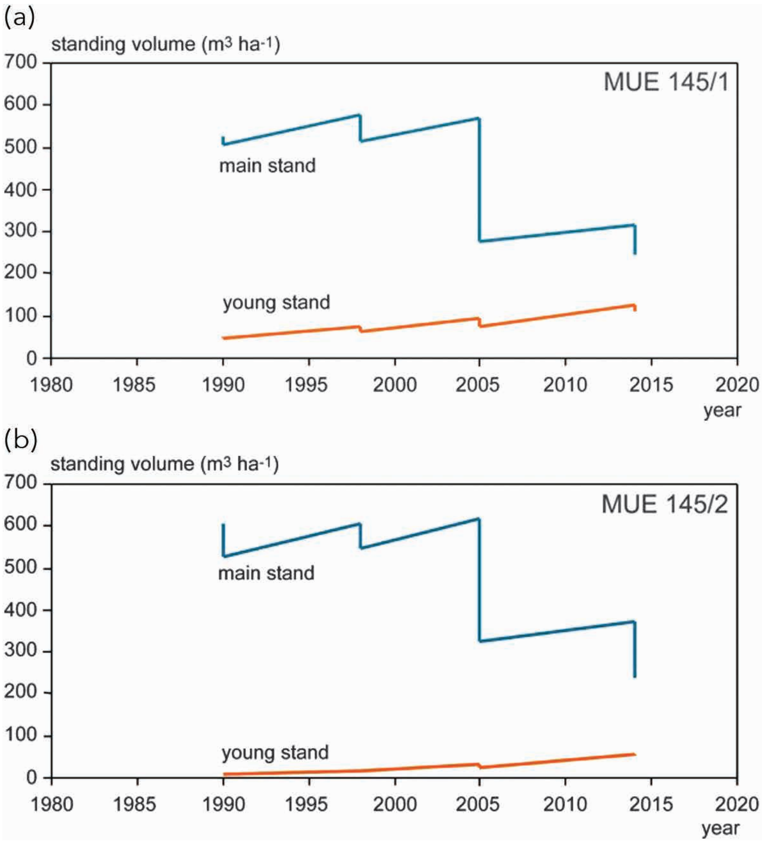

Figure 8 Development of the standing stock in the transformation phase of the experimental plots München 145/1 and 145/2 (transformation from mono-layered Norway spruce stands to mixed stands of Norway spruce, silver fir and European beech). The standing stock of the old stand has been reduced continuously, while the volume of the young stand is increasing. Due to the stronger volume reduction on (a) MUE 145/1, the young stand is ahead of the young stand on (b) MUE 145/2.

where the establishment started at the same time in 1955 but was better promoted by volume reduction. The volume reduction started moderately on both plots to improve the stand stability. After initial stabilization, several stronger thinnings followed with removal of 200–300 m^3 ha^{-1} in the year 2005. In classically managed age-class forests, the standing volume in this age phase would accumulate up to 500–1000 m^3 ha^{-1}. On the experimental plots MUE 145 standing volume is reduced to about a third in order to favour the stand structure and growth of the natural and artificial regeneration which started in 1955 and was completed by additional planting and promoted by volume removal in the main stand from 1995 to 2014.

The inventory of the stands in 1990 considered the old stand (age >90 years and dbh ≥6.5 cm), the young understorey stand (age <90 years and dbh ≥6.5 cm) and the regeneration (dbh <6.5 cm).

5.2 Developing the tree number–diameter distribution of the main stand and young stand

The tree number–diameter distribution of the young and main stand is bimodal on both plots (Fig. 9a and b), with a higher initial number on MUE

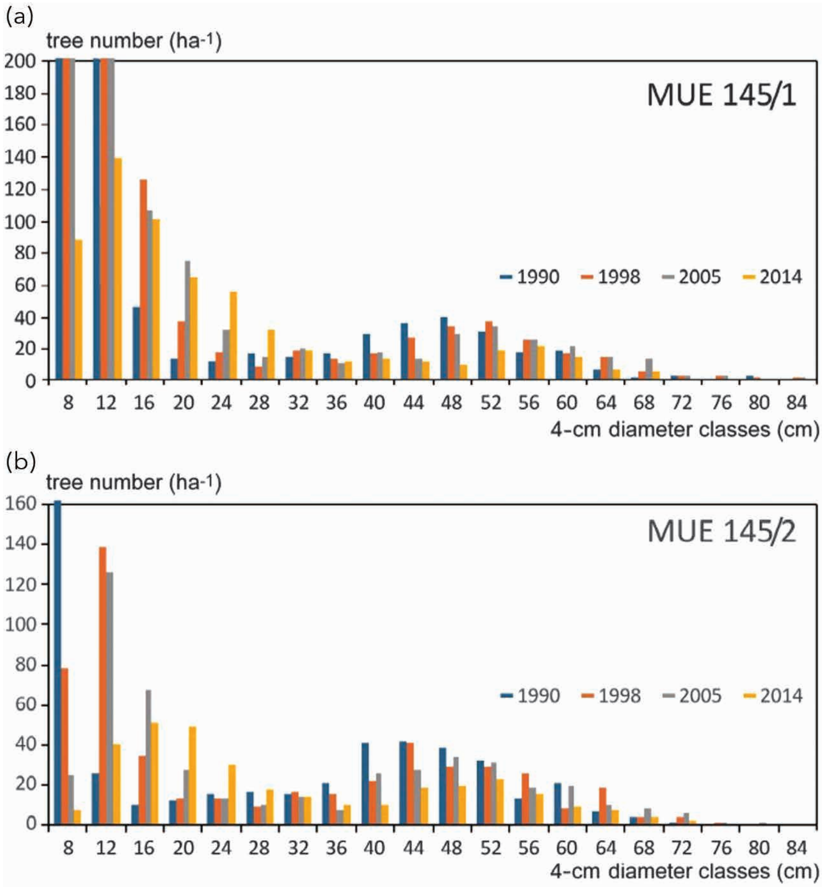

Figure 9 The tree number–tree diameter distribution for the surveys in 1990, 1998, 2005 and 2014 on plots MUE 145/1 and 145/2 of the transformation experiment München 145. Starting with a relatively bell-shaped and narrow diameter distribution at the beginning of the survey in 1990, the frequency distribution becomes wider and planting with small tree increases at the expense of the tall trees, which are continuously removed to promote the young stand and regeneration.

145/1, where the standing volume was lower than on MUE 145/2 since the start of the transformation thinnings. Together with the tree numbers of the natural regeneration (trees <6.5 cm at breast height), which amounts to 1000–1500 trees ha^{-1}, the distribution is already nearly exponentially shaped. From the first survey in 1990–2014, the distribution on both plots shifted to the right, as new natural regeneration accumulated and the tall trees were left and growing taller over the 25 years of transformation cutting.

5.3 Horizontal and vertical structuring of the stand

The old stand, the trees of the young stand (≥6.5 cm) and the regeneration (<6.5 cm) are distributed differently on the two plots (Fig. 10a and b). While the strong opening up of the canopy on MUE 145/1 caused a clustered and homogeneously layered regeneration and young stand (Fig. 10a), the stand structure on MUE 145/2 is more heterogeneous and suitable for a selection

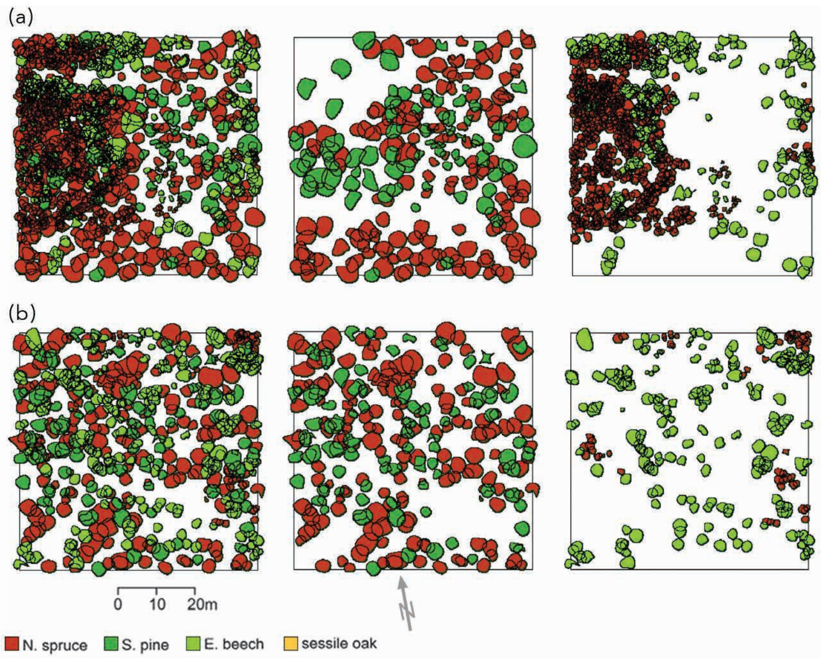

Figure 10 Crown maps of the transformation experiment München 145/1 and 2 at the survey in 1998. Plot MUE 145/1 (a) shows a cluster-wise opening of the canopy, while on plot MUE 145/2 (b) the opening of the canopy is more heterogeneous and tree- to group-wise opening and causes more heterogeneous light and growing conditions for the understorey. Crown maps for the whole stand and the old stand and the young stand (≥6.5 cm) separated (from left to right).

