Growth of advanced European beech trees in the transformation phase in the southern Black Forest

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1.1 BACKGROUND

In recent years close-to-nature forestry has been favored by many forest owners and the public. In the state forest administration of Baden-Württemberg, a concept of close-to-nature forestry involving species enrichment, structural diversity and other ecological benefits through the conversion of even-aged into multi-layered uneven-aged forest stands is being implemented (MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) 1993). To transform the stands in the southern Black Forest into this well structured, mixed species, uneven-aged system, some of the present stands require transformation from their current species mix and diameter distributions. The successful application of this transformation system requires a better understanding of the growth responses of individual trees than is currently available.

Forest practitioners responsible for this transformation management process require more insight into growth dynamics than is required for other classic management systems. In particular, practitioners require detailed information concerning the growth responses and spatial arrangements of individual trees both before and after release and also whether release can be effective in accelerating the development/stabilization of advanced European beech trees in transformation forests.

The ideal approach to investigate the response of old aged trees to release would be to conduct replicated long-term experimental trials. However, these plots would need to be monitored for a long period of time in order to obtain meaningful results on the magnitude of the response and to answer the question of whether treatments could substantially shorten the time required to promote the growth of large trees in transformation. Before making a commitment to long-term experiments, it may be desirable to evaluate growth responses in stands that have received a variety of treatments in the past.

Therefore, this study attempts to conduct a retrospective analysis of the reaction of basal area increment, height increment and crown expansion of trees with different dimensions that have experienced changes in competition. This research study was conducted within the German state-funded Bundes Ministerium Forstung (BMBF) project entitled "Zukunftsorientierte Waldwirtschaft, Projektverbund südlicher Schwarzwald" (Future-oriented forest management for the southern Black Forest). This research project mainly focuses on the transformation of single-layered, even-aged stands of Norway spruce (*Picea abies* (L.) *Karsten*), silver fir (*Abies alba* Mill.) and European beech (*Fagus sylvatica*) into mixed species close-to-nature forests. The quantification of the growth responses of trees of different dimensions to different changes in competition was the central focal point of this study.

1.2 STATEMENT OF THE PROBLEM

The main problem this study investigated was how to manage advanced European beech growth when transferring from a less structured to a highly structured stand. Specifically, the study sought to determine:

1. What is the reaction ability of advanced European beech when released?
2. What variables are associated with this ability for trees to react?
3. What role can canopy expansion measurements take in the preparation of appropriate silvicultural guidelines for uneven-aged transformation management of European beech?
4. What gap sizes are appropriate for aiding the regeneration of understory canopy trees and also for maximizing the development of the canopy trees?

The study is important for four reasons. Firstly, this study will provide detailed empirical information on the ability of advanced European beech to react to release in a variety of competition states. Virtually all descriptions of this impact occur either on the stand level and/or with young stands. This study attempts to fill a gap in the literature on release, as there has been very little research conducted on advanced European beech stands.

Secondly, the study will identify those variables considered to be important in the production of large stable trees in transformation forests. Identifying such factors will help forest managers predict individual tree and stand responses (canopy and crown) to different disturbances or management events (changes in local crown competition).

Thirdly, the study may add valuable data to the literature on how this transformation process can be accelerated in order to minimize the risk of destabilization. Prior to this study, the crown release of trees as a tool for managing the transformation process was not thoroughly researched.

Finally, the study may support the development of new silvicultural policy and operational guidelines for the southern Black Forest, based on crown-architecture modeling and gap size simulations.

1.3 PURPOSE AND OBJECTIVES

The purpose of the study was to examine the release response of advanced European beech trees in the southern Black Forest. The study looked at several different factors which could be related to the growth reaction of a tree responding to release. These factors included the current competition of the tree, change in competition for the tree, tree size, relative size and tree age. The dependent variables modeled in this study included diameter increment, height increment and crown radius increment. The following objectives were examined in the study:

1. To demonstrate that the basal area increment response of advanced European beech trees to release is correlated with initial tree size, relative tree size, tree age and local competition terms;
2. To demonstrate that the height increment response of advanced European beech trees to release is correlated with initial tree size, relative tree size, tree age and local competition terms;
3. To demonstrate that the crown expansion of branches in gaps is greater than that in branches that are overlapped by competitors;
4. To demonstrate the appropriate gap size for transformation processes using gap simulation.

1.4 RATIONALE OF THE STUDY

The first objective outlined above employs one dependent variable, basal area increment response, and four categories of independent variables, namely initial tree size, relative tree size, tree age and competition terms. The literature on basal area increment response to release dates back over several decades. The responsiveness of basal area increment to changes in density has been extensively examined in the literature. To quote SJOLTE-JØRGENSEN (1967): “in practically all experiments, the mean diameter of trees is increased with increasing spacing”; and SMITH (1962) “the variation in diameter that can be induced by thinning is very wide”.

The crown competition both prior to and after release has been shown to influence the response of the trees to treatment. STAEBLER (1965) found that Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. menziesii) responded more to release when additional competitors were cut. DUNNING (1922) reported ponderosa pine (*Pinus ponderosa* Laws.) stems with longer crowns exhibited a greater response than trees with shorter than average crowns in the same diameter class. MINKLER (1957), having selected white oak (*Quercus alba* L.) stems with both fast and slow past growth rates, found release response to be related to crown class. Fast-growing trees had the greatest absolute diameter increment after thinning. In white pine (*Pinus strobes* L.) thinning trials HUNT (1968) reported crop trees responded rapidly to increased growing space and concluded that the response was correlated with total foliage weight.

In addition to competition, change in competition, tree size, age and length of suppression and the genetic composition of the tree are also recognized as affecting growth response to release. Genetic variation among residual trees may play an important role in the variation in growth observed. KONNERT & SPIECKER (1996) found the genetic variability of European beech was affected by selection thinning. Growth variation can also result from variations in the length of the growing season. FRANK (1973) using white spruce (*Picea glauca* (Moench) Voss) determined that the number of days a tree grows increases as release increases. Growth initiation of white pine was shown to be controlled by both photoperiod and temperature (HUSCH 1959). ADAMS (1935) reported that thinning white pine resulted in increased soil and crown temperatures, allowing early growth initiation. Soil moisture, which limits the length of the growing season (HUSCH 1959), was found to be greater on thinned plots allowing longer growth (ADAMS 1935; HUSCH 1959; HUNT 1968). Thus, release intensity can alter the physical micro-environment immediately adjacent to retained trees.

CLUTTER et al. (1983) suggests that where competition has caused a reduction in basal area increment compared to open-grown trees, the response to increases in growing space resulting from thinning varies with species, age and quality of site. The authors state that "older trees with greatly reduced crowns do not respond as much as younger trees of comparable stem size, and dominant trees which have been relatively less affected by competition respond less to increased growing space in terms of relative diameter growth rate than smaller trees [of the same age] in the same stand". Unfortunately, within the literature only a few short-term experiments have investigated increased basal area increment of released advanced trees (PETRINI 1932; ZIMMERLE 1936; ZIMMERLE 1938; ASSMANN 1965; WILLIAMSON 1966; JOHANN 1970; PREUHSLER 1981; SMITH & MILLER 1991). In addition, to these studies ALTHERR (1971) and KLÄTDKE (1999) have investigated the growth of advanced European beech trees in Baden Württtemberg.

In summary, competition, change in competition, tree size, age, length of suppression, and genotype all contribute to the ability of an individual tree to respond to release. Conceptually, a tree's measured growth response to release is a function of these variables and a model can be constructed to predict the growth response of a tree to release using direct measurements of these variables. In this manner, the importance of these variables in controlling growth response can be tested. The intensity or type of release modifying these factors may result in a response of varying magnitude. Based on this, it seems logical to hypothesize that advanced European beech trees will respond to release as a function of some of these variables.

The second objective outlined above employs one dependent variable, height increment response, and the same four categories of independent variables as the first objective (initial tree size, relative tree size, tree age and competition terms). The literature on height increment response to release dates back over several decades. Ample evidence of the relative insensitivity of height increment to density was collected by SJOLTE-JØRGENSEN (1967) in a comprehensive review of spacing effects. As HILEY (1959) has expressed it "within a reasonable range of thinning, the height growth of the trees is not materially affected by their density". ASSMANN (1961) states that "the development of the mean diameter in stands is much more dependent than the height increment on stocking and the resultant growth area available" (translated by the author). MITSCHERLICH (1970) also comments that "all changes in environmental relationships, for example increasing competition from neighboring trees or release due to thinning, have a greater effect on diameter increment than on height increment" (translated by the author). He goes on to state that height increment is relatively insensitive to changes in density. It is almost axiomatic that the height increment of canopy trees is insensitive to initial spacing and to the changes in spacing following release. In contrast, as previously noted, there is extensive literature on the response of basal area increment to both.

SMITH (1986) concluded that "stand density has little effect on growth in height, except where the stand is extremely dense or so open that the trees are distinctly isolated" and that "within the range of densities involved in thinning, height growth of the main canopy trees remains nearly constant". CLUTTER et al. (1983) state that "empirical evidence from thinning experiments indicate that for many commercially important species height growth is not greatly affected by the manipulation of density", especially if "the comparison is restricted to dominant and codominant trees". The technical literature has continued to yield examples of the relative unresponsiveness of height increment to density (DAHMS 1974; SCHMIDT et al. 1976; SEIDEL 1984). There has been little assessment of height increment in transformation systems, but there have been some studies that suggest that height increment decreases with release (ABETZ & UNFRIED 1984; THOMASIUS 1988). As there are some conflicting results within the literature, it seems logical to investigate whether the height increment of advanced European beech trees will respond to release.

The third objective outlined above tests whether a branch growing in a gap has a faster lateral expansion than a branch not growing in a gap. Since the crowns of forest grown advanced European hardwood trees can become quite asymmetric, it is important to understand the mechanisms of this asymmetrical crown development if individual-tree simulation models capable of accurately predicting the small-scale spatial dynamics of uneven-aged stands, are to be developed. Within the literature, two hypotheses of lateral crown radius increment patterns have been presented that would explain the development of asymmetrical crowns in advanced European beech trees. One hypothesis, a release model, suggests that tree crowns respond to adjacent canopy openings with increased lateral crown radius increment rates for some time after gap formation. This accelerated growth response is suggested by RUNKLE (1982) and RUNKLE & YETTER (1987). A second hypothesis, one of crown shyness, proposes that the branches of a crown grow until the physical proximity of an adjacent crown somehow becomes limiting. In other words, asymmetric crown development may simply be due to the availability of growing space in a given direction. MITCHELL (1969) reported for white spruce that "branches facing potential competitors show a slight decline in the rate of growth immediately before the crowns make contact". He further stated that branches just above the point of crown contact grew at a rate significantly less than branches without direct spatial competitors. PUTZ et al. (1984) also suggest that under the "crown competition" of trees in dense competition the branching complexity is less, and less foliage is carried on the tree. They state that due to the physical crowding, crowns rub against each other in the wind, causing bud loss and lower foliage production.

Experimental evidence in a lodgepole pine (*Pinus Contorta*, Dougl.) stand also tends to support the crown shyness mechanism for conifers (SMITH et al. 1990). SMITH et al. (1990) found that crown swaying and branch intermingling caused significant damage to adjacent crowns, with more crown abrasion and damage as total tree height increased. Little is known about this process in hardwoods. The actual crown expansion process in gap border trees is probably a combination of these two basic mechanisms. Based on these studies it seems logical to hypothesize that the lateral extension of branches in gaps is greater than branches overlapped by competitors. Therefore, it also seems logical to hypothesize that the lateral branch length increment is a function of whether it is located in a gap or not.

The fourth objective outlined above examines the smallest possible gap required to recruit a 4 m high sapling into the canopy before lateral expansion closes the gap. In Europe, gaps in natural European beech stands of varying age have been measured and it was found that for stands 50-200 years old, the mean number of gaps per hectare was 5-8, with sizes varying between 10-156 m^2 (SCHNITZLER & BORLEA 1998). In comparison, gaps in French deciduous forests were found to vary in size between 68-738 m^2 with the gaps often having irregular shapes (BRUCIAMACCHIE et al. 1994).

Recently, COATES & BURTON (1997) advocated the partial cutting of managed forests to create gap size distributions customized to match or extend those found under natural conditions. It is also clear that the variously sized gaps within a forest are an important factor contributing to the maintenance of species diversity within the forest. However, most research represented in the literature is based on work in protected natural forests, where the abiotic and biotic factors influencing regeneration may be somewhat different from those found in managed forests. Therefore, the findings and models based on research in unmanaged forests should be applied with care.

There has been very little research conducted on the role gaps play in the transformation of forestry. HANEWINKEL & PRETZSCH (2000) provided a transformation management scheme to convert even-aged Norway spruce stands into uneven-aged mixed forests. This scheme included a proposed intensity and size of gaps to ensure successful transformation of the stands. Unfortunately, there is a deficit of this type of research within the literature on European beech.

MOSANDL (1984; 1991) investigated gap formation in uneven-aged forests in southern Germany. He studied the ability of trees to naturally regenerate within 15 m diameter gaps and concluded that 15 m was sufficient for this process to occur, but the successful outcome depended on whether sufficient seedlings were present before the gap was created.

Based on the gap sizes occurring in natural stands and the results of these studies, it seems interesting to investigate whether a 10 m diameter gap is sufficient to recruit saplings into the canopy in transformation silviculture. Therefore, it is hypothesized that a minimum diameter of 10 m is required for successful gap phase transformations.