forest approach (Fig. 10b). If the canopy of the old stand is opened up too strongly and on too large areas, as on MUE 145/1, the mono-layered old stand will be replaced by another mono-layered stand in the next generation. In contrast, a more local, gap-wise opening up, such as on MUE 145/2, will pave the way for a multi-layered stand with a rich horizontal and vertical structure as is typical for a selection forest (Fig. 11).

The stand components' old stand, trees of the young stand (≥6.5 cm) and regeneration (<6.5 cm) are distributed differently on the two plots (Figs. 11 and 12).

Due to the extensive opening up of the canopy of the old stand over the last 20 years, the young stand and natural regeneration developed homogeneously on the plot MUE 145/1. A few non-regenerated parts remain in the northwestern and southern parts of the experimental plot, while the rest of the plot is largely regenerated homogeneously in a mono-layered fashion. This is caused by a too homogeneous opening-up of the canopy on plot MUE 145/1, compared to a more diverse structure on plot MUE 145/2 (Fig. 10b).

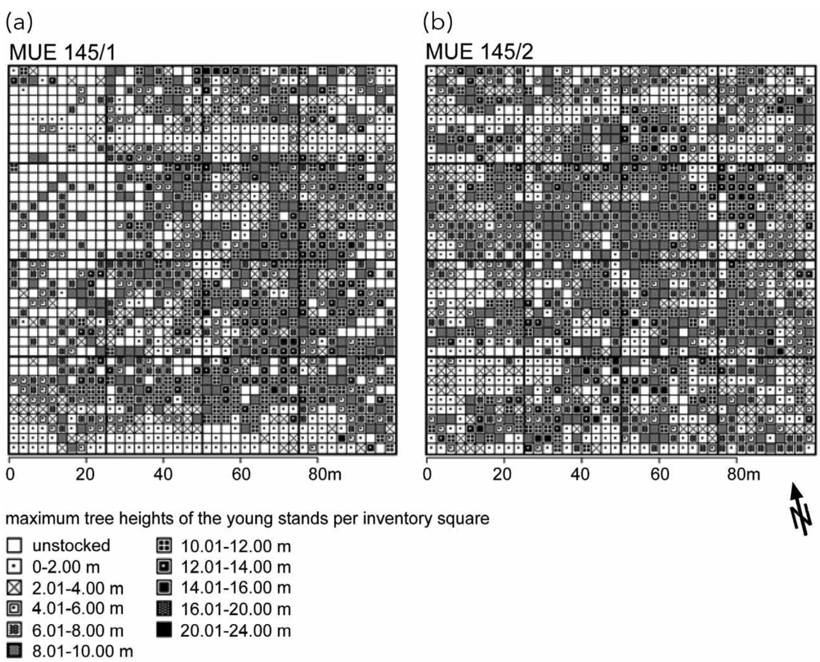

Figure 11 Horizontal (a) and vertical (b) structuring of the young stand and regeneration on the transformation experiment München MUE 145/1 in the 1998 survey.

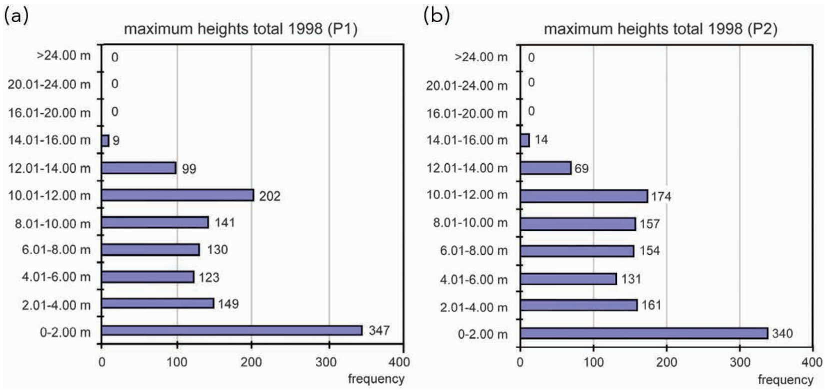

Figure 12 Tree number–tree height distribution of the young stand on the transformation experiment München MUE 145/2 at the survey in 1998.

6 Models for scenario analysis

6.1 Scenario analysis with simulation models for developing guidelines for transformation of even-aged forest into selection forest stands

Growth models integrate knowledge on tree and forest structure and functioning. They can simulate the dynamics of stands they have been parameterized for – and more. When based on general rules and relationships, they can also simulate the behaviour of stands and treatment options for which model stands or experimental plots are still mostly lacking (Pretzsch et al., 2008, 2015a,b). In the following sections, we apply the growth simulator SILVA (Pretzsch et al., 2002) for simulation of transformation scenarios (Pretzsch et al., 2002). Although models cannot replace respective experiments, they can bridge empirical knowledge gaps using simulation (Utschig, 1999; Hanewinkel and Pretzsch, 2000). Waiting several decades for experiments using transformation operations does not represent a real alternative. The challenge of transformation has to be faced now.

Below, we present example scenario runs for the development of silvicultural guidelines for the transformation of even-aged mono-specific Norway spruce stands in the mountain zone of the Bavarian Alps into uneven-aged mixed-species stands (Fig. 13).

Scenarios were run for different site and initial stand conditions (Bayerische Staatsforsten (2018a,b). They reflect the growth reactions of Norway spruce, silver fir and European beech and sycamore maple in pure and mixed-species stands. We calculated scenarios for different regeneration procedures, for

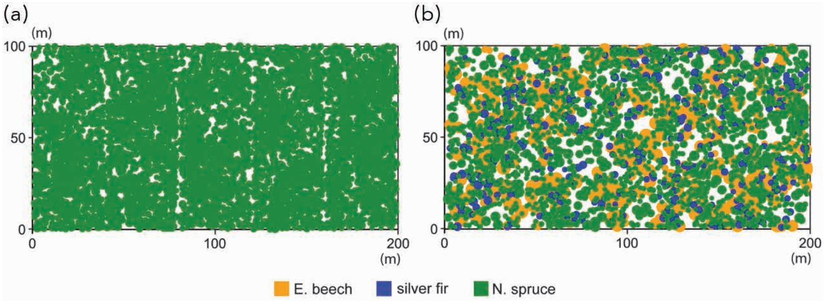

Figure 13 Initial stand of Norway spruce (a) and uneven-aged mixed-species stand of Norway spruce, silver fir and European beech as target state (b). The options of transformation may be analysed by scenario analyses with spatially explicit stand simulators.

the over- and understorey and the processes triggered by gaps, fernal coups (thinning), cable crane openings and regeneration slits. We simulated different procedures of opening up stands by planting, natural regeneration and threshold diameter harvest. The SILVA model simulates silvicultural procedures including macrostructures (femel gaps, regeneration slits, cable crane routes) and a broad spectrum of silvicultural measures of tending, thinning and final harvest (selection thinning, future crop tree thinning, mixing regulation, threshold diameter harvest) (Fig. 14). The scenarios reflect the long-term consequences of various procedures of canopy opening up, forest utilization and final harvest over 150 years (Fig. 14).

6.2 Approaches to simulation and scenario analysis

The simulations start with 2 ha of 20-year-old monocultures of Norway spruce generated based on the inventory data of the respective area. The position-dependent character of the simulator SILVA allows for a broad range of different temporospatial approaches of stand treatment and regeneration (Hilmers et al., 2017). Figure 15 shows the development of the main stand development (a) without treatment, (b) with cable crane lines and slit cut, (c) combined shelter–femel coup, (d) gap cut and (e) strip-wise clear cut.

6.3 Results

The scenarios were run over 150 years to cover the regeneration phase. They reveal the long-term effects of different silvicultural options on, among others, standing stock and stand growth (Fig. 15). Two of the five options shown, that is the establishment of cable crane lines and slit cuts as well as the combined shelter–femel coup, arrive at an equilibrium at a stand age of

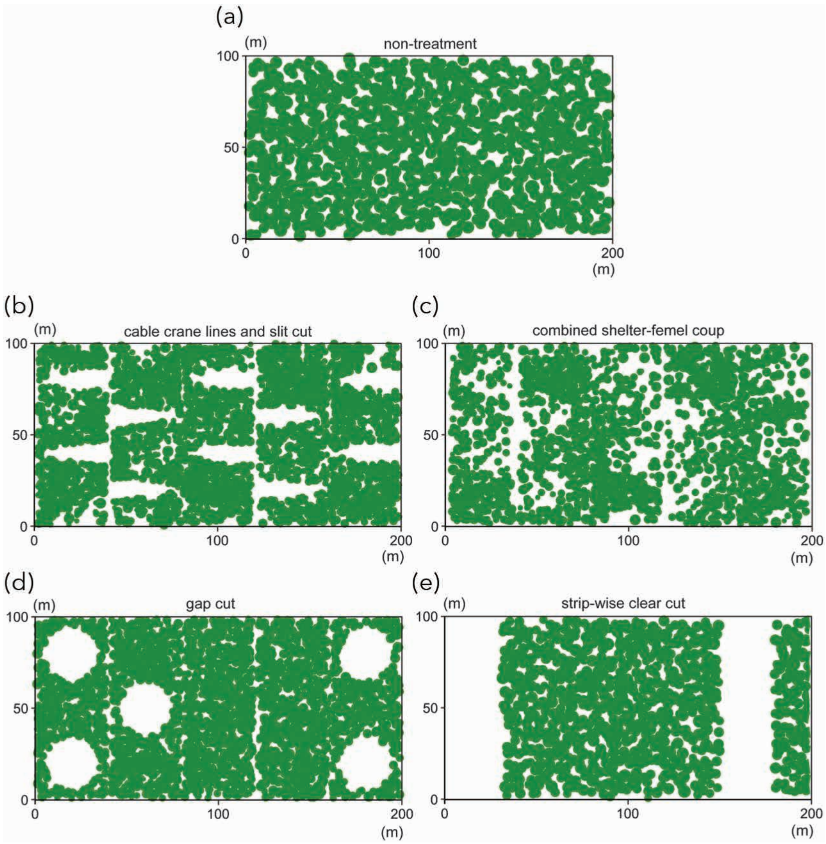

Figure 14 Simulation of the development of the main stand (a) without treatment, (b) with cable crane lines and slit cut, (c) combined shelter–femel coup, (d) gap cut and (e) strip-wise clear cut. The simulator SILVA allows for a broad range of different temporospatial approaches for stand treatment and regeneration (Hilmers et al., 2017).

100 years. The steady state of standing volume and annual volume growth lasts at least until the end of the simulation run at a stand age of 150 years. Both options are of special interest for the transformation to selection forest (Hilmers et al., 2017). The steady state in both cases is achieved by a standing stock of 400–500 $m^3\,ha^{-1}$, which enables a continuous stand growth of 10–12 $m^3\,ha^{-1}\,year^{-1}$. Both options enable a transformation to a selection forest.

6.4 From scenario simulation to guidelines

The scenario analyses resulted in silvicultural guidelines for creation and management of Norway spruce–silver fir–European beech mixed-mountain

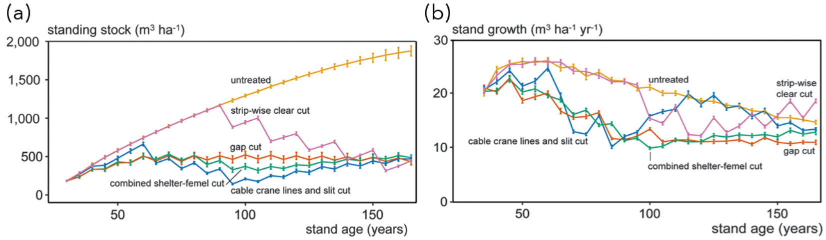

Figure 15 Development of (a) standing stock and (b) stand volume growth according to the simulation of non-treatment, strip-wise clear cut, establishment of cable crane lines and slit cut, combined shelter–femel coup and gap cut. The establishment of cable crane lines and slit cuts as well as the combined shelter–femel coup result in an equilibrium of standing volume and stand growth at stand age 100, which lasts at least until the end of the simulation run at age 150. Both options are of special interest for the transformation to selection forest (Hilmers et al., 2017).

forests in regions where Norway spruce monocultures have, so far, dominated. Based on a broad set of temporospatial treatment options, the guidelines propose a silvicultural and technical procedure as shown in Fig. 16. This applies to the transformation of Norway spruce monocultures into selection forests, but also to the long-term management of already-existing Norway spruce–silver fir–European beech mixed-mountain forests.

The procedure starts the regeneration by the establishment of cable crane lines (vertical lines) and slit cuts (oval and rectangular branches) in 50–60-year-old stands (Fig. 16a). In this way, existing gaps and openings (hatched areas) are integrated.

Subsequently, the stand is accessed via the same cable crane lines to cut around the edges of the slits and open above the upcoming regeneration (Fig. 16b).

Next, the regeneration process is continued from new cable crane lines between the existing ones. The main approach consists of threshold diameter cuts, structure generating thinnings in the still dense parts of the stands and establishment of more slits for artificial and natural regeneration. Thus, the way to the selection forest structure with various tree species, multi-layered structure and cohort of different development stages is paved (Fig. 16c).

Further femel and selection coups finally establish selection forest structure; subsequently, the first tending and thinning measures commence in the ingrowing stand (Fig. 16c).

The spatial and temporal pattern of the silvicultural interference can be modified very flexibly with the simulator SILVA, until a set of reasonable options is found. Of particular interest is the achievement of a steady state in terms of standing stock and standing volume growth. Figure 17a and b shows a set of options which may be recommended for the management and maintenance

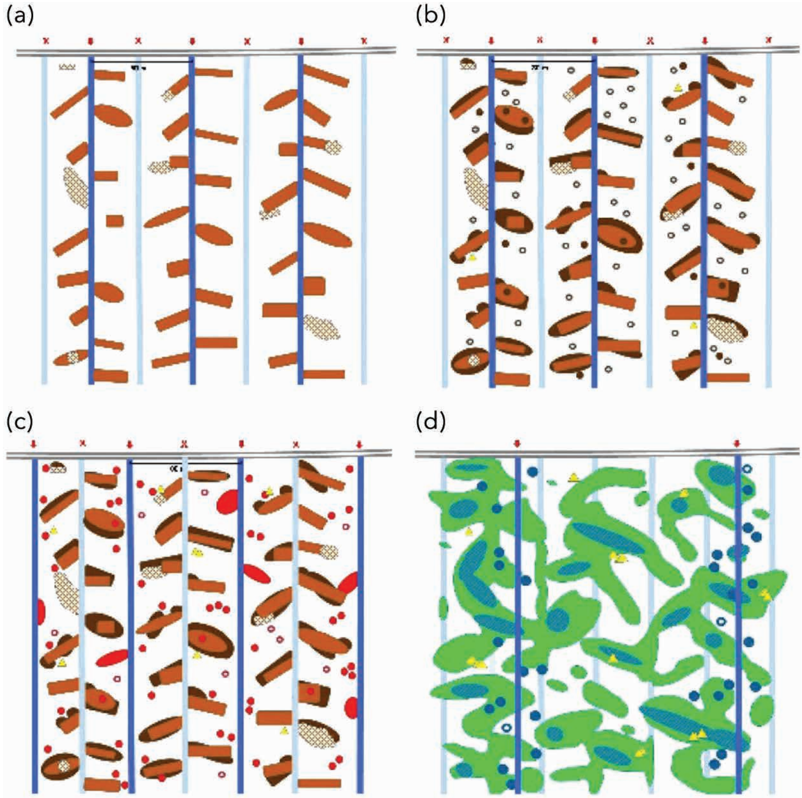

Figure 16 Spatial and temporal order of the canopy openings for regeneration (slits, circles, clusters and spots) in the mountain forests in combination with using cable crane lines (vertical lines). (a) Initiation of the regeneration by establishing slit cuts (rectangular stripes) starting from the cable crane lines (vertical lines) and integrating already-existing gaps (hatched areas). (b) Follow-up interventions proceeding from the same cable crane lines by opening up further and moderately extending the stripes and gaps (dark border zones). (c) Continuing the regeneration process, this time starting from the cable crane lines in between, by threshold diameter cutting, structure promoting thinnings from above and creation of more slits and gaps. (d) Transition to the selection forest phase by connecting stand areas in different development phases. Continuous femel- and selection cuts for improving the uneven-aged and multi-species structure towards a selection forest structure. First selective tending and thinning in the partly naturally and artificially created lower and medium stand layer (after Bayerische Staatsforsten 2018b, p. 109).