1.5 DEFINITIONS OF TERMS

For clarification, the following terms are defined

Term	Definition
Close-to-nature Forestry.	(see section 2.1.1)
Selection Forest	a silvicultural system where trees of all dimensions in a small area occur next door to each other, adapted from MITSCHERLICH (1970)
Transformation	process whereby a regular stand structure, such as an even-aged plantation, is converted to an irregular structure with a range of tree sizes and where some tree cover is maintained in perpetuity
Release	a disturbance event that increases the growing space available to a tree
Advanced European beech trees	defined in this study as being older than 80 years old and larger than 35 cm in diameter

1.6 LIMITATIONS OF THE STUDY

The study was restricted by certain conditions that were beyond the researcher's control. The nature of the sampling potentially limited the results of the study. It is possible that because the trees were not randomly selected, the statistical analysis will not be fully appropriate. The sample might more appropriately be termed an "incidental sample", i.e. in which subjects were selected on the basis of availability. This factor may restrict the generalizability of the findings regarding the availability of subjects.

The study was also restricted with regard to the individual characteristics of the selected trees. Since these data were gathered retrospectively within a relatively short period of time, there is no method in the procedures to measure how these characteristics may be expected to change in the near future. In short, these retrospective descriptions may not be a reliable description of the sample in some future re-testing period.

Finally, the study was restricted to easily measurable independent variables. This restriction was imposed by the researcher. It is possible that more detailed and in-depth investigations involving more complex physiological independent variables may have revealed different results.

1.7 DELIMITATIONS OF THE STUDY

The scope of the study has been delimited in a number of ways. Firstly, the study was restricted to European beech trees. Therefore, results of this study may not be descriptive of other similar species.

Secondly, the study has been delimited to advanced European beech canopy trees defined in this study as older than 80 years and larger than 35 cm in diameter at breast height and therefore, the results may not be generalized to smaller and/or younger trees.

Thirdly, the study has been restricted to the southern montane Black Forest. Findings from the study may not be generalized to assume that other geographic areas would produce the same results.

Fourthly, data was gathered within a three year time period. A different time interval may have revealed different results.

Finally, the release that occurred in each stand ranged over a time period from 1980 to 1995, inclusive. Research results may not apply to individual trees that receive release over a different period of time.

1.8 OVERVIEW OF THE STUDY

As previously stated, the purpose of the study is to examine the release response of advanced European beech trees. The second chapter deals with a review and analysis of the supporting literature relevant to this topic. The methods and procedures of the study are presented in Chapter 3 and the results of the statistical analysis of the data are presented in Chapter 4. The final chapter of the study is concerned with the summary of findings, discussion, implications and suggestions for further research.

2 REVIEW OF SELECTED LITERATURE

The purpose of this study is to examine the release response of advanced European beech trees in transformation in the southern Black Forest. This chapter provides both a review and an analysis of relevant literature. The literature review is divided into six sections. The first section provides an historical overview of the utilization and silvicultural management in the Black Forest, in particular, the role of European beech in close-to-nature forestry systems. The second section examines previous studies which have compared close-to-nature forestry to even-aged forestry in central Europe. The third section focuses on the importance of advanced European beech trees in the transformation process. The fourth section examines the literature on the analysis of the release response of trees, concentrating on those variables considered important to measure and model. The fifth section focuses on the appropriate data collection methods available for transformation studies. The final section provides a summary identifying the main issues worth researching in the context of transformation forestry in the southern Black Forest.

In addition to providing a theoretical basis upon which the current study is based, it is hoped that this review in English provides an introduction to transformation research issues in central Europe for the non-German and non-French readers. This is important due to a large majority of the historical research into transformation being in German and French.

2.1 OVERVIEW OF CLOSE-TO-NATURE FORESTRY IN THE BLACK FOREST

2.1.1 Definition of Close-To-Nature Forestry in the Southern Black Forest

Finding one single definition for close-to-nature forestry proves quite difficult as it is not a silvicultural system in itself, but rather encompasses a range of systems. However, it is based on certain principles and these shall be expanded upon here in an effort to explain exactly what close-to-nature forestry consists of in the context of this study (adapted from (KÖNIG 1849; GAYER 1886; MÖLLER 1922; HELLIWELL 1997)).

Principle 1: Adapt the Forest to the Site

Close-to-nature forestry seeks to work with the site and to respect both ecological processes and inherent variation rather than impose artificial uniformity. In practice, this tends to leads to a presumption towards the use of natural regeneration and the development of mixed species and mixed-age stands.

Principle 2: Adopt a Holistic Approach to Forest Management

Close-to-nature forestry regards the whole forest ecosystem as the "production capital" of the forest. This conception extends to encompass the soil, the forest micro-climate, associated fungi, flora, and fauna and the trees themselves. Management for timber production is directed towards the creation, maintenance and enhancement of a functioning ecosystem rather than the periodic creation and removal of individual crops of trees.

Principle 3: Maintain Forest Conditions and Avoid Clear-felling

Close-to-nature forestry regards the maintenance of forest conditions as an essential tool in achieving its aims. The overstory is used to influence the amount of light reaching the forest floor, to limit ground vegetation, to trigger regeneration, and control of its development is crucial. If clear-felling takes place forest conditions are lost, the benefits of shelter reduced, and climax species regeneration becomes more difficult.

Principle 4: The Growing Stock (Individuals)

Under close-to-nature forestry management, stand improvement is primarily concerned with the development of preferred individuals rather than the creation of a block of stems, with uniform spacing and average stem characteristics. The handling of individuals or groups of stems takes place within the context of the whole growing stock of the stand, the size and composition of which is manipulated to achieve the desired rate of regeneration and to produce the required range of timber products. A characteristic of permanently irregular stands is that yield control is based on measurements of stem-diameter and increment rather than age and area.

With particular reference to conditions in the southern Black Forest, the stands managed in accordance with the above principles will generally, over time, develop a permanently irregular structure at the stand level. The transformation process (i.e. the initial period when close-to-nature forestry principles are applied to even-aged stands) may also involve temporary even-aged elements, either through the use of small-scale clear-fellings or the use of shelterwood or selection systems.

Management along these lines may be seen as more natural than clear felling, but that may not always be the case, and arguments about what is and what is not natural may not always be helpful. The main aspects of close-to-nature forestry are that the forest conditions are retained at all times. This ensures that there is no sudden or drastic change in the landscape. Plants and animals which thrive under permanent woodland conditions are conserved, and the production of timber is more regular. It is relatively easy to leave some standing and fallen dead trees for wildlife and to concentrate on producing a steady supply of large diameter stems rather than a larger number of stems of less than average size.

For the purposes of this study, the “selection system” historically practiced on various sites in the Black Forest will be used as an template for close-to nature forestry in this region. This selection system is described later on in this chapter in detail.

2.1.2 The Recent International Move Towards Close-To-Nature Forestry

Although in Germany the contribution of the forestry sector to the gross national product has declined to less than one percent, the forests of Europe are still considered a “Central Resource” essential for the existence of human life and culture (VOLZ 1995). Several studies have indicated that woodland conservation and recreation are more highly ranked by the public than timber production (DUNKEL et al. 1994). They have also shown there is a growing emphasis on maintaining forest biodiversity, recreational, landscape, protective, socio-economic and cultural factors.

Numerous political events, (for example, the growing influence, both domestically and internationally, of the "green" movement) as well as non political (climate change forecasts, low profitability of wood production and the use of wood as a renewable natural resource to name a few) have resulted in increasing public pressure in recent times to diversify ("transform") forests in both species composition and structure. A particularly evident ongoing trend is the increased emphasis on "new" conceptual models for forestry, for example "new forestry" (FRANKLIN 1989), "continuous-cover-forestry" (GRISEL & GADOW 1995), "close-to-nature forestry" (MLINŠEK 1996), "semi-natural silviculture" (SPATHELF 1997) , "nature-orientated silviculture" (KOCH & SKOVSGAARD 1999) and "diversity-orientated silviculture" (LÄHDE et al. 1999).

Although this close-to-nature approach has gained considerable momentum over recent decades, disenchantment with the newly created "wood factories" was expressed as early as the mid-1800s by scientists such as KÖNIG (1849), who addressed issues of forest health and aesthetics, and GAYER (1886), who demanded a return to mixed forests. It was the influence of these people combined with other factors, outlined later in this section, that were largely responsible for the movement towards natural forestry. These developments have cumulated in the enactment in several European countries of forestry programs that include elements of a more close-to-nature silviculture (SCHABEL & PALMER 1999). These systems have attempted to fulfill both production and environmental targets, yielding a high production of wood with high quality, while maintaining natural biological processes. In Germany, this has resulted in several of the State Forest Administrations starting to promote close-to-nature forestry (OTTO 1989; NIEDERSÄCHSISCHE LANDESREGIERUNG 1991; WEIDENBACH & KARIUS 1993; MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) 1993; MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) 1999; BROSINGER & ROTHE 2002). In the state forest administration of Baden-Württemberg this concept of close-to-nature forestry involves species enrichment and other ecological benefits through the conversion of even-aged into multi-layered uneven-aged forest stands (MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) 1993). An additional aim of this concept is to reduce the required input for forest management through "biological automation".

2.1.3 Silvicultural and Stand Dynamics of European Beech in the Black Forest

To fully understand this movement towards close-to-nature forestry with respect to the Black Forest it is necessary to recognize that the current levels of genetic, species and ecosystem diversity cannot be considered as natural characteristics of the forest. The stands in which European beech plays an important part in the Black Forest are the result of natural, cultural and economic development over the last 3000 years. The current situation is a product of post-glacial forest evolution, the cultural and industrial development of society, past forestry management and recent usage. However, it must be noted that currently the most natural forests in the Black Forest are probably those forests where European beech plays an important part in species composition.

2.1.3.1 Post-Glacial Forest Evolution up Until the Middle Ages

Scots pine, birch and hazel were among the first tree species to spread back into central Europe after the last ice age. These species were displaced slowly by different, more nutrient demanding, or more shade-tolerant tree species (sycamore, lime, ash, alder, spruce) due to improving climatic conditions (WILLIS & MCELWAIN 2002). Later, tree species characterized by a slower rate of spread, (oak) colonized in the post glacial Atlantic period. European beech first colonized during the cooler and more humid sub-Atlantic period 3000 years ago, when man had already started to affect the landscape through his activities as farmer and cattle breeder. The influence of man on vegetation in the Black Forest since that time has been clearly shown by pollen analysis (HAUFF 1961; HAUFF 1969; HAUFF 1978; DIETERICH & HAUFF 1980)

The largest changes due to human influence in the natural forests of Germany occurred in the early medieval period (1,100-1,300AD) when settlements were developed and forests were cleared to provide new arable land. The early settlement of the central Black Forest began in the 10th century in the north with the Kinzig valley, and in the south with Feldberg mountain. Until the end of the Middle Ages, the main utilization of forests was for firewood production and as forest pastures for rural communities.

2.1.3.2 Cultural and Industrial Revolution

By the second half of the eighteenth century, the forest condition in Germany had reached a critical state. An increasing population, the demands of businesses such as mining, ore smelting, glass production, the Dutch timber trade and growing industrialization, all led to a rapid increase in the demand for timber. Some of these forest uses are briefly reviewed here to illustrate their effect on forest composition.

Mining and Ore Smelting

The wood requirements for mining and ore smelting were varied and extensive. Wood was required for building, (both under and over ground) fires for the smelting of ore, as well as for firewood and building material for all people employed in the mining industry (ROMMEL 1990). The ironworks required wood as an energy source in the form of charcoal. The wood requirements for 1 m^3 of iron were approximately 70-100 m^3 of wood (BAUER 1962; MANTEL 1990). The average ironworks, with an annual production of 80 m^3 of iron required approximately 8,000 m^3 of wood. The ore smelting plant in Albbruck in the southern Black Forest was supplied annually with 20,000 m^3 through a forest lease (MANTEL 1990).

Glass Production

The glassworks tended not to be located on permanent sites. They shifted their work and residential buildings when the local wood supply was exhausted (KREMSER 1990). Wood was used as a fuel for glass melting (approximately 10% of the wood requirement) but more importantly approximately 90% of the wood was required for the production of potash, an important material input for the production of glass. To produce 1 wine glass, approximately 2.5 m^3 of wood was required (MANTEL 1990). The glass industry at this time was deemed to be unstable and consequently suitable woodlands were not opened up by the nobility (HASEL 1985). However, large scale forest destruction was the consequence of this economically lucrative use activity.

The Dutch Timber Trade

In the 16th century, Dutch buyers were looking for new sources of wood supply for ship building. Large forest resources, with good transport facilities on the Rhine, were located in the Black Forest. A wood contract between Württemberg and the Netherlands was signed as early as the end of the 16th century. However, it was not until 1691 and 1692 that the first timber was transported from the northern forest districts of Bad Wildbad and Bad Liebenzell. At the beginning of the 18th century this trade experienced an enormous boom. The price for conifers increased by 6,000 percent during the period 1692 to 1820.

However, by the second half of the 18th century, the conifer wood supplies for export to the Netherlands were beginning to be exhausted. Despite attempts to decrease the number of logs exported and to spread the felling of trees over wider areas, large areas of forest were almost totally depleted of export quality timber by the end of the 18th century. SCHEIFELE (1986) estimates that in 1817 approximately one third of the Württemberg

State Forest was completely devastated. It was at this time that the Dutch timber trade in this area almost completely stopped.

The Dutch timber trade in the central part of the Black Forest began around 1699 and increased in importance from 1715 onwards (SCHEIFELE 1986). The reason that different methods of forest management were practiced in this area from those practiced in the northern parts of the Black Forest was partially due to the absence of forest partnership agreements with the nobility. The individual owners, typically farm foresters, sold their wood independently, and therefore had a vital interest in maintaining a sustainable practice.

The Dutch timber trade did not play a significant role in the management of forests in the southern part of the Black Forest. SCHIEFELE (1986) attributed the lack of importance of the Dutch timber trade in this area to coal and firewood production, a higher European beech proportion and the lower amount of forest due to high altitude agriculture.

2.1.3.3 The Development of Regulated Forestry in Germany and the Inference on Species Composition

Devastated forests and an increasing timber demand led to the start of regulated forestry as an independent commercial sector in Germany between 1750-1850 (LEOPOLD 1936; PLOCHMANN 1992). With the establishment of the first forest laws, for example the forest law of the former state of Baden in the year 1833, regulated forestry with silvicultural planning was introduced (SCHÜTZ 1999e). This was an attempt to inhibit irresponsible forest owners from uncontrolled exploitation. At the same time there was a strong movement towards restoring the level of standing volume in the forests. The challenge was to return under-stocked forests and degraded land to greater timber production in the shortest time period possible.

This movement towards restoration of forest was aided by the following factors: (BRANDL 1992; PLOCHMANN 1992):

- forestry had been developed as a new field of science and had been established at universities;
- these institutions produced well-trained professionals able to tackle the tasks at hand;
- the newly formed states created modern and effective forest services;
- modern forms of agriculture were developed, making forest pasture redundant;
- artificial fertilization was developed;
- the feudal hunting policy was abolished.

This rehabilitation of the forest is usually dated as having began in the 1820s, (LEOPOLD 1936) with foresters discovering that the fast growing, undemanding Norway spruce and Scots pine (*Pinus sylvestris* L.) promised much higher returns and soil rents than the natural hardwood forest. In addition, Norway spruce and Scots pine had the advantage of being hardy, undemanding species that could be easily seeded or planted on open land. Therefore, the rehabilitation of the forests was achieved mainly with an early form of plantation management, often irrespective of the natural distribution of these species.

Consequently, devastated and exploited forests as well as natural hardwood forests were converted into softwood monoculture plantations by seeding and planting. Rotations were shortened, natural regeneration was replaced by plantations, and old forms of silviculture, such as single tree selection in forests mainly owned by small farmers, were replaced by clear-felling. Standing volume, annual increment, and the flow of harvested timber increased sharply as did the income of the forest owners. Rehabilitation was completed in less than a century. On the whole, a more or less even-age-class distribution was achieved (SPIECKER 2000). Considering the original objective, this rehabilitation was a success. However, there was a large shift in the composition of the German forests from 60-70% broadleaved trees in the 14th century to 60-70% coniferous trees in the early 20th century (MANTEL 1990).

The adverse impacts of practicing these methods became apparent at the end of the 19th century, and even more intense by the beginning of the 20th century, when severe damage to plantations was caused by insect and disease epidemics and natural catastrophes resulting from strong winds and snow. These were mainly due to the inferior endurance of even-aged monocultures.

At the same time, various physical and biological scientific branches of forestry were developed, such as plant sociology, ecology, ecophysiology, site quality science, syndynaics, synecology and soil science.

2.1.3.4 Change in Forest Composition due to Recent Usage

There has been a clear shift in species composition since the introduction of regulated forestry. There are many causes for this change including the devastation from overuse, litter racking, grazing and price conditions. The relation of prices between different species has changed greatly with time (SPIECKER 2001). Recently, the value of broadleaf species such as European beech has increased more than that of conifers. However, this has not always been the case. It can be seen from Figure 1 that 30 to 40 years earlier, European beech had a lower value than the conifers.

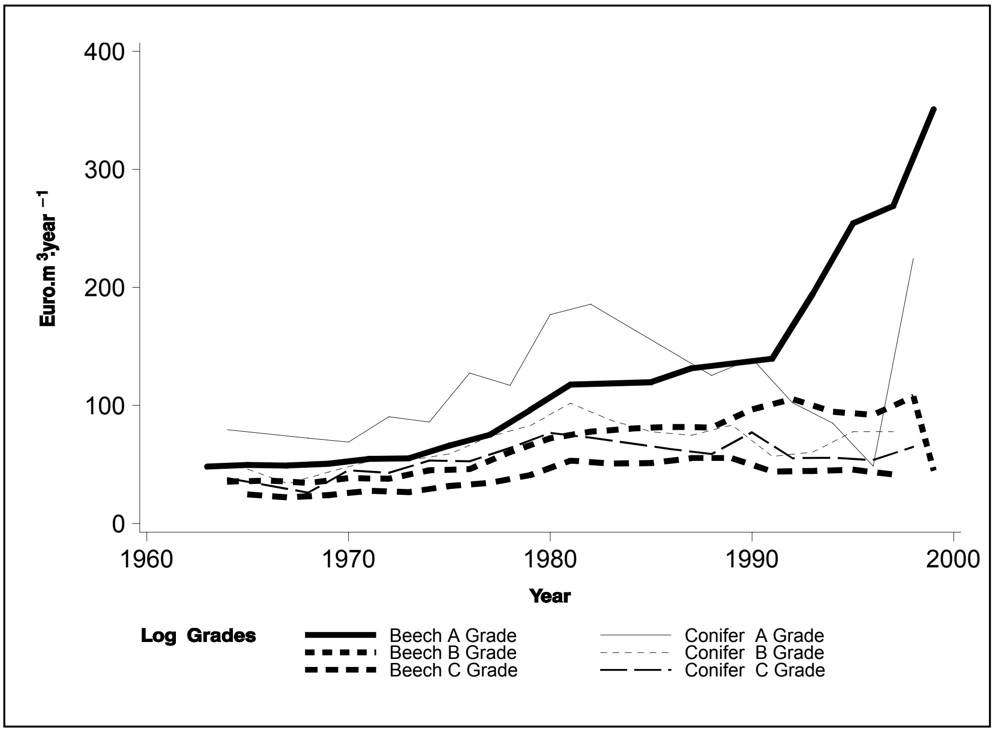

Figure 1: Price of different species in Baden Württemberg State Forest from 1965 to 1999 (MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) 1965-1999)

Looking at the development of species composition from 1850, it can be seen that the proportion of spruce has been steadily increasing (Figure 2). In contrast, the proportion of European beech has been decreasing over this period. As previously mentioned, there is now a tendency in Baden Württemberg to reverse this development to a degree and have more natural stands, consisting of a higher percentage of broadleaves (MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) 1993).

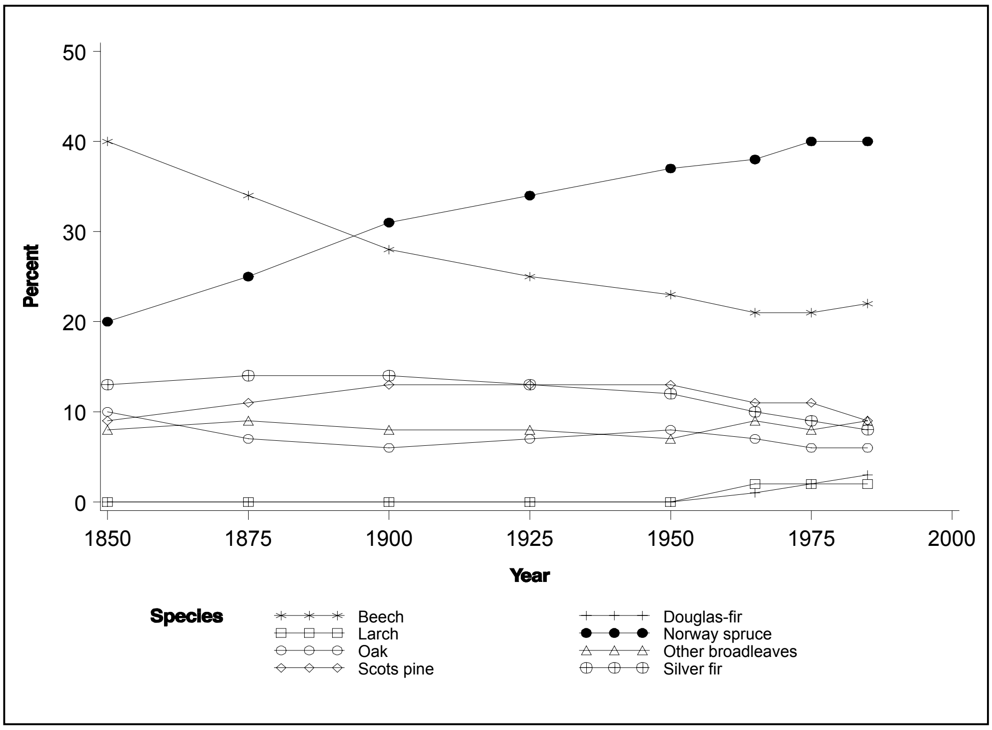

Figure 2: Change in main species proportions in Baden Württemberg State Forests since 1850 (MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) 1994a)

2.1.4 The Proportion of European Beech Ecosystems in the Black Forest and a Comparison with the Potential Natural Vegetation

In the Black Forest approximately 238,000 hectares are covered with forests (MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) 1994a). The most important species are summarized in Figure 3. European beech covers an area of approximately 36,000 hectares, almost all of which consists of pure even-aged stands.

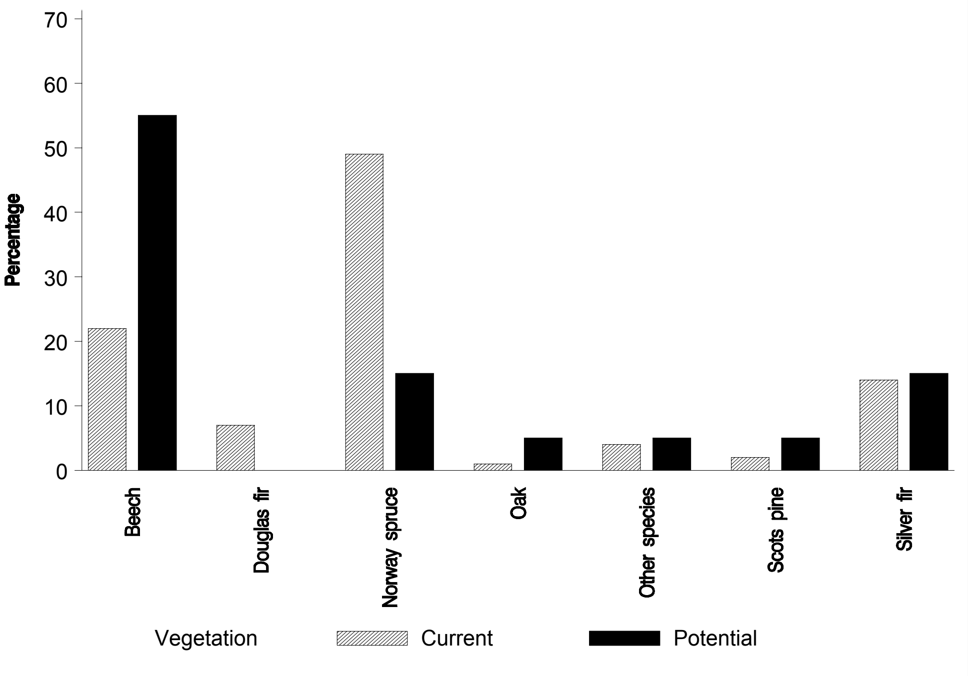

Figure 3: Comparison of current vegetation versus potential natural vegetation for Black Forest (adapted from MÜLLER & OBERDORFER (1994a) and MINISTERIUM FÜR LÄNDLICHEN RAUM (1974))

Figure 3 shows that there is a drastic difference in the potential natural vegetation compared with to the current composition of forests. Comparing the actual vegetation with the potential natural vegetation for the Black Forest gives a good insight into the effect of man on the composition of the forest. Clearly, European beech has been drastically reduced, while Norway spruce has been promoted through human intervention. In addition, exotic species like Douglas fir have been introduced.

In close-to-nature forestry the use of tree species which are native to the site, and are therefore well adapted to growing and self regenerating, are usually preferred. The potential natural composition can therefore be seen as a guideline for future planning in transforming stands to close-to-nature forestry systems.

2.1.5 Description of a Selection Forestry as a Template for Close-To-Nature Forestry System in the Black Forest

In the mountainous areas (between 500 and 1000 m a.s.l.) of the Black Forest region a long tradition of single tree selection system management on a close-to-nature basis has been both economically and ecologically successful (HANEWINKEL 1998). These selection forests exist only in a few areas, usually as small scaled farm forests where trees of all dimensions are cut regularly (rather artificial but somewhat sustainable). However, the practice of selection forestry systems has not always been fully appreciated in Baden-Württemberg. Selection forests in the former state of Baden were prohibited by the forest law of 1833 (SCHÜTZ 1999e) due to the irregular cutting of timber being regarded as unsustainable practice (HASEL 1985). However, single tree selection continued to be practiced in a number of areas despite the attempts of the forest service to implement a regulated and controlled system of forest management. The reason for this has been attributed to the strong economic interest in the selection system due to the fact that large trees could be sold to Dutch buyers for shipbuilding. Only silver fir could produce the dimensions necessary for masts (BAUER 1921). The selection systems persisted primarily along large rivers because timber was mainly transported on rafts. The term "Dutch felling" often appears in historical sources, especially regarding those regions connected to the River Rhine (SCHÜTZ 1999e).

In other regions, where forests were owned privately by small farms and where conditions for farming were harsh, these forests were often used as a kind of savings account which provided for unforeseen expenses, such as weddings or urgent repairs for the farm. Since both large and small trees were regularly needed, the single tree selection system was perceived as the best way to manage these small private forests. In these areas, tradition played a more important role than the influence of the forest service.