of already-existing Norway spruce–silver fir–European beech mixed-mountain forest in regions and for the transformation of Norway spruce monocultures to selection forests of Norway spruce–silver fir–European beech mixed-mountain with a certain admixture of sycamore maple.

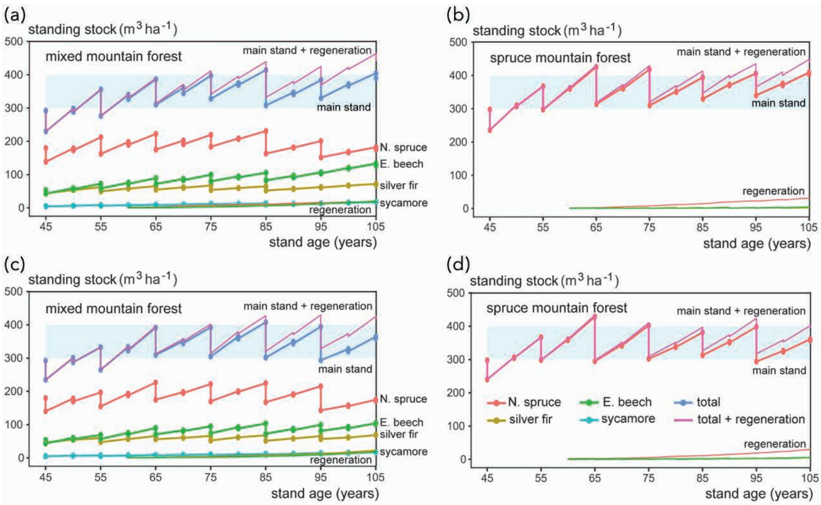

Figure 17 Scenario analyses of the standing volume stock in (a and c) mixed-mountain forests of Norway spruce, silver fir and European beech and (b and d) Norway spruce monocultures of high-site quality. (a) and (b) show the trajectories for stand development after establishment of cable crane lines and slit cuts, respectively, and (c) and (d) for combined shelter–femel coup and gap cut (modified after Bayerische Staatsforsten, 2018b, p. 91).

The scenario analyses resulted in the silvicultural guidelines for creation and management of Norway spruce–silver fir–European beech mixed-mountain forest in regions where Norway spruce monocultures have so far dominated. Based on a broad set of temporospatial treatment options, these guidelines propose a silvicultural and technical procedure as shown in Figs. 16 and 17. It applies to the transformation of Norway spruce monocultures into selection forests.

For practical application, the results can be summarized in set level stocking curves as shown in Fig. 18. They reflect the target level of the standing stock for various stand development states, which allows for a transformation with upcoming regeneration for fertile, medium and poor sites (upper, medium and lower level of the curve bundle). In the advanced development state, the guidelines recommend a steady-state stock of 300–400 m^3 ha^{-1} (volume harvested without bark). This stock allows for a continuous covered forest with diverse vertical layering and a continuous stand growth of 10 m^3 ha^{-1} $year^{-1}$ (Hilmers et al., 2018).

The development of guidelines is further influenced by other ecological, economical and social criteria (Hilmers et al., 2018). However, the development of the standing stock and growth and the achievement of a long-term steady state play a crucial role; and most other criteria depend on this steady state

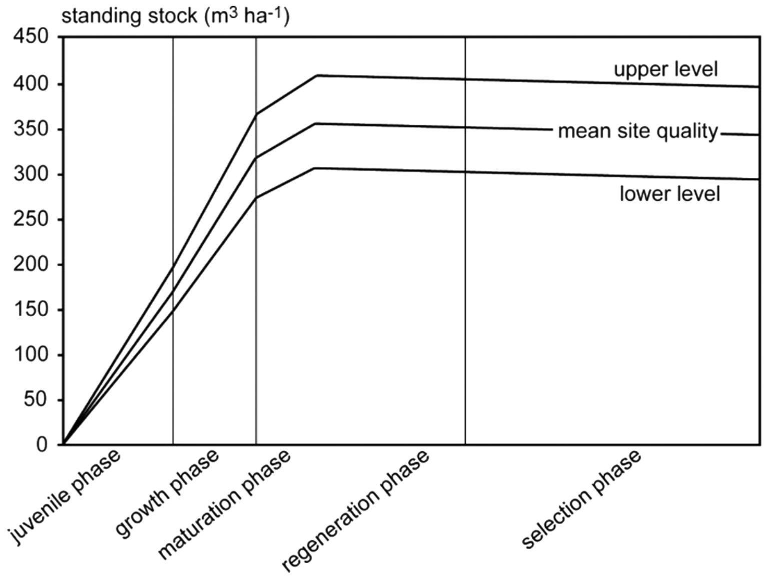

Figure 18 Standing stock guidelines for the transformation of age-class forest stands into selection forests. After the juvenile, growth and maturation phase, the accumulation of the standing stock is restricted so that regeneration and vertical structure may be established, and selection forest structure achieved (modified after Bayerische Staatsforsten, 2018b, p. 41).

structure, volume and growth (Forest Europe, 2011; MCPFE, 1993; Dieler et al., 2017).

7 Principles of selection forest management

7.1 Regulation and maintenance of the resulting selection forest structure

Under steady-state conditions, when the tree number decreases exponentially with increasing tree diameter, all height classes within the canopy are occupied (Fig. 19a). The steady-state and exponential relationship between tree number and diameter can be achieved by different levels of standing volume stock. The figure represents respective stands in steady state with high, medium and low standing volume (Fig. 19a, from top to bottom). Their common characteristic is that all canopy layers are occupied with trees of the three species (Köstler, 1956). To maintain the structure in a steady state, silvicultural measures should regularly remove tall and medium-sized trees and tend to the understorey by selection and promotion of high-quality ingrowth and small trees.

Delayed silvicultural interventions may cause a surplus of tall trees, a closure of the canopy and an outshading of the small- and medium-sized trees in the

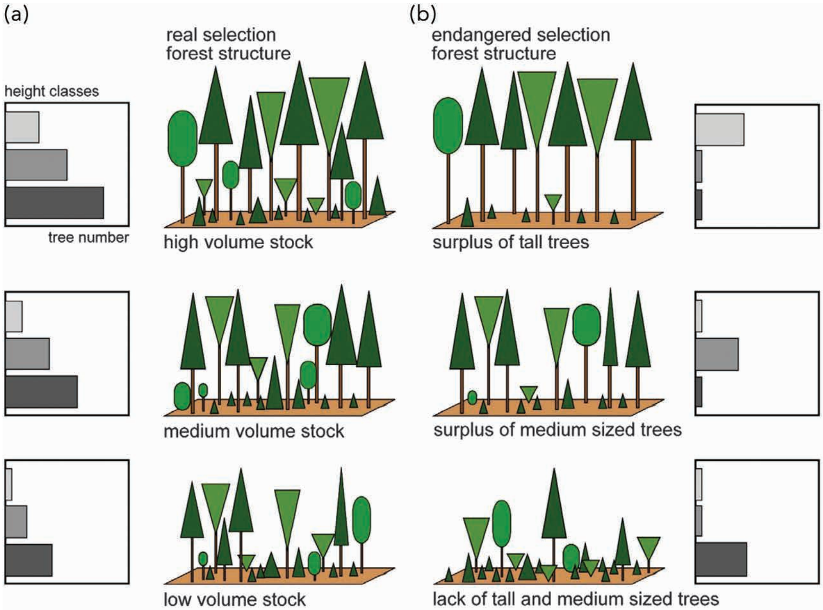

Figure 19 Stands with a (a) real and (b) endangered selection forest structure. Tree number per height classes and sectional views for both kinds of selection forest structures (according to Köstler (1953, 1956), Mayer (1984) and Pretzsch (1985)). (a) A real selection forest structure can be established with high, medium or low standing stock. (b) A surplus of tall trees, medium-sized trees or a lack of tall and medium-sized trees may endanger the real selection forest structure.

understorey. Over time, this may endanger the true selection forest structure (Fig. 19b). Similarly, overly strong density reductions, for instance too much removal of tall and medium-sized trees, may endanger the true selection forest structure, as they may trigger an overly mono-layered natural regeneration on the whole stand area.