2.1.5.1 Site

Examples of the selection system can be found in mountainous regions within the natural range of silver fir (SCHÜTZ 1999d). Stable selection forests can only exist on deep soils that allow a good development of the root system. This deep root system protects the trees from storm events, which is important because of the rough crown surface of selection forests (SCHÜTZ 2001a). Sufficient water supply is also an essential requirement for selection forests. Therefore, selection forests occur in the Black Forest in the higher elevations (500-1000 m a.s.l., mountain zone), characterized by high annual precipitations (800-2000 mm.year^{-1}) and low average annual air temperatures (5-8.5ºC) (TRENKLE & RUDLOFF 1981). The typical soil types in these regions are brown earths formed from the parent materials of granite, gneiss and sandstone bedrock ((UBW) UMWELTMINISTERIUM BADEN WÜRTTEMBERG 1995).

2.1.5.2 Species

The tree species in selection forests must be shade-tolerant, especially during the early phases of development. The typical species composition for selection forests in the Black Forest consist of silver fir, Norway spruce and European beech. This mixture of rather shade-tolerant species is necessary in order for natural regeneration to occur under the canopy of the older trees.

It must also be mentioned that European beech plays an important role in special hardwood selection forests of east Germany. A classic example of this type of selection forest can be found in northwest Thüringen (BIEHL 1996).

2.1.5.3 Silviculture

KORPEL (1982; 1985) has discovered that the selection forest structure described here is rarely found in natural forests. This is because forest ecosystems have a tendency to accumulate biomass. They tend to close their canopies over time and produce regular stand structures. The selection system is, therefore, a man-made system, which nevertheless when established possesses a high degree of self regulation and resilience.

As a result the maintenance of a selection forest on a sustainable basis often requires frequent intervention activities in all parts of the stand. Selection forest systems tend to reduce the number of non-shade-tolerant species and thereby can reduce both species diversity and process diversity. If clear-cut phases are completely lacking, vegetation formations containing special successions such as pioneer plant systems cannot exist. On the other hand, sudden heavy intervention reduces the vitality of the remaining trees (SPIECKER 1986; SPIECKER 1991b). Although silvicultural interventions in selection forests are practiced in every development stage, they are often less intensive than even-aged forests (SPATHELF 1997). Trees in selection forests often exhibit typical growth patterns with generally slow growth in their youth and a consistent growth rate after release (MITSCHERLICH 1952; SPIECKER 1986; SPIECKER 1991b). When trees are released at this early stage, they tend to develop long crowns and have a greater vitality (SPIECKER 1986). Thus, their individual stability against storm and snow damage is high.

2.2 RESEARCH INTO TRANSFORMATION IN CENTRAL EUROPE

2.2.1 Overview of Transformation

There have been several attempts to quantify the goals and targets for selection forests in central Europe with respect to diameter distributions, standing volumes and annual yields (BOREL 1929; SCHAEFFER et al. 1930; ZIMMERLE 1936; FRANCOIS 1938; PRODAN 1949; SCHÜTZ 1989a; SCHÜTZ 1994; SCHÜTZ 1999b). However, there has been little research into the transformation process required to develop such uneven-aged structures.

This transformation can be described as the process whereby a regular stand structure, such as an even-aged plantation, is converted to an irregular structure with a range of tree sizes and where some tree cover is maintained in perpetuity. To fully understand this process the distribution of the tree dimensions has to be characterized (ALBERT & GADOW 1999; SCHÜTZ 1999b). There is an obvious difference in the diameter distributions between even-aged forestry and selection forestry. In even-aged forestry systems a normal diameter distribution is usually exhibited. This distribution becomes more skewed to the left as the stand gets older, through the self-promotion of trees that are already dominant (KRAMER 1988). The selection forest has a fundamentally different diameter distribution. This type of forest system has more trees in the smaller diameter classes (KRAMER 1988). The diameter distribution is usually described by a negative exponential function. This diameter distribution of a selection forest in equilibrium should remain steady over time, and the number of trees in each size class should be constant.

The main silvicultural problem of transformation is therefore, to shift the diameter distribution from a normal curve to an exponential curve. This process of transformation is depicted in Figure 4 .

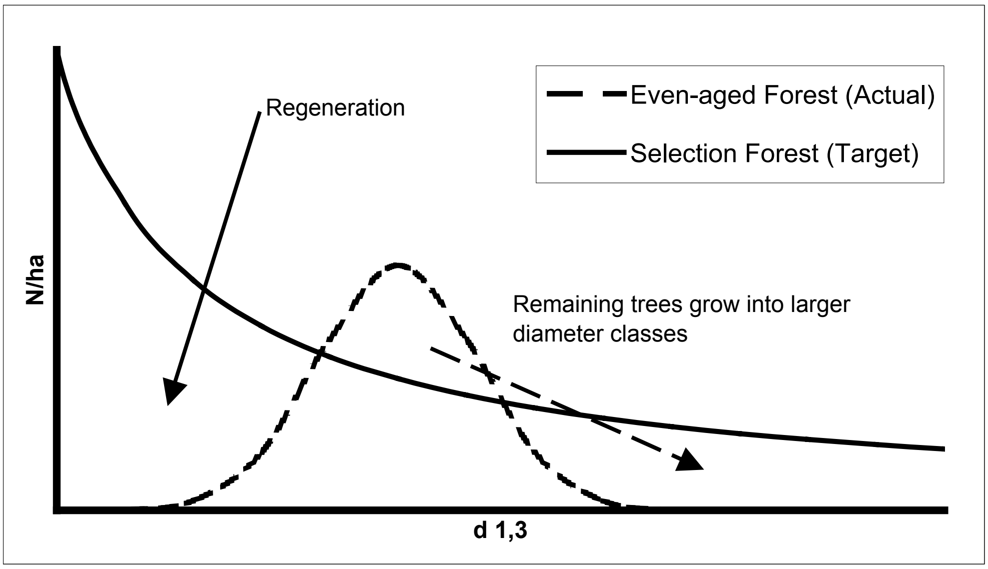

Figure 4: Schematic representation of the effect on the diameter distribution of even-aged forests when transferring to a selection forests (Adapted from BUONGIORNO (2001)).

The middle diameter classes of the even-aged forest are removed through a strong intervention. This intervention tends to have two main effects. Firstly, through the breaking up of the crown canopy, the soil receives sufficient light so that regeneration of a new cohort of trees can be established. The second effect is that the intervention destabilizes the stand. Therefore, the transformation phase is also a period of increased risk. Stabilization of the stand is achieved through the development of the crowns and root systems of the remaining trees.

2.2.2 Current Concepts of Transformation

Selective thinning and target diameter harvesting are two different concepts for transformation which can be singled out in the literature. These two types of transformation will be briefly described and compared here.

2.2.2.1 Selective Thinning

The selective thinning concept can be defined as carefully thinning to transform a structurally poor stand into a structurally rich stand. SCHÜTZ (1981; 1986; 1989a; 1989b; 1989c; 1992; 1994; 1997; 1999a; 1999b; 1999c; 1999d; 1999e; 2001a; 2001b) is one of the few authors who has tried to describe and quantify this process. SCHÜTZ suggests that the first rule of transformation is to ensure that sufficient time for the completion of the process has been allowed for. The second rule is that it must be decided whether to attempt transformation on the present generation of trees or to wait for the subsequent one. If the stand appears sufficiently structured with adequate numbers of stable cover building trees, then the transformation process is possible and progresses with selection cutting. SCHÜTZ has divided this selective cutting process into four distinct phases:

- A phase which attempts to spread the diameter distribution more broadly. This is conducted through promoting the dominant trees by removing the co-dominant and smaller trees;
- The stage of regeneration promotion, where the principal focus is on favoring new decentralized regeneration groups;
- The stage of structural development, where the focus is to achieve good horizontal and vertical distribution of structural elements;
- The stage of structural achievement, where the focus is to achieve vertical individualization of the remaining groups.

HANEWINKEL (1998) has suggested a similar process for transforming forests, also using selection cutting. He also uses a conversion process which is divided into distinct phases (HANEWINKEL 1996; HANEWINKEL & PRETZSCH 2000). These phases and their silvicultural meaning are briefly described here:

- The phase of stabilization and selective thinning, where future crop trees are selected and strongly favored. After future crop trees reach a stable height, selection thinning halts, leading to a complete regular coverage of the stand area with future crop trees of equal dimension.
- The quality improvement cut and graded regeneration phase is conducted in already existing gaps for natural regeneration or via advance planting.
- In order to guarantee a long phase of single tree harvesting and thereby a vertical differentiation within the stand, the third phase of the conversion takes place as a variable target diameter harvest, in which the target diameter is smaller at the beginning and rises with the duration of the conversion.

Both strategies begin with a stand that is sufficiently structured before further modifications occur by carefully disrupting the diameter distribution. Then, by strongly opening up the stand, the taper ratio of the trees is increased and a bi-modal diameter distribution is produced. Finally, further selective cutting is required across the diameter distribution to ensure that the correct number of trees in each diameter class is retained

2.2.2.2 Structural Thinning

In order to convert the even-aged forests of Schägel-Monastry in the north-western edge of Austria, REININGER (1976; 1987) introduced a target-diameter harvest silvicultural system. This concept requires the selection of 300 primary final crop trees and 300 secondary final crop trees per hectare at the beginning of the transformation phase. All selected trees have to be well developed, and the primary trees must be larger than the secondary trees. Through the execution of target-diameter harvesting, first the primary crop trees are removed, enabling the secondary crop trees to slowly take over their social positions in the stand. STERBA & ZINGG (2001) further investigated the use of target diameter harvesting as a tool for transformation. They concluded that although the steady state uneven-aged system has not been fully achieved in these stands, it will be in the near future.

GOLTZ (1991) has proposed a similar strategy, but restricted the selection of primary and secondary final crop trees to 150-200 each. TRUHLÁR (1995; 1997) has also described a successful transformation of forest in parts of the former Czechoslovakia using similar methodology.

The general idea of the structural thinning concept is that the uneven spatial distribution of crop trees throughout the stand and the different temporal stages of thinning ensure that the regeneration of the sub-canopy occurs at different rates. As a result the subsequent structure of the forest stand will be more structured vertically.

2.2.2.3 Comparison of the Two Transformation Concepts

The aim of both selection cutting and structural thinning strategies is the same; to convert a regular structure into an irregular structure with a range of tree sizes and maintain some tree cover in perpetuity. The basis of the selection thinning concept is to partition the transformation process into distinct phases, characterized by pre-defined targets. However, this is not the case with the structural target-diameter harvest concept. This concept is usually associated with silvicultural systems applicable for even-aged management. However, by ensuring a long phase of single tree, target diameter harvesting causes a vertical differentiation within the stand. In both systems, trees are selected for release.

2.3 THE IMPORTANCE OF ADVANCED EUROPEAN BEECH TREES IN THE TRANSFORMATION PROCESS

2.3.1 Maintaining Advanced European Beech Trees in the Canopy

Transformation of pure even-aged stands into uneven-aged mixed stands requires stable sites and the possibility of maintaining cover building trees in the upper story (SCHÜTZ 1989a). There must be either sufficient numbers of cover-building trees with potentially long life spans or this must be achievable using crown release. If this is not the case, transformation by differentiating the present stand should not be attempted. It is important to achieve a better structured heterogeneous, mixed generation first, as this will support transformation in later stages. If not, there is the risk of unwittingly opening the crown cover when advanced European beech trees die before transformation has been achieved, which leads to homogenization of the second growth. Consequently, when dealing with older stands it is vital to establish whether there are enough trees (40-60/ha) capable of supporting transformation over a long period of time.

To accurately know which trees have the potential to become cover building trees and whether their vitality is sufficient to survive the transformation process detailed information on the growth and reaction of the larger trees is required. Unfortunately, there are only a few short-term experiments that have investigated increased diameter and volume growth of released old trees (PETRINI 1932; ZIMMERLE 1936; ZIMMERLE 1938; ASSMANN 1965; JOHANN 1970; PREUHSLER 1981).

2.3.2 The Role of Advanced European Beech Trees in the Stabilization Process

The question of whether crown release might hasten the stabilization of large trees in the transformation forests has not been extensively examined in the literature. Stabilization is achieved by releasing trees so that the tree crowns and the root systems are better developed. Also, the height increment decreases and the diameter increment increases (THOMASIUS 1988). Trees with this type of crown and stem architecture are considered to be more stable.

To achieve successful crown release for the stabilization of trees, it is necessary to select residual trees that can respond to treatment. Ideally, the selected trees will give the greatest magnitude of response, but selection criteria are not clear. Commonly, release studies report a positive response as a discrete increase in diameter, basal area or volume increment. These reports are usually stand averages, with individual tree responses falling below and above the mean. An exception to this for European beech in the Black Forest, are the studies from ALTHERR (1971) and KLÄDTKE (1999) which describe the reaction of European beech future crop tree after release. However, no explanation is given for the large response of some individuals or the lack of response of others. Further information regarding the correct selection criteria for crown release is required to ensure the speedy and successful stabilization of the stand in transformation management.

2.3.3 Age Distribution of European Beech in Southern Black Forest

The current age distribution of European beech in the Black Forest clearly shows that approximately 50% of the stands are in excess of 80 years old (Figure 5). If transformation is to occur in these stands, then knowledge of how the trees react to the transformation interventions is vital. Due to the fact that a large proportion of these stands are at an advanced age, it is necessary to acquire knowledge of how these advanced European beech trees will react to the transformation process.

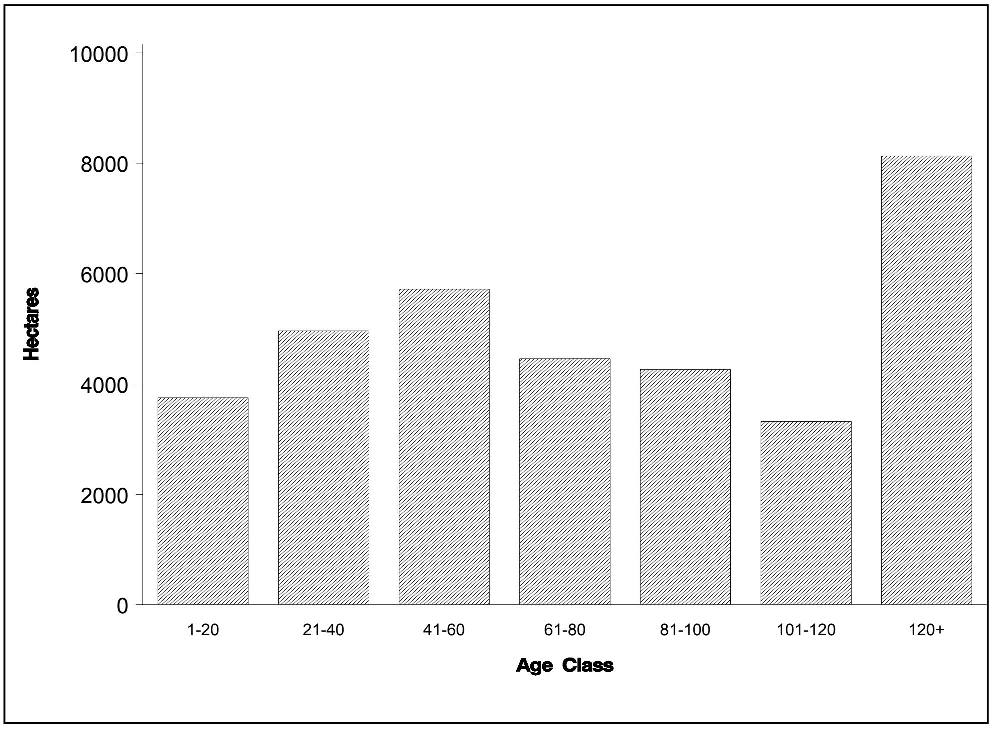

Figure 5: Age class distribution of European beech in the Black Forest (MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) 1994a)

2.3.4 Value of Advanced European Beech Trees

It can be seen from Figure 6 that there is a strong relationship between dimension and the price a log-grade receives. This demonstrates the importance in economic terms of maintaining advanced European beech trees in the canopy, which when sold command a high price.

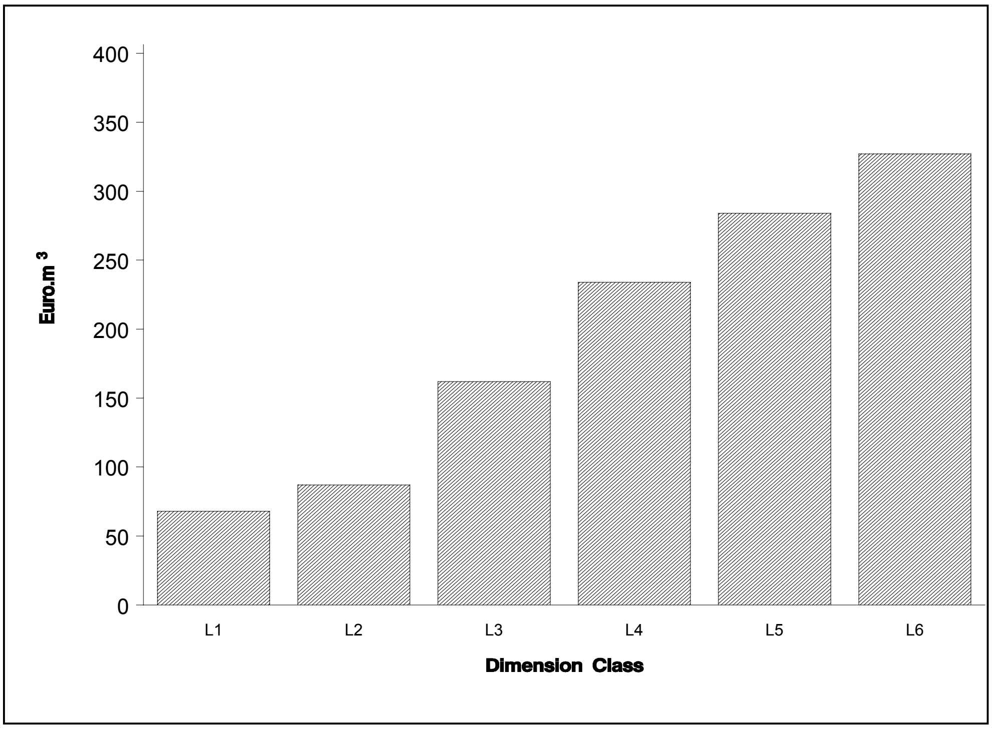

Figure 6: Price and dimension relationship for European beech in Baden Württemberg from 1994-1998 (MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) 1994b-1998)

2.3.5 The Role of Advanced European Beech Trees in Determining Structural Diversity.

The effect of retaining advanced European beech trees in the canopy on stand vertical structure diversity is examined here in terms of a theoretical vertical structural index. Structural indices have been used as surrogate indicators of biodiversity (KERR 1999). The main factors affecting the vertical structure of a forest stand are the branches and the foliage of the tree species present (KERR 1999). The connection between this variation and bird species diversity was first investigated by MACARTHUR & MACARTHER (1961). They found that there was a direct relationship between the number of bird species and an index of the vertical distribution of foliage (foliage height diversity). Similar results have been reported for forests in Baden Württemberg by NIPKOW (1995).

Although there are numerous methods of assessing the vertical structure of forests there are few, if any, attempts to compare it with different silvicultural systems. A theoretical comparison between clear-cutting and the single tree selection system, operated on the same landscape, is presented in Figure 7.

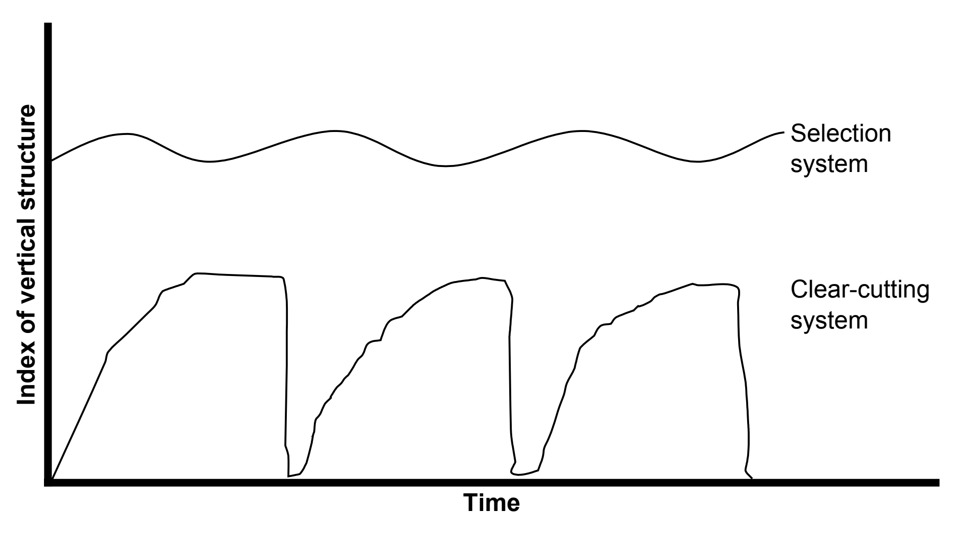

Figure 7: Schematic diagram showing changes in vertical structure clear-cut and selection forestry systems through time (adapted from KERR (1999))

The vertical structure of clear-cut stands increases during the stand development and then falls dramatically when the trees are cut. In this theoretical example, the index of vertical structure of the single tree selection system is higher than that of the clear-cut system, and because of the nature of the stand interventions and pattern of regeneration, the index of vertical structure remains fairly constant. Therefore, the retention of groups of advanced European beech trees in the canopy in selection forestry increases the level of vertical structure, which in turn aids the structural diversity of the stand.

2.4 THE QUANTIFICATION OF GROWTH RESPONSES TO RELEASE

2.4.1 Defining Growth Response

The change in a tree's growth that can be attributed to release is the difference between the actual growth and the growth that would have occurred had the tree not been subjected to release. The former growth is measurable, the latter is hypothetical. To obtain an idea of the size of the growth change as a result of thinning, the actual growth must be compared with some actual entity that represents the unaffected growth as closely as possible.

This growth response is usually positive because its beneficial effect – improved access to growth resources – normally exceeds the possible negative effects due to poor acclimation of trees to sudden reductions in canopy closure. When the effect of release is negative, then it is often referred to as release stress. This can be defined as the growth difference between a released tree and a non released tree of exactly the same size, age, growing space for the same site and the same climatic conditions. Growth is less for the released tree in this case because a tree facing an abrupt change in growing conditions may not be able to utilize the resources as efficiently as a tree that has had time to acclimatize itself to the ample growing space (SPIECKER 1991b).

The release response of a tree can be defined in a variety of ways. MCWILLIAMS & BURK (1994) list eight different ways to quantify the response of trees. This list includes simple differences, ratios and covariance estimators. One simple method is to take the ratio between the actual growth of a released tree and that of a tree unaffected by release. The release response, according to this definition, coincides in principle with the Näslund response ratio, which is an expression of the response in annual-ring width caused by thinning (NÄSLUND 1942). SUNDBERG (1971) developed this response ratio further for his own purposes and gives a theorectical commentry. An example of a positive release response using this definition is depicted in Figure 8. It is hypothesized that the affect of releasing on growth should begin at zero and increase to some maximum, then diminish and approach a pre-released condition (LIU et al. 1995). The reason why the release response does not return exactly to a pre-released condition is because the released tree is now a larger tree and consequently has a higher growth rate.

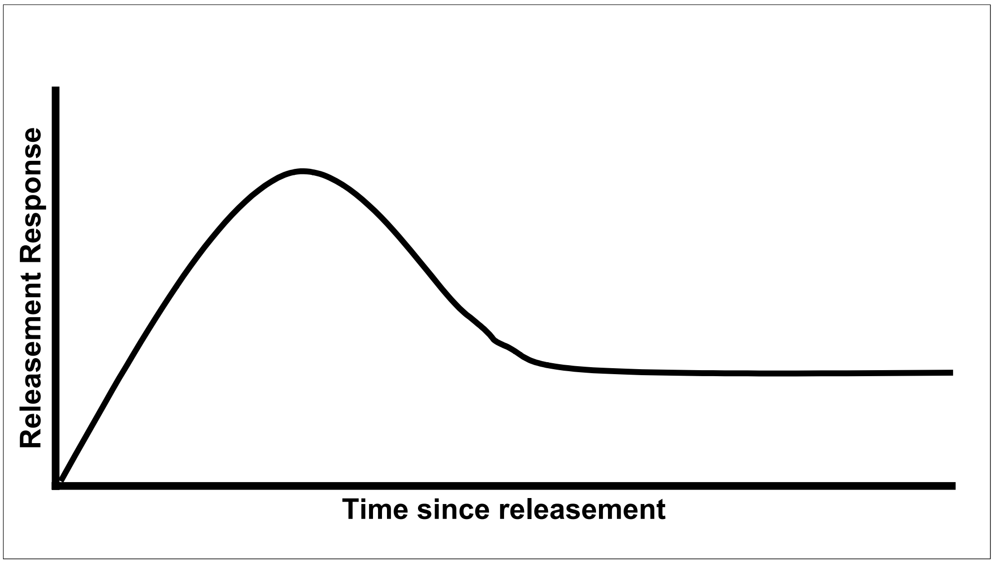

Figure 8: Schematic diagram representing a positive release response over time

Release response defined in this way is the sum of several effects. Certainly crown competition prior to and after treatment influences the response. STAEBLER (1965) found that Douglas fir responded more to release as additional competitors were cut. DUNNING (1922) reported ponderosa pine stems with longer crowns had a greater response than trees with shorter than average crowns in the same diameter class. MINKLER (1957) having selected white oak stems with both fast and slow past growth rates, found release response to be related to crown class. Fast-growing trees had the greatest absolute diameter increment after thinning. In white pine thinning trials HUNT (1968) reported crop trees responding rapidly to increased growing space and that the response was correlated with total foliage weight.

In addition to competition, change in competition, tree size, age and length of suppression and the genetic composition are also recognized as affecting growth response to release. Genetic variation among residual trees may play an important role in the variation in growth seen. KONNERT & SPIECKER (1996) found the genetic variability of European beech was affected by selective thinning.

Growth variation can also arise from variations in the length of the growing season. FRANK (1973) using white spruce, determined that the number of days a tree grows increases as release increases. Growth initiation of white pine was shown to be controlled by both photoperiod and temperature (HUSCH 1959). ADAMS (1935) reported that thinning white pine resulted in increased soil and crown temperatures, allowing early growth initiation. Soil moisture, which limits the length of the growing season (HUSCH

1959), was found to be greater on thinned plots, allowing longer growth (ADAMS 1935; HUSCH 1959; HUNT 1968). Thus, release intensity can alter the physical micro-environment immediately adjacent to crop trees.

In summary, competition, change in competition, tree size, age, length of suppression and genotype all contribute to the ability of an individual tree to respond to thinning. Conceptually, a tree's measured growth response to release is a function of these variables and a model can be constructed to predict the growth response to release from direct measurement of these variables. In this manner, the importance of these variables in controlling growth response can be tested. The intensity or type of release modifying these factors may result in a response of varying magnitude.