Similarly to the age-class forest, where it takes a long time to achieve a normal uniform area distribution over the various age classes, the remediation of imbalances in the size distribution in the selection forest may take decades or even centuries. Postponed silvicultural interventions and delayed density reductions remain visible through deviations from characteristic tree number–tree diameter distributions even decades later. This underpins the highly artificial character of selection forests and the need for continuous tree removal and selection cuts over the whole diameter range; otherwise, its characteristic structure will cease to exist. For more detailed instructions on how to quantify guidelines for management of mixed-species and selection forests, see Mason et al. (2018) and Pretzsch and Zenner (2017).

7.2 Thinning based on diameter class or target diameter

By sorting the trees in a stand into diameter classes with a width of for example, 1 or 5 cm, a stem number–diameter distribution is obtained, where the mean diameter, variation, skewness and excess of the frequency distribution reflect the underlying stand structure. The stem number–diameter distribution of an even-aged pure stand can be approximated through a normal distribution, whereas that of mixed-species mountain forests and selection forests is approximated best by an exponential inverse J-shaped distribution (Pretzsch, 1985). Assmann (1970) described the diameter classes as numerical tree classes because the trees within a class, such as the tree classes defined by Kraft, are comparable in size and social status.

Therefore, the type of thinning can be defined also by specifying the stem number–diameter distribution to be maintained. By comparing the actual stem number–diameter distribution with the desired, programmed distribution, the treatment is regulated. When the desired tree number is surpassed, a thinning is carried out to reduce it.

Figure 20 provides an example of this method for the silvicultural treatment of the selection forest experiment, Freyung 129. An equilibrium curve can be obtained from,

$$n = k \times e^{-a \times d},$$

which describes a declining exponential distribution that can be represented as a line in the semi-logarithmic coordinate system:

$$\ln(n) = \ln(k) - a \times d$$

where n represents tree number per diameter class, d the diameter class, k the intercept, a the slope of the line and ln the natural logarithm. The presentation of the stem–diameter distributions in a semi-logarithmic coordinate system (Fig. 20) shows clearly whether the stem number lies above or below the reference curve. The curve parameters k and a can be determined from the target diameter d_t and the corresponding stem number n_t in this diameter class, and the mean diameter of the first diameter class d_i and the corresponding stem number n_i, respectively. The curve parameter a reflects the process of recruitment.

$$a = \frac{\ln(n_t) - \ln(n_i)}{d_t - d_i},$$

where k is determined by,

$$k = n_i \cdot e^{a \cdot d_i}.$$

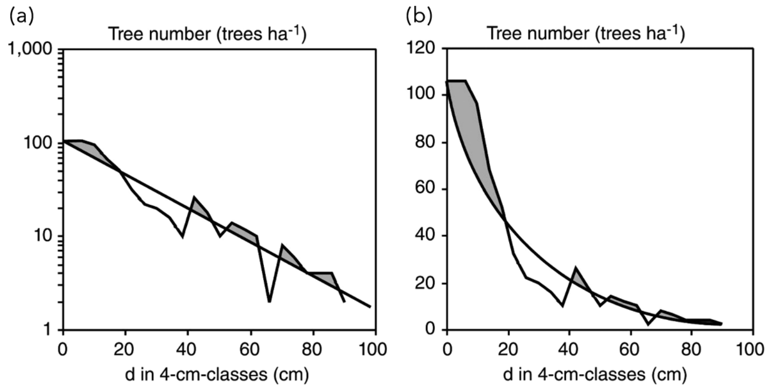

Figure 20 Silvicultural prescriptions using target stem number–diameter distributions. Observed stem number–diameter distribution (black solid jagged line) for the selection forest experiment Freyung 129, plot 1, and corresponding equilibrium curves are displayed (a) on a semi-logarithmic scale and (b) linearly: hatched areas between observed tree numbers and the model curve indicate supposed thinning; white areas indicate diameter classes with an undersupply of trees.

Bachofen (1999) and Schütz (1997) suggest a simple algorithm for determining the equilibrium curves for selection forests to obtain the desired distributions. These approximate exponential distributions as a rule. Diameter distribution models and individual-tree models offer an even more convincing approach for the derivation of reference curves. No matter how the reference curve is developed, its application is rather simple: the desired stem number–diameter distribution is compared to the actual distribution. Any deviation from the equilibrium curve can be addressed by removing the excess tree numbers in the diameter classes. In our example (Fig. 20), intensified thinning in the middle and large tree classes would improve the regeneration conditions and recruitment.

The final cutting can also be quantified through a threshold diameter, derived in relation to ecological and economical considerations. In this case, all trees, or a defined proportion of those trees exceeding the final diameter stipulated, are removed in each thinning operation. The severity of the thinning is regulated by designating the proportion of the trees outside the threshold that need to be removed. Figure 21 provides an example of the development of the stem number–diameter distribution for the European beech thinning trial, Wieda 99, plot 1, at the age of 113–170 years. It shows how the distribution gradually approaches the target diameter. In each thinning, the trees over 68 cm diameter at breast height (cf. Fig. 21, hatched area) were removed. The first thinning occurred at 135 years of age. By the time the trees were 170 years

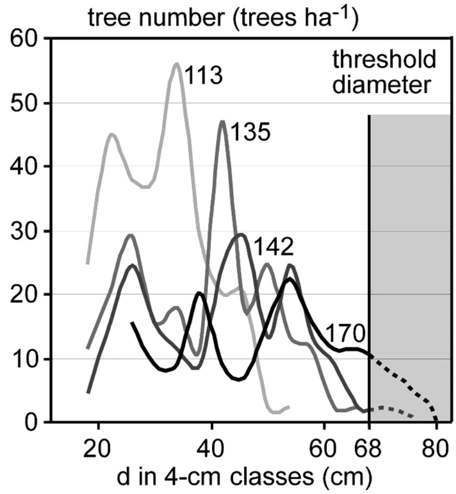

Figure 21 Quantifying the type of thinning by setting a target diameter of 68 cm, above which all trees or a defined portion of trees are removed. The stem number–diameter distributions are presented for the European beech thinning experiment, Wieda 99, plot 1, at the age of 113, 135, 142 and 170 years. The right tail of the distribution is capped in target diameter utilization.

old, the majority of the right tail of the stem number–diameter distribution had been removed.

7.3 Deviation from the guideline curve and steady-state diameter distribution

While age-class forest stands represent only a part of the whole age spectrum, a selection forest stand represents a whole management unit. Moreover, whereas an age-class forest is balanced and in normal state when the management unit is made up of a uniform stand area-stand age distribution, a selection forest is stable and balanced when the tree number decreases exponentially with increasing tree diameter class (Fig. 22). A surplus or lack of tree numbers in certain diameter classes triggers a long-term imbalance of the structure, harvest and assortment yield. Only when in balance, a selection forest provides a continuous and constant volume and assortment and, other functions and services yield over time.

In the age-class forest, any deviations from normality may occur, because some age classes are missing due to the initial structure of the estate, storms or windthrows. In selection forests, the imbalance may be stand internal, caused by delay of harvest or over-cutting. Over-cutting of tall trees may result in a lack

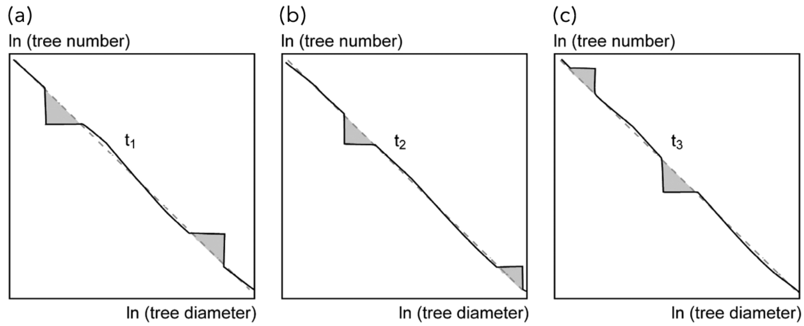

Figure 22 A disturbance of the ln(N)-ln(d)-relationship of a selection forest at time point t_1 caused by an overstocking and surplus of tall trees. This triggers a lack of natural regeneration which will remain visible in the tree number–tree diameter distribution decades later at time points t_2 and t_3 (from a to c). The grey areas above and below the baseline represent deviations from the guideline curve for steady state.

of tree numbers in higher diameter classes, but also a surplus of tree numbers in lower diameter classes, due to the opening of the stand and the stand-wide promoting of the understorey trees. These deviations will remain visible in the diameter distribution and stand structure for a long time, as a respective age or size cohort is missing, similar to the lack of stand area of old and a surplus area of young stands in an age-class forest.

It requires decades and the application of measures similar to transformation and structuring to remedy this structural deficit and imbalance in selection forests (Fig. 22).

8 A practical example of selection forest management

8.1 Tree number–diameter distributions

We use the selection forest experimental plots of Norway spruce, silver fir and European beech in Freyung and Bodenmais in the Bavarian Forest (FRY 129, BOM 130) and Ruhpolding and Kreuth (RUH 113, KRE 824) in the Bavarian Alps as model examples to show some characteristic traits of achieved and continuously maintained selection forests.

The experimental plot FRY 129 represents six variants of levels of the standing stock and threshold diameter goals. The plot-specific differences between the tree number–diameter distributions become more obvious in the semi-logarithmic (Fig. 23b) compared to the linear representation (Fig. 23a) on their tree number–diameter distributions. The broken lines represent the regression lines of the function $\ln(N) = \ln(a) - k \times n$ fitted to the observed tree number–diameter distributions on the six plots in 2011.

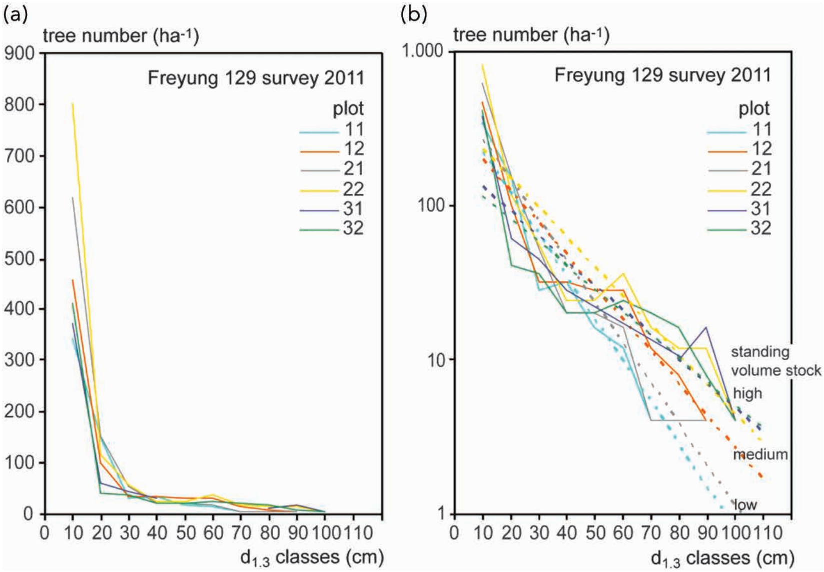

Figure 23 Variation of the relationship between tree diameter (10-cm classes) and number of trees with $d_{1.3} \geq 7$ cm on the selection forest experiment Freyung 129. In the year 2011, the plots 11, 12, 21, 22, 31 and 32 had a standing stock of 292, 498, 360, 767, 572 and 669 $m^3 ha^{-1}$. The plots 11 and 21 had a low level of volume, 12 and 31 a medium level and 22 and 32 a high level of standing volume. The broken lines result from linear regression analyses of the tree number–tree diameter distribution using the equation $\ln(N) = \ln(a) - k \times n$, which is $N = a \times e^{-k \times n}$ in delogarithmic representation. The curves and lines represent steady-state conditions for different volume stocks and threshold tree diameters.

The plots 11, 12, 21, 22, 31 and 32 had a standing volume of 292, 498, 360, 767, 572 and 669 $m^3 ha^{-1}$ in 2011. The plots 11 and 21 represent low volume levels, plots 12 and 31 medium volume level, while 22 and 32 are on a high-volume level. The threshold diameter increases with increasing standing stock. The different steady states can be quantified by the intercept and slope of the regression lines $\ln(N) = \ln(a) - k \times n$ and $N = a \times e^{-k \times n}$, respectively (a and k are the coefficients, N represents the tree number and n the diameter class). The intercept and slope of the regression lines amount to a = 328, k = 0.056 on plot 11, a = 314, k = 0.048 on plot 12, a = 484, k = 0.061 on plot 21, a = 349, k = 0.044 on plot 22, a = 187, k = 0.034 on plot 31 and a = 158, k = 0.035 on plot 32.

On all plots, we recognize a slight difference from the linear relationship (Fig. 23b) with a deficit of low sizes and a surplus of tall trees. This results in a slight s-shaped tree number–diameter distribution curve stressed by Schütz (1989, 1997). Even so, for the purpose of simplicity we approximate the distribution by a linear tree number–diameter distribution in the semi-logarithmic coordinate system as shown in Fig. 23b.

Figure 24 shows the tree number–tree diameter distribution of plot FRY 129/11 since 1980; the standing volume has been continuously reduced. The tree number–tree diameter relationship became continuously steeper and the intercept moved upwards. The intercepts a and slopes k of the regression function for FRY 129/11 were a = 231, k = 0.037 in 1980, a = 227, k = 0.042 in 1986, a = 270, k = 0.048 in 1993, a = 252, k = 0.049 in 1999, a = 259, k = 0.048 in 2005 and finally a = 328, k = 0.056 in the latest survey in 2011. The reduction of the standing stock and shift of the regression line (Fig. 24b) on the plot FRY 129/11 was conducted in order to bring the different plots into different steady states and analyse the respective responses of the stand volume growth (Fig. 27).

In contrast, the standing stock and tree number–tree diameter distribution of the plot FRY 129/32 was kept constant from 1980 to 2011 (Fig. 24c and d). The regression lines vary only slightly, as indicated by a = 105, k = 0.029 in 1980, a = 80, k = 0.030 in 1986, a = 104, k = 0.030 in 1993, a = 144, k = 0.033 in 1999, a = 139, k = 0.031 in 2005 and a = 158, k = 0.035 in the last survey in 2011. In this case, the relatively similar coefficients indicate the steady state of the selection forest plot in the last decades on a rather high-volume level (low a-values and k-values).

8.2 Alternative guidelines for the silvicultural regulation of the Kreuzberg forest

The relationship between tree number and tree diameter is often used as a guideline for the silvicultural management of selection forests. The observed tree numbers per diameter class are compared with the guideline curves, and the surplus of trees can be reduced, so that the stand is kept close to the steady-state curve. The number–tree diameter relationships can be used for practical management, but also for the quantitative prescription for scenario analyses of different treatment regimes in simulators.

Figure 25 shows different guideline curves for eastern Bavarian selection forest according to Knoke (1998). The alternative guideline curves for the Kreuzberg selection forest are presented in (a) linear and (b) in semi-logarithmic coordinate systems. They can be used for simulation studies with growth models in order to analyse the long-term effect of different treatment options. The curves 1, 2, 3, 5 and 7 can be quantified by using the intercepts a and slopes k of the relationship $\ln(N) = \ln(a) - k \times n$. They represent different steady states with threshold diameters of 51–154 cm and standing volumes of 148–513 $m^3\,ha^{-1}$.