2.4.2 Stand Versus Tree Level Resolution

Even after several decades of long term studies, planning for silvicultural management remains a difficult and complex problem. Forest management has approached the problem with a variety of sophisticated analyses, but the main emphasis of recent analyses usually depends on statistical growth models fitted to data from empirical field trials. However, statistical growth-and-yield simulators often interface poorly with modern forest management analyses. Even though there is no better predictor of the next rotation than the performance of the previous rotation, historical data does not exist for every stand and the combinations of species, density management, silviculture and sites create a matrix too large to test with spacing/silvicultural studies. Therefore, forest growth models have been developed with several levels of detail, and with an emphasis on mechanistic processes representation or on accurate long-term forecasting. Tree-level models specify the diameter, height and/or other variables, for each tree in a stand. Stand-level models describe the stand by a small number of aggregate “macro“ variables, such as mean diameter, top height and number of trees per hectare.

Tree-models can be spatial (or distance-dependent, spatially explicit, spatially extended) if the position of the each tree and its competitors is part of the description, or aspatial (distance-independent) if it is not (MUNRO 1974). Alternatively, aspatial tree-level models are sometimes classified as distribution-based models; a set of tree sizes (a “tree list”) being equivalent to an empirical distribution (VANCLAY 1994).

When modeling is used mainly as a research tool to investigate stand development processes, tree-level models can be extremely useful. Here, qualitative agreement with hypothesized mechanisms is paramount, while questions of quantitative accuracy and precision are largely irrelevant. Often the benefits arise from building the model through the synthesis of previously isolated facts and identification of gaps in knowledge. Highly detailed spatial models are likely to be the most useful, at least in the early stages of understanding silvicultural problems.

Foresters have been the pioneers in individual-based spatial modeling. Following the early work by STAEBLER in the 1950's, the idea really took off with the availability of digital computers in the mid-60s. The peak of activity was reached during the 1970s. See DUDEK & EK (1980) for an annotated bibliography. Many of these models were ultimately intended to be used for forest management and not just as research tools.

The great majority of spatial forest growth models, and almost all aspatial ones, use the tree diameter as the main or only input variable. From a biological point of view this can be seen as a limitation. Tree growth rates are not driven by the amount of wood that has accumulated on the stem, rather growth rates are a consequence of growing-space. Consequently, there is often a good correlation between the diameter and growing space, especially in unmanaged natural stands where most of the work has been done. This correlation, however, breaks down with stand interventions, such as those practiced in transformation management. Stand interventions create an imbalance in the natural structure and provide situations where the diameter might be relatively small compared to the amount of growing space. In this case, the diameter increment may be better correlated with change in growing space or residual growing space, rather than with absolute diameter.

As the amount of research published on transformation is still not very extensive, there may be an argument for making the spatial individual tree model the basis for the initial investigating studies into transformation. It is with these highly detailed spatial models that researchers can start to understand the hypothesized mechanisms behind the actual transformation process. It is important for researchers to improve their understanding of the processes of development in stands undergoing transformation before they start building models where quantitative accuracy and precision are paramount.

2.4.3 Defining the Magnitude of Release

Measurement of changes in competition in forest stands has been a topic of considerable research, partly because competition-tree growth relationships are key components in many types of models in forecasting long-term stand development or response to silvicultural treatments. There are many possible mechanisms for one plant to affect the growth of other plants in the near vicinity. HARPER (1977) lists 13 such ways and stresses that the list is incomplete. Some of these ways are observable, but most are not. Thus researchers are faced with the problem of either doing long-term, intricate experiments to measure actual changes in competition or of finding easily measured attributes of the system (i.e. competition indices).

Therefore, most models that simulate the growth of individual trees use some type of competition index to measure competitive stress (see review by DALE et al. (1985)). These indices are generally classified as either distant-dependent or distant-independent, based on whether knowledge of inter-tree distances is needed to compute the index (MUNRO 1974).

Among the distant-dependent indices, are the influence-zone overlap (NEWNHAM 1966; OPIE 1968; BELLA 1971) and the growing-space polygon approach (e.g. BROWN (1965), MOORE et al. (1973), NANCE et al. (1988)), each providing some estimate of the growing space available to each tree based on stem maps and initial tree diameters. Distance-weighted size ratios (e.g. HAMILTON (1969) and HEGYI (1974)) have no clear geometric interpretation, but produce a dimensionless number related to the relative size and density of competitors around the subject tree.

Although the desire for greater spatial sensitivity is the major reason for the development of distance-dependent competition indices, most evaluations of competition indices have shown that simple size-ratio indices perform almost as well as the more complex geometric types (DANIELS 1976; ALMEDAG 1978; MARTIN & EK 1984; HOLMES & REED 1991; BIGING & DOBBERTIN 1992). Moreover, among the size-ratio indices, the evidence suggests that knowledge of inter-tree distances is largely redundant. In recent years, the predominant trend in forest growth modeling has been toward that of simple size-ratio competition indices (HEGYI 1974; DANIELS & BURKHART 1975) or distant-independent approaches (BELCHER et al. 1982; MARTIN & EK 1984; HILT 1985; HARRISON et al. 1986; WAN RAZALI & RUSTAGI 1988; TECK & HILT 1991).

However, transformation management is one application for which increased spatial resolution in individual tree models is desirable. Canopy gap dynamics generally play a minor role in even-aged stand development (OLIVER 1981) and are often ignored in simulations, but gaps have a major influence on the structure stability and sustainability of transformation management. Sustained even flow of timber in uneven-aged stands is believed to require maintenance of a diameter distribution approaching a negative exponential curve (KRAMER 1988). In such forests, a steady influx of young trees into canopy positions is maintained in response to canopy gaps created by tree harvesting (ALEXANDER & EDMINSTER 1977; SMITH 1986; SCHÜTZ 2001a). If, however, canopy gaps are predominately closed by lateral expansion of border crowns, canopy recruitment is inhibited and the diameter distribution is likely to depart from a sustainable condition. Lateral gap closure is especially likely in stands managed with a relatively small maximum diameter and high q ratio, stands that have had excessive harvesting in the larger size classes, and in young even-aged stands managed by single-tree selection (ROACH 1974; ERDMANN 1986). The long-term effects of silvicultural interventions on stand structure in these cases could be difficult to predict if crown and gap configurations are not modeled directly. For example, a typical diameter distribution index cannot reliably distinguish between a gap in young trees and an overtopped young tree of the same size in stands. The most likely reason for this is that crown and gap configurations cannot be inferred accurately from stem maps (LORIMER 1983).

A distant-dependent competition index which has been previously found to be more strongly correlated with the growth of European beech than other indices is the Area Potentially (*APA*) index (HAHN 1995). A brief overview of this index is provided here.

2.4.3.1 Area Potentially Available

MOORE (1973) modified BROWN'S (1965) concept of the *APA* index to a tree as a measure of point density for use as a competition index. The modified *APA* index is defined as the area of an irregular polygon constructed around a subject tree. The edges of the polygon are formed by intersecting lines that divide and are perpendicular to lines connecting the subject tree with each of its competitors (Figure 9).

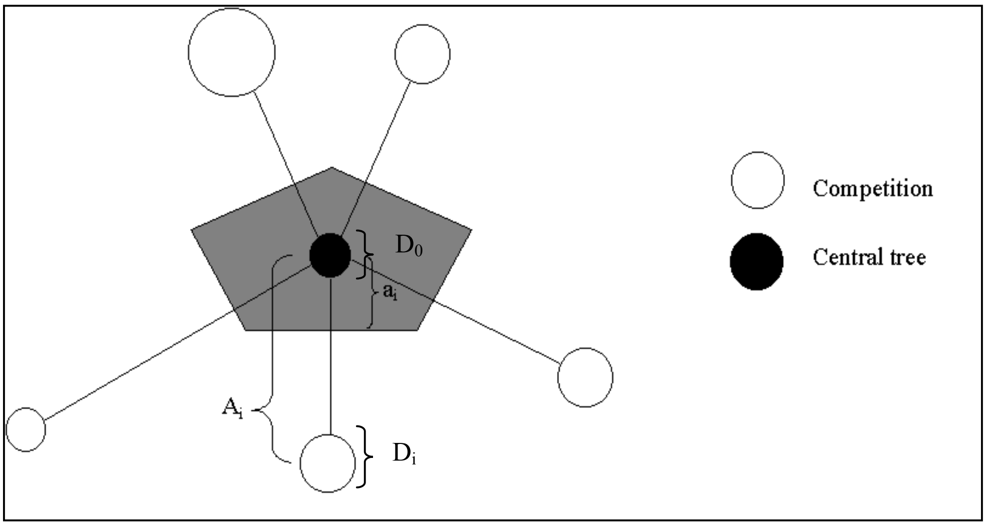

Figure 9: Schematic diagram of Area Potentially Available index

This modified *APA* index is intended to express aerial and root competition by describing the zone of primary influence and growing space for an individual tree as being limited by competition from surrounding trees. The distance a_i from the middle of the central tree to the edge of the polygon can be calculated using the following formula from MOORE (1973):

$$a_i = \frac{D_0^2}{D_0^2 + D_i^2} \times A$$

Equation 1

where a_i = distance from middle of the tree to the edge of *APA* polygon (m);
A_i = distance between subject tree and competitor tree (m);
D_0 = diameter at breast height of subject tree (cm);
D_i = diameter at breast height of competing tree (cm).

This index was further modified by NANCE et al. (1988) to limit the maximum distance of a_i to be no greater than the crown radius (*CR*) of an open-grown tree of the same size diameter (*D*). This stops the index expanding too far when there are extreme irregular spacing patterns. It is assumed that the crown width of an open grown tree represents the maximum distance a tree has influence on. A suitable equation to predict the expected crown radius for open grown European beech in Baden-Württemberg can be constructed using data from FREISE & SPIECKER (1999) with the following form:

$CR = 3.3373 + 0.6035(D)$ $\overline{R}^2 = 0.73$

Equation 2

Where CR = crown radius (m);
D = diameter at breast height (cm).

This type of constrained *APA* index has been found by HAHN (1995) to be highly correlated with the diameter increment of European beech.

Most competition indexes are actually measures of crowding. The *APA* is unique in that it is a quantitative measure of the competition status of the tree. The *APA* has four desirable features:

1. the areas of the trees in a stand are mutually exclusive;
2. the area between two trees is divided relative to tree size;
3. the *APA* is sensitive to changes in the relative tree sizes over time:
4. high correlation has been found to exist between diameter increment and *APA* index.

The area around each tree is influenced by the size and proximity of neighboring trees. In general, the defined polygon of a large subject tree will be restricted only by its nearest neighbors, while a small tree will be affected by larger trees at greater distances. The effect causes “holes” or unused spaces between the polygons where no tree dominates.

The edges of the polygons divide the line connecting the subject tree with its neighbors. The point of division is based on the relative size of the trees. Due to the location of the side of the polygon between competing trees being relative to tree size, the *APA* number is sensitive to changes over time. If one tree grows faster than another, the dividing line between them moves towards the slower growing tree, which is an indication of their relative vigor and the faster growing tree’s ability to command a larger share of the available resources.

2.5 DATA COLLECTION METHODOLOGIES APPROPRIATE TO TRANSFORMATION RESEARCH

Silvicultural studies have a tendency to rely on long-term records from permanent spacing and thinning trials. Unavoidably, these reflect opinions or concerns of socioeconomic values that were applied decades ago, although they may include treatments judged extreme at the time. In this respect, setting up a new trial implies decades of observations before it can be useful. To predict the effects of recently speculated treatments, it is necessary to widen the basis of the data provided by existing permanent stands. This can be done, for instance with "temporary" or "semi-temporary" sample plots, measured once or over a period of a few years. Generally, it is difficult to find contrasting stands in this case because the management practices tend to standardize the treatments.

These types of investigations are described as *Ex-post facto* studies. These are studies where pre-existing and non-manipulated variables are measured. They are often made retrospective by linking some variable in the present to some phenomenon in the past. This type of study is excellent for correlation research purposes to determine relationships among variables but unfortunately cannot infer cause and effect relationships.

To anticipate the response of a wide variety of treatments that have never been put into practice, there has been an increasing tendency to rely on basic information of general applicability and immediate availability of these *Ex-post facto* studies. This kind of information is best found at the level of individual tree growth (DAUME & ROBERTSON 2000). An advantage of this approach is that large amounts of stand data are not necessarily needed for the model construction, and it is easier to find trees, rather than stands, in practically all possible growing conditions.

Consequently it has become more apparent that the studies of stand dynamics that allow the most diverse explorations of treatments are based on retrospective individual tree growth, including information on crown development, and its connections with stem growth and development. This has been done to some extent by MITCHELL (1969). The work of MITCHELL (1975) in particular showed the full potential of this procedure. Relying on stem and branch analysis, his methods resulted in relationships expressing laws of individual tree growth in general stand conditions. Similar works were later presented by INOSE (1982; 1985).

2.5.1 Retrospective Measurement of Diameter Increment

During the last few decades, the science known as "dendrochronology" or tree-ring dating (STOKES & SMILEY 1968; FRITTS 1976) has become well established and accepted as an analytical tool. Dendrochronologic techniques, based on ring width analysis, are appropriate to reconstruct past growth of trees, but they have mostly been used either to trace climatic variations or to analyze the response of trees to climate (HARI & SIRÉN 1972; CHANG & AGUILAR 1980; FRIEND & HAFLEY 1989; SPIECKER 1991a).