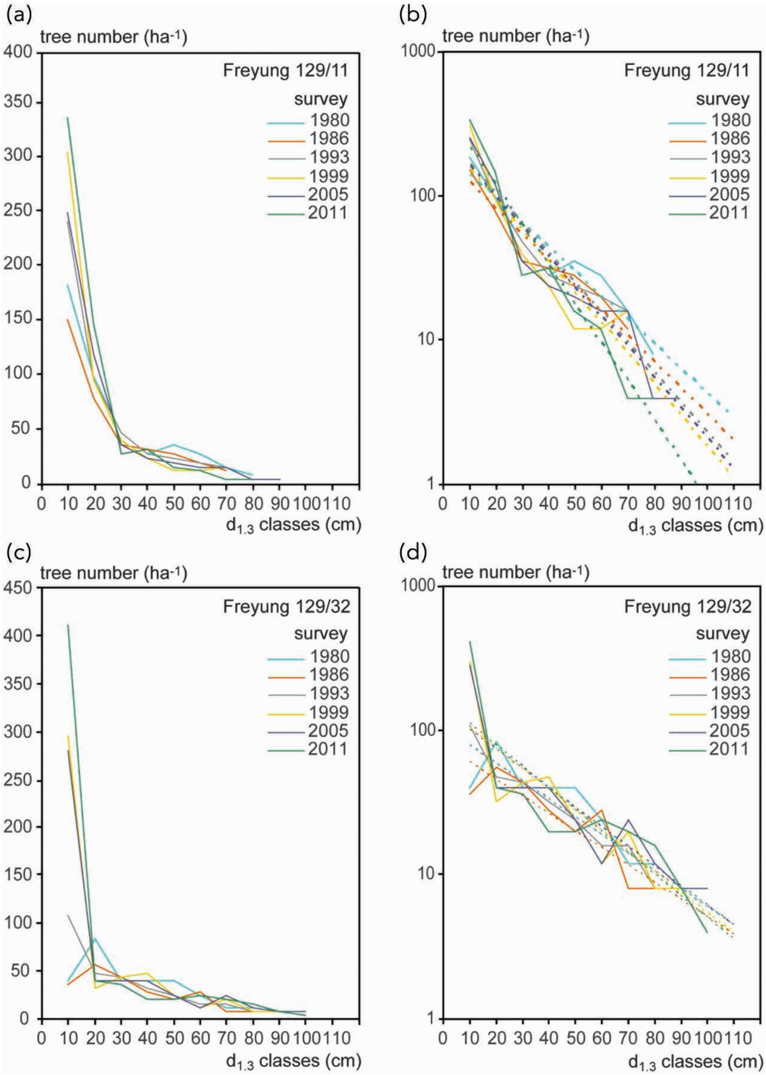

Figure 24 Development of the tree number–tree diameter distributions from 1980 to 2011 on the low volume level plot 129/11 (a and b) and the high volume-level plot 129/32 (c and d) of the long-term selection forest experiment Freyung 129. The broken lines result from linear regression analyses of the tree number–tree diameter distribution using the equation $\ln(N) = \ln(a) - k \times n$, which is $N = a \times e^{-k \times n}$ in delogarithmic representation. The curves and lines represent steady-state conditions for different volume stocks and threshold tree diameters. (a and b) Development of the tree number–tree diameter distribution on the low volume level plot FRY 129/11 (total standing stock in 1980–2011 ranging from 436 to 587 m^3 ha^{-1}), shown in linear and semi-logarithmic scale. (c and d) Development of the tree number–tree diameter distribution on the high volume level plot FRY 129/32 (total standing stock in 1980–2011 ranging from 603 to 772 m^3 ha^{-1}), shown in linear and semi-logarithmic scale.

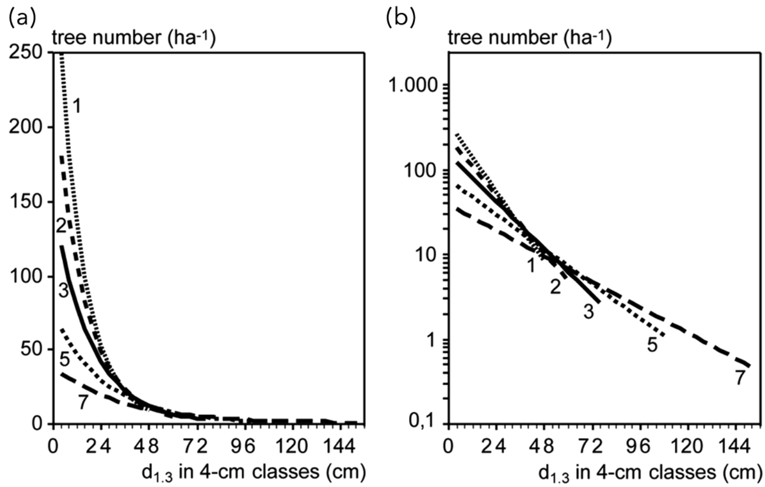

Figure 25 Alternative guidelines for tree number–tree diameter frequency distributions and silvicultural regulation of selection forest stands of Norway spruce, silver fir and European beech stands in the Kreuzberg forest in east Bavaria. The tree number–tree diameter frequency distributions are represented in linear-Cartesian (a) and semi-logarithmic (b) representation. The alternatives 1, 2, 3, 5 and 7 with the curve parameters a_1 to a_7 and k_1 to k_7, respectively, represent different steady states with threshold diameters of 51–154 cm and standing volumes of 148–513 $m^3 ha^{-1}$ (according to Knoke 1998). The underlying curves are $N = a \times e^{-k \times n}$ and $\ln(N) = \ln(a) - k \times n$, respectively.

8.3 Standing stock

The exponentially decreasing tree number–tree diameter distribution can be broken down to the tree species level (Fig. 26). Target values for the standing stock, threshold diameter and diameter distributions should be considered the mixing proportions of the contributing species, as the growing space requirements can considerably vary between the tree species for trees with equal diameter or volume. For instance, a mature European beech requires about double the growing area as a Norway spruce of the same age and size.

Due to the cubic relationship between tree diameter and tree volume, the standing stock per diameter class (Fig. 26c and d) increases even when the tree number per diameter class (Fig. 26a and b) decreases exponentially. Most of the standing volume of selection forest stands is accumulated in the medium- and tall-sized trees. The standing volume of beech often decreases with increasing diameter class, as the wood quality can be bad and bad-quality trees get primarily removed by successive thinnings and selection cuts.

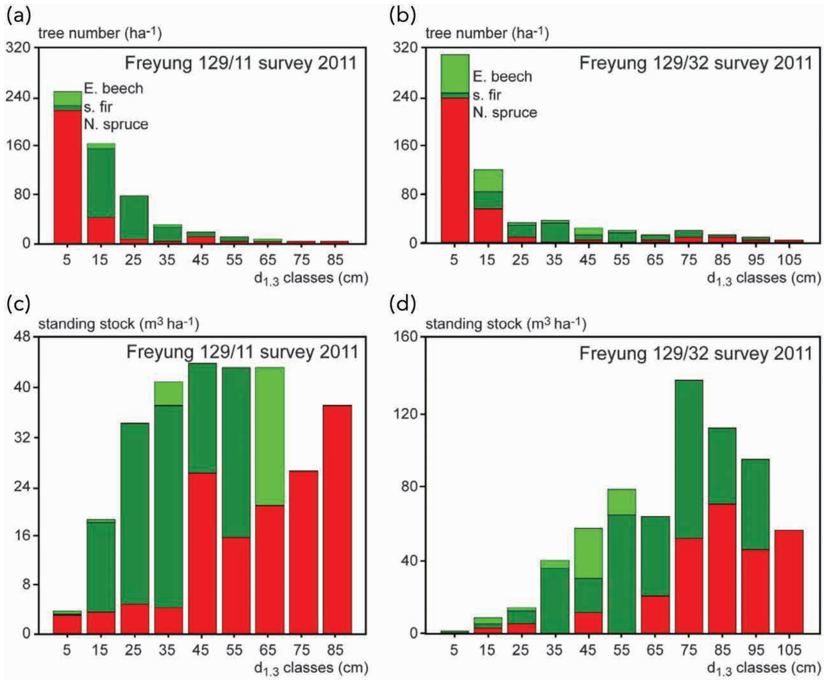

Figure 26 Distribution of the tree number and standing stock of the trees with $d_{1.3} \geq 7$ cm over 10-cm-diameter classes on a selection forest plots with low standing stock (FRY 129/11) and high standing stock (FRY 129/32) of the long-term experiment Freyung 129 at the survey in 2011. (a and c) Tree number and stem volume distribution on the low volume level plot FRY 129/11 with a tree number of 584 ha^{-1} and a standing stock of 292 $m^3 ha^{-1}$. (b and d) Tree number and stem volume distribution on the high volume level plot FRY 129/32 with a tree number of 600 ha^{-1} and a standing stock of 669 $m^3 ha^{-1}$.