Since the work of FRITTS (1966) most of these later studies do not examine the effects of silviculture treatments but rather try to avoid or smooth away such effects along with those relating to age. However, there are a few studies that have used dendrochronological techniques to investigate growth in terms of silvicultural practices. ABETZ & UNFRIED (1984) investigated the growth of spruce using these retrospective methods. SPIECKER (1991c) investigated the growth of oak trees using tree ring analysis. CUTTER et al. (1991) accounted simultaneously for silviculture and climate effects on tree growth by comparing the yearly basal area increment of trees in treated stands with that of comparable trees in untreated stands. GOFF & OTTORINI (1993) investigated the thinning and climate effects on the growth of European beech in the northeast of France. BÖRNER (1997) investigated the reaction of European beech trees after release, but found a large unexplained amount of variation in his analysis. SPATHELF (1999) studied the reaction of Norway spruce and silver fir to thinning as a function

2.5.2 Retrospective Measurement of Height Increment

One direct method for measuring the height increment of trees is to conduct a height analysis. ROLOFF (1986; 1988) has shown that by using bud scars and secondary branches it is possible with careful measurements to backdate the height increment of European beech for a number of years (20-30 years). This methodology has been used and validated by DOBLER et al. (1988) and BÖRNER (1997).

2.5.3 Retrospective Measurement of Crown Radius Increment

There is a lack of specific data on the lateral crown radius increment of canopy trees. This data is required to study the competitive processes taking place following selective thinning. The crown radius increment data for advanced forests trees is necessary to resolve this gap closure issue and is not easy to obtain. A number of methods have been used in previous studies to estimate lateral crown radius increment rates. TRIMBLE & TRYON (1966) used an indirect method to estimate lateral crown radius increment rates for red oak and yellow-poplar in West Virginia, based on a regression equation of the form:

$$CR = \gamma_0 + \gamma_1 D + \gamma_2 GA$$

Equation 3

where CR = crown radius (m);
D = diameter at breast height (cm);
GA = gap age (years).

In this equation, crown radius (*CR*) is correlated with tree diameter (*D*), and is predicted to have an additional increment due to accelerated growth into a gap. With known diameters and gap ages at the beginning and the end of a given growth period, lateral crown radius increment rates can be estimated. RUNKLE (1982) used the same equations (parameters derived from his data) to estimate gap closure rates on mesic hardwood sites in the southern Appalachians, USA.

More direct measures of crown radius increment have also been made. RUNKLE & YETTER (1987) measured the lateral crown radii on the same trees used in RUNKLE'S previous study (1982) to verify crown radius increment rates into gaps. Another direct analysis technique for estimating lateral crown expansion rates is the measurement of recent annual internode lengths on branches extending into gaps (MITCHELL 1969; HIBBS 1982; COLE & LORIMER 1994). This method requires approximations to correct actual internodal lengths to horizontal growth along the gap/crown radius axis, but only requires one set of measurements, rather than repeated measurements at the beginning and the end of the growth period.

GUERICKE (2001) is one of the few researchers to investigate the crown expansion dynamics in European beech. He re-measured after 10 years the crown projection area on 907 trees (refer to SPIECKER (1991c) for information on crown projection area measurement). The annual crown radius increment was calculated from this indirect measurement. Due to the azimuth of the 8 radii not being held constant for the re-measurement, an adjustment was required. The annual crown radius increment ranged from approximately –52 to 42 cm.year^{-1}. The mean for the positive crown radius increment was approximately 10 cm.year^{-1}.

2.5.3.1 Branch Expansion

Crown expansion is a global response to tree competition. HAUTOT (1992) had found a negative effect of grass competition on crown extension. This result is in accordance with a global branch response to competition for water and nutrients. All branches are affected by a decrease in the amount of nutrients and water available to each tree. However, MADGWICK (1986) found that fertilized trees have a more rapid decrease in branch expansion, so that water deficiency could be the main factor against crown extension. The decline of water potential in a tree has a global negative effect on the growth of all branches in the system (SPRUGEL et al. 1991).

CANNEL & MORGAN (1990) noticed that a shoot that elongates strongly every year has less assimilates available for net export, so the decrease in elongation could also be a response of the balance between cost and occupying sufficient space. Through water or nutrient stress, branch increment could decrease in order to maintain a minimal carbon export.

Branch length increment decreases along the branch from stem to branch tip (MAO-YI & TAMM 1985) with:

- bud aging (FRITTS 1976);
- increase in distance for water and nutrient translocation;
- increase in mechanical constraints (HORN 1971);(MORGAN & CANNELL 1988)
- more unfavorable carbon balance (MORGAN & CANNELL 1988).

2.6 SUMMARY AND IMPLICATIONS OF LITERATURE ANALYSIS

Chapter 2 presented and examined selected literature relevant to the release response of old aged European beech trees in the transformation process in the Black Forest. The chapter built a theoretical foundation upon which the current study is based upon. The major research issues from the literature review are provided below, with their implications with respect to the research methodology adopted in the present study.

Research Issue 1: European Beech is an Important Species in Transformation Forestry in the Southern Black Forest

The first section of the literature review dealt with the historical aspects of European beech in the southern Black Forest and the role it has to play in close-to-nature forestry within this region. This section provided a definition of close-to-nature forestry within the context of the current study and followed the recent international movement towards close-to-nature forestry, including the recent legislation in German states including Baden Württemberg. Due to European beech naturally occurring in the Black Forest, its role over the last 3000 years was reviewed with special emphasis on how other species like Norway spruce have displaced it. Under the definition of close-to-nature forestry in this study, native species which are well adapted to the site are favored. Therefore European beech, as a native species of the Black Forest has an important role in the transformation forestry in the southern Black Forest. Consequently, European beech is the species investigated in this study.

Research Issue 2: Lack of Research in Previous Studies on the Role of Released European Beech in the Transformation Process

The second section reviewed the two major transformation concepts found in the literature. The similarities and differences between the two concepts were reviewed. A major element of both transformation concepts was the release of selected trees to aid the transformation process in central Europe. The majority of the small number of studies investigating the transformation process have been limited to Norway spruce and silver fir. Consequently, there is a deficit of studies investigating the role of European beech. A major focus of this study is to expand the knowledge of the role released European beech play in the transformation process in the southern Black Forest.

Research Issue 3: Lack of Research on the Role of Advanced European Beech in the Transformation Process in the Black Forest

The third section of the literature review investigated the importance of advanced European beech in the transformation process. Advanced European beech trees were found to be important in the following aspects of the transformation process:

- maintenance of perpetual cover in the upper story;
- stabilization of the stand;
- providing economic returns;
- providing structural diversity.

Therefore, a major focus of this study is to establish what role can advanced European beech trees play in the transformation process in the southern Black Forest.

Research Issue 4: The Tree-Level is an Appropriate Level for Transformation Research Purposes

The fourth section reviewed the literature on quantifying the growth response to release. A definition of growth response was developed from the literature. An overview of tree-level versus stand-level investigations was provided. The advantages of the individual tree-level approach for investigatory work was highlighted. The variables which are important to quantify release and a short annotated bibliography of competition indices from the literature, with a brief overview of Area Potentially Available (*APA*), was provided. Therefore, this investigatory transformation study is conducted at the individual tree-level using *APA* to quantify changes in competition.

Research Issue 5: Retrospective *Ex-post Facto* Methods are Appropriate for Transformation Research

The fifth section of the literature review summarized the data collection methods appropriate for transformation research. *Ex-post facto* methods were focused on, especially retrospective methods for estimating diameter, height and crown width growth. Consequently, this study utilizes retrospective analysis at the tree-level. This includes dendochronological, height increment analysis and branch internode analysis techniques.

3 METHODS AND MATERIALS

Chapter 3 presents the methods and procedures for the study. The chapter is divided into six sections: Description of the Null-Hypotheses, Description of the Material, Description of the Field Methods, Description of the Laboratory Methods, Description of the Data Preparation and Description of the Data Analysis.

3.1 NULL-HYPOTHESES

The specific null-hypotheses (NH) posited for testing in the study were as follows:

NH1) There is no significant difference at the 0.05 level of statistical confidence in the basal area increment of advanced European beech trees from before to after heavy release.

NH2) There is no significant difference at the 0.05 level of statistical confidence in the height increment of advanced European beech trees from before to after heavy release

NH3) There is no significant difference at the 0.05 level of statistical confidence in the growth of an exposed branch to an unexposed branch for advanced European beech trees

NH4) A gap diameter of 10 m is insufficient in size at the 0.05 level of statistical confidence to assure the recruitment of a 4 m high sapling into the canopy.

3.2 DESCRIPTION OF THE MATERIAL

3.2.1 Study Sites

Study sites were established in the winters of 1999, 2000 and 2001 in four European beech stands in the southern Black Forest. In order to provide variation in individual tree competition, stands that had undergone recent thinning (between 5-21 years previously) were selected as the focal point of this study. The stands were located in the forest regions of Bad Säckingen, Schopfheim, St. Märgen and Todtmoos (refer to Figure 10) and were selected to represent the broad range of European beech ecosystems typical of the southern Black Forest. By sampling such a range of sites, the external validity of the research results was increased.

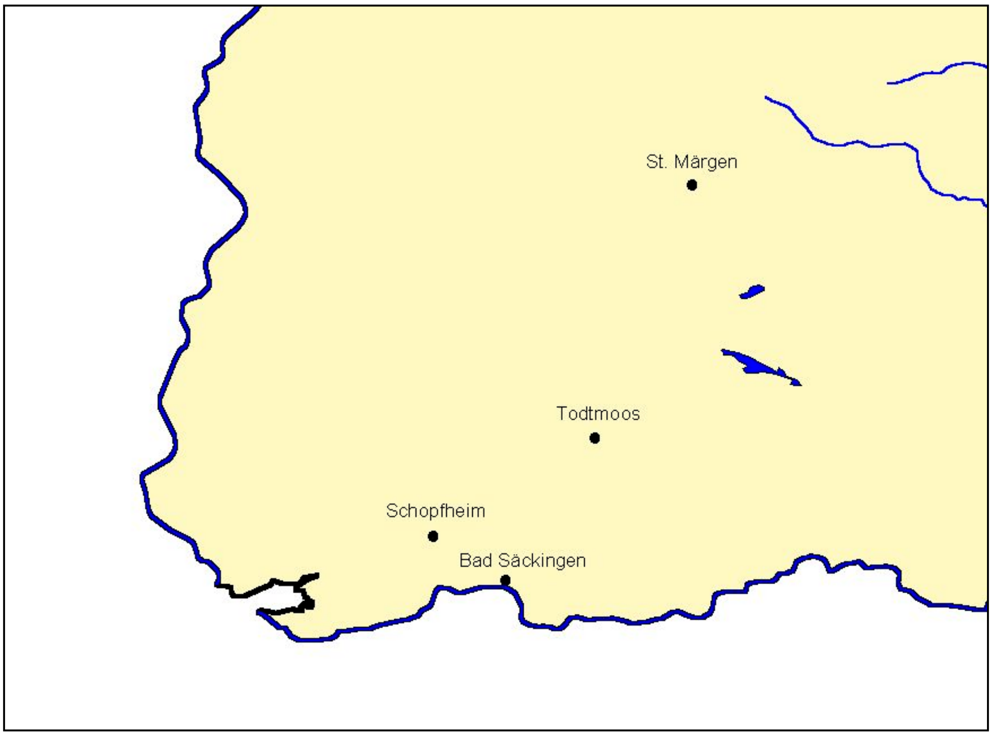

Figure 10: Location of the four study sites in the southern Black Forest

According to measurements taken at the climate stations located near the four study sites, the local mean annual air temperature for the climate normal 1961-1990 ranged from 6.2 ºC in Todtmoos to 9.5 ºC in Bad Säckingen (MÜLLER-WESTERMEIER 1996). The mean annual precipitation ranged from 1100 mm in Bad Säckingen to over 1700 mm in St. Märgen. Figures for the mean air temperature and mean precipitation for the vegetative period (defined as 1st May to 30th September) are provided in Table 1.

The general soil classification for all four study sites is brown earth, which is derived from granite, gneiss and sandstone bedrock. The soil type in Bad Säckingen was a moderately fresh, fine loamy brown earth. In Schopfheim, the soil was classified as a moderately fresh loamy brown earth with stone debris. The St. Märgen study area soil type was an acidic, moderately fresh deep, loamy podzolic brown earth. While in Todtmoos, the soil was classified as a fresh, coarse loamy brown earth.

All four study sites were located on submontane to montane landforms. The altitude ranged from 550 m in Bad Säckingen to 1050 m in Todtmoos. The study sites at Schopfheim and Todtmoos can be described as having steep slopes. The exposition of these two sites is northwest facing. In contrast, Bad Säckingen and St. Märgen can be described as possessing a plain topography with gentle to slight slopes.

The overstory trees species included European beech, Norway spruce and silver fir. The mean canopy-age ranged from 110 to 140 years old, while the ages of individual trees selected for sampling ranged from 82 to 221 years old. The most recent cuttings for the four stands took place between 5 and 21 years ago.

The site index (base age of 100 years) for each study site was estimated by using a sample of co-dominant and dominant European beech index trees. The trees selected had no signs of early suppression in their cross-sectional breast-height disks and no evidence of upper crown breakage, sweep, crook or forking. Total tree age was estimated by adding 10 years to breast height, which was the mean age difference between breast height age and stump age. Individual tree site index estimates were calculated using the regional height curves from SCHOBER (1969). These individual tree site indices were averaged at the stand level to calculate mean stand estimates (Table 1).