8.4 Stand density–productivity relationship

When stand density is reduced in selection forests, productivity eventually also decreases; however, the decrease starts off at much lower density and proceeds much slower than in even-aged monocultures. The reason for this broader saddle and lower steepness of the stand density–productivity relationship is the trees of the medium and lower layer, which can buffer and compensate the growth losses of the removal stand immediately (Pretzsch and Forrester, 2017, pp. 190–7). The primarily tree-wise interventions and removals only cause small gaps, which can be closed quickly by trees in the lower layers and by neighbours. This halving of the standing stock from 600 to 300 $m^3 ha^{-1}$ on the experimental plot Bodenmais results in a growth reduction of only 20% compared to the fully stocked stand (Fig. 27). It indicates a high-growth resilience of the selection forest to silvicultural or natural disturbances compared with the age-class

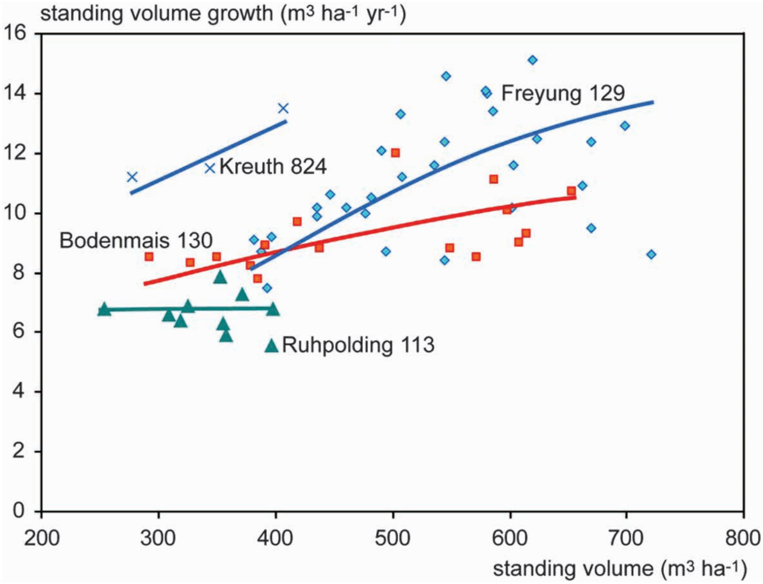

Figure 27 Relationship between the standing stock at the beginning of the growth period and the volume growth during the respective periods (1980–2011), shown for the selection forests in Freyung und Bodenmais in the Bavarian forest (FRY 129, BOM 130) and Ruhpolding and Kreuth (RUH 113, KRE 824) in the Bavarian Alps. Standing stock and volume growth are reported in cubic meters of stem volume with bark (>7 cm at the smaller end). The different growth levels on the plots result from differences in the site conditions.

forest. In the latter, any gaps in the canopy may be closed much more slowly due to the mono-layering and lack of natural regeneration.

9 Future trends and conclusion

Tree-species mixing can result in a risk distribution and stabilization of growth in view of climate change (del Río et al., 2017). In European forests, tree-species assemblages should consider drought stress, as climate prognoses predict extended summer droughts and a shift of rainfall to the winter season. Tree-species mixture can adapt to such climate changes in several aspects; an admixture of drought resistant species may avoid strong growth losses due to drought events; due to mixing interactions such as hydraulic redistribution or temporal and spatial niche separation mixed stands may contribute to a better water supply, uptake or use-efficiency. These effects may stabilize growth and stand stability under climate change.

The mixing of Norway spruce, silver fir and European beech in the European mountain forests (Fig. 28a) provide an example for growth

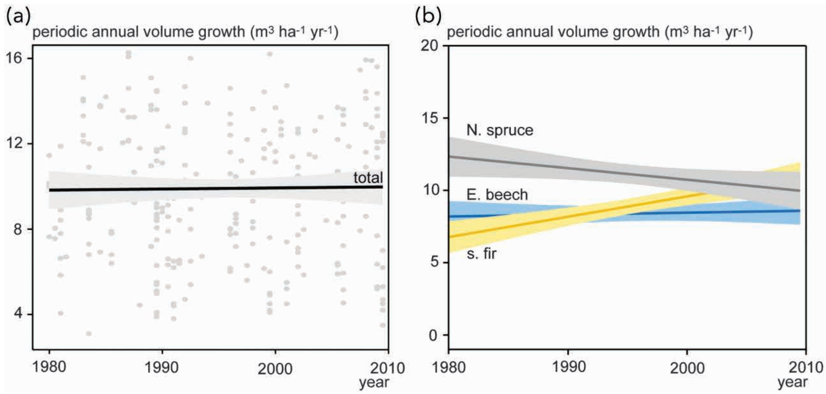

Figure 28 Growth on 105 long-term experiments in mixed-mountain forests of Norway spruce, silver fir and European beech covering a region from Bulgaria to Switzerland and Poland to Italy with the German Alps in the centre. (a) Continuous stable growth of the stands as a whole over the last 30 years and (b) significant increase of growth of silver fir, decrease in case of Norway spruce and constant growth of European beech (according to Hilmers et al., 2018).

and yield stabilization by tree-species mixing (Hilmers et al., 2018). The experiments cover the mountain forests in Austria, Bosnia Herzegovina, Bulgaria, Germany, Poland, Serbia, Slovakia, Slovenia and Switzerland. On average, over 105 long-term experiments of the growth of mixed-mountain forests remained relatively constant over the last 30 years on a level of 9.8 m^3 ha^{-1} $year^{-1}$ (Fig. 28a), which is about 20% above the productivity expected by common yield tables. The database covers experiments established and re-measured between 1906 and 2017. The elevation is 425–1569 m a.s.l. (mean 973), the mean temperature 2.3–9.3°C (mean 6.5) and the precipitation ranges from 680 to 2632 mm $year^{-1}$ (mean 1528). The standing volume 175–1204 m^3 ha^{-1} (mean 554), stand age 80–240 years (mean 120), stand basal area 14.3–76.5 m^2 ha^{-1} (mean 40.2), volume growth 0.5–22.8 m^3 ha^{-1} $year^{-1}$ (mean 9.8), and the mixing proportions vary between 3% and 97%; on average, all three species have a share of about a third in the stand basal area. The site index ranges from 27 to 39 m (mean 32) dominant height at an age of 100 years.

An analysis of the growth behaviour by species reveals that the stable growth results from an interplay of a significantly increasing growth of silver fir, decreasing growth of Norway spruce and constant development of European beech (Fig. 28b). The growth increase of silver fir may be a result of a recovery from the acid rain damage in the 1970s–80s and an improvement of its growing conditions regarding environmental factors (extended growing season, higher temperatures etc.) and inter-specific competition (growth and competition decrease of Norway spruce). Norway spruce may decrease in growth due to climate warming and higher frequency of drought years. European beech seems to be the most stable climate resistant species compared with the other two. Notice that the trend lines in Fig. 28 result from mixed-model evaluation and control of other influencing factors such as elevation, slope, mixing proportion and precipitation (Hilmers et al., 2018).

So far, dominating conifers such as Norway spruce, European larch or silver fir are relatively drought sensitive and may be replaced by more drought resistant species, such as European beech, sessile and common oak or Scots pine. Of special interest are mixtures with at least one drought resistant species. For instance, combinations of Scots pine and European beech, Scots pine and sessile oak or Scots pine, European beech and sessile oak may be adapted to climate change.

While research so far has focused mainly on mono-specific stands, there is still a lack of empirical knowledge and models for heterogeneous forest stands. Future experiments, models, quantitative silvicultural guidelines, inventory and forest planning methods, as well as biomonitoring approaches, should focus on heterogeneous mixed-species forest stands.

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