Table 1: Summary of study area characteristics

	Bad Säckingen II/12	Schopfheim XV/7	St. Märgen IV/5	Todtmoos II/15
Year Measured	2001	2001	2000	1999
Total number of trees sampled	300	300	300	300
Number of standing trees measured	50	50	50	50
Number of felled trees measured	40	40	44	46
Number of reference trees	10	14	12	12
Altitude (m a.s.l.)	550	600	950	1050
Mean daily air temperature (°C)*	9.5	8.8	6.9	6.2
Mean daily air temperature in vegetative period (°C)	16.4	15	12.0	11.1
Mean annual precipitation (mm)*	1104	1208	1736	1702
Mean annual precipitation in vegetative period (mm)	537	546	635	638
Slope (°)	0	30	5	30
Exposition (°)	265	259	288	312
European beech site index (h_{100})	31.2	33.8	26.2	22.8
Principal age cohorts (years)	140	110	120	140
Canopy tree diameter (cm)	44	48	48	51
Percentage European beech in canopy	70	90	80	30
Time since last intervention (years)	6 and 12	6 and 17	21	5 and 14

* Climate data was taken as the average for the climate normal 1961-1990 from the nearest climate stations to the study site (MÜLLER-WESTERMEIER 1996).

3.3 DESCRIPTION OF THE FIELD METHODS

3.3.1 Sampling Methodology

A two stage sampling procedure was adopted. It was felt that this approach would provide the most accurate data available for analysis, given that large numbers of trees could not for a variety of reasons, including time and costs, be felled for this specific study.

In the first stage, within each of the four stands selected for measurement, three hundred randomly selected trees with a diameter at breast height (*D*) greater than 35 cm were selected for initial sampling. Trees greater than 35 cm were selected to ensure advanced aged trees were sampled. For the purposes of this study small suppressed advanced trees were not chosen for analysis. Using non-destructive measurements 1,200 trees were used to assess, an estimate of the range of past changes in competition for individual trees within each stand. During this stage, the past competition scenarios of these trees were characterized by a matrix containing four elements. These were diameter (*D*), crown class (*CC*) as defined by SMITH (1986), current competition (*C*) and change in competition (Δ*C*) from recent release. Each of these elements, (excluding *D*), comprises one of four possible subjective divisions. The resulting matrix of the initial sample possibilities is illustrated in Table 2.

Table 2: Classifications of initial sampling categories

Diameter (D)	Crown class (CC)	Current competition (C)	Change in competition (ΔC)
35-44 cm	CC*	C*	ΔC*
45-54 cm	CC*	C*	ΔC*
55-64 cm	CC*	C*	ΔC*
>65 cm	CC*	C*	ΔC*

where: *CC** is classified either as dominant; co-dominant; intermediate; or suppressed:
*C** is classified either as light; medium; heavy; or extreme:
Δ*C** is classified either as none; small; medium or heavy.

During the second stage, within each stand a smaller secondary sample of 50 trees was selected to be felled and additional measurements were undertaken (see section 3.3.3 Felled Tree Measurements). The restriction of 50 trees per site was due to the possible damage to other trees and measurement costs. The selection of these 50 trees was deliberately biased towards attempting to uniformly cover the whole range of competition modes encountered in the initial sample of each stand. If a random approach to the selection of the 50 trees was adopted, in many instances a number of competition scenarios would be represented by few, if any, trees in the smaller sample.

The aim of the two stage sampling process was to ensure that a broad cross-section of competition scenarios was included in the database for the analysis of the release response of advanced European beech trees. The approach adopted in this study assists in improving the likelihood of accurately and precisely estimating regression parameters in the models examined.

In addition, in the winter of 2000, twenty gap trees per study site were collected (80 trees in total) for height analysis. A gap tree is defined in this study as a tree which is growing in a recently opened canopy gap. This data was collected in order to predict the height increment of gap trees. These gap trees ranged in height, between <1 m to just over 22 m.

3.3.1.1 Bad Säckingen: Comparisons of Initial Trees Sampled with Trees Actually Selected

In Bad Säckingen this two stage sampling process was extremely successful in achieving a wide range of competition scenarios for modeling purposes. The distribution of the trees initially sampled compared to the distribution of the trees actually measured differs markedly for the categories sampled (refer to Figure 11).

Examining the figure for the diameter class, it can be quite clearly seen that the initial sample is strongly distributed around trees with a diameter 35-54 cm. The sampling has achieved a fairly even selection of trees across the four diameter categories. Similar success in avoiding over-representation of certain sub-categories was achieved for both current competition and change in competition. However, the two stage sampling strategy was unable to create a uniform distribution for the social class categories. There were insufficient number of trees in the suppressed crown class. The reason for this is that the sampling process was limited to trees with diameters greater than 35 cm. Very few trees with this minimum diameter fall into the suppressed crown class. Ten trees were selected with no change in recent competition as reference trees for the analysis.

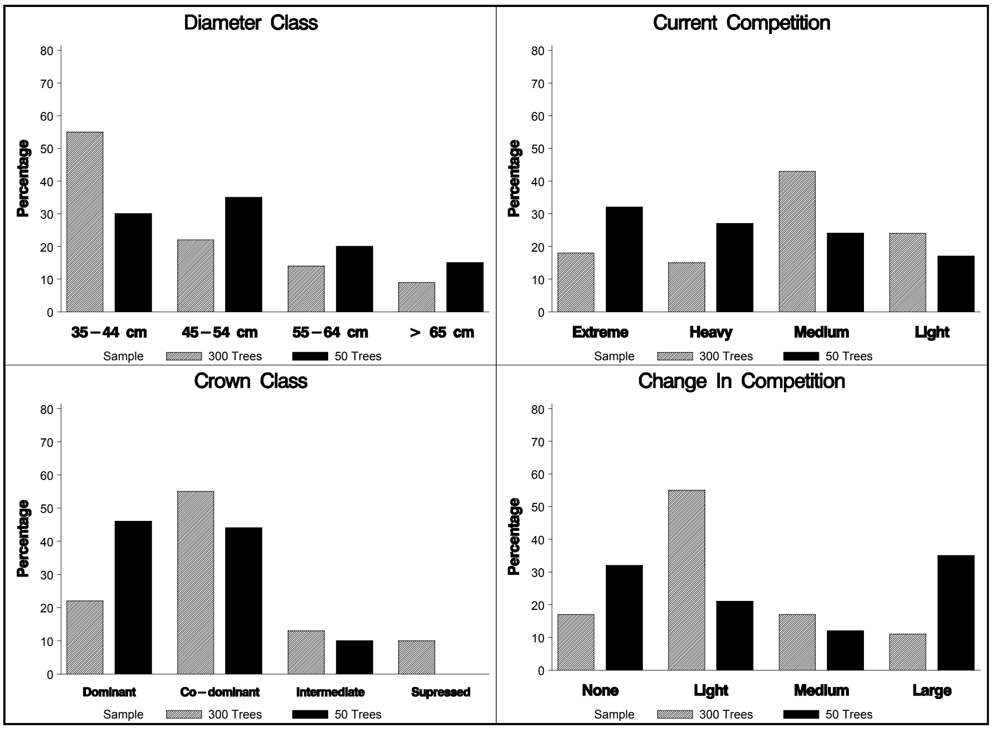

Figure 11: Comparisons of initial trees sampled (300 Trees) with trees actually selected for measurement (50 Trees) in Bad Säckingen

3.3.1.2 Schopfheim: Comparisons of Initial Trees Sampled with Trees Actually Selected

In Schopfheim, the sampling process was reasonably successful in achieving a uniform distribution of trees actually measured (refer to Figure 12). The initial sample showed that most trees in the stand had diameters in the 35-44 cm diameter class category. The one classification where general uniformity was not achieved was the crown class classification. As in Bad Säckingen, there were no suppressed trees represented at all in the trees actually measured, and in this case, only a few intermediate trees were measured. This under representation of the lower crown classes was once again due to the limitation of the diameter of sampled trees to a minimum of 35 cm. Twelve trees that had no recent changes in competition were measured and used in subsequent analysis as reference trees.

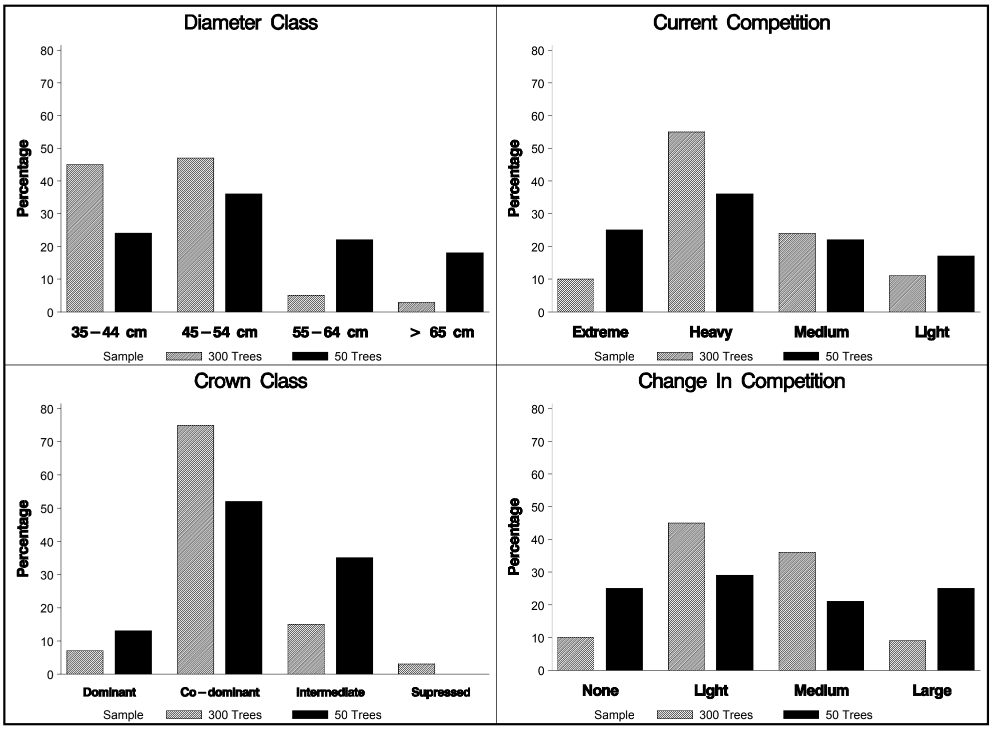

Figure 12: Comparisons of initial trees sampled (300 Trees) with trees actually selected for measurement (50 Trees) in Schopfheim

3.3.1.3 St. Märgen: Comparisons of Initial Trees Sampled with Trees Actually Selected

In St. Märgen, the sampling process was also reasonably successful in achieving a uniform distribution of trees actually measured (refer to Figure 13). The initial sample showed that the majority of trees in the stand had diameters in the 45-54 cm diameter class category. The one classification where general uniformity was not achieved was the crown class classification. As in Bad Säckingen and Schopfheim, there are no suppressed trees represented among those trees actually measured, and in this case, the majority of the trees measured fell into the co-dominant class. Fourteen trees that had no recent changes in competition were measured and used in subsequent analysis as reference trees.

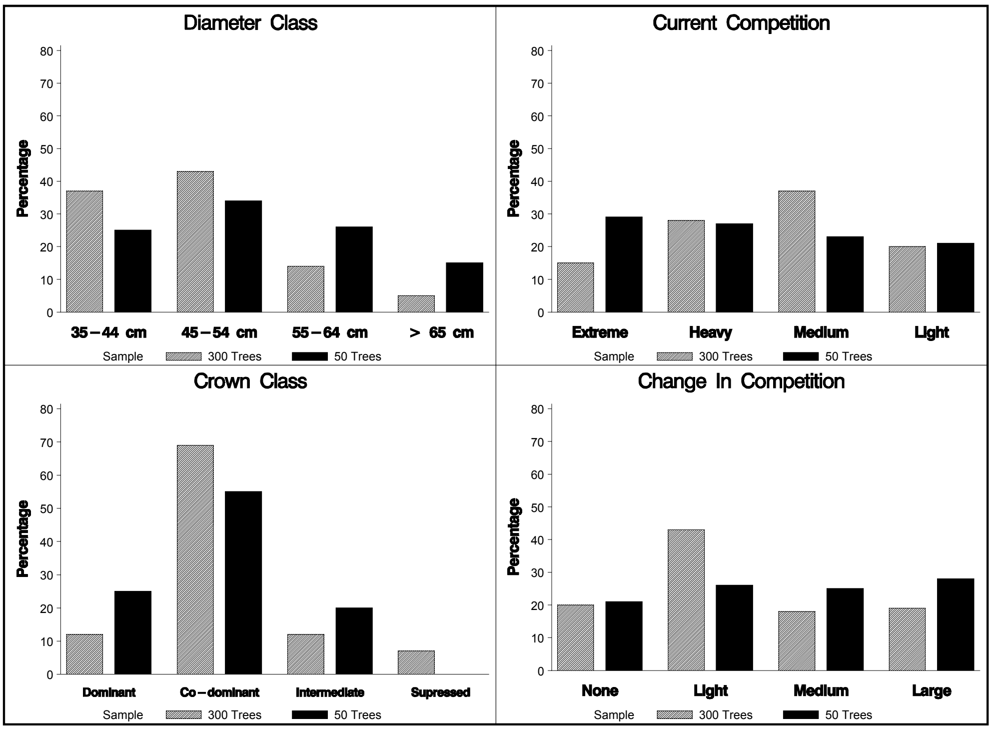

Figure 13: Comparisons of initial trees sampled (300 Trees) with actual trees selected for measurement (50 Trees) in St. Märgen

3.3.1.4 Todtmoos: Comparisons of Initial Trees Sampled with Trees Actually Selected

It can be seen from Figure 14 that the two-stage sampling process employed in Todtmoos was also successful in achieving a rough uniform distribution in three out of the four sampling categories. Once again, crown class was limited to dominant, co-dominant and intermediate trees. Twelve trees, that had undergone no recent changes in competition, were selected for reference for later analysis.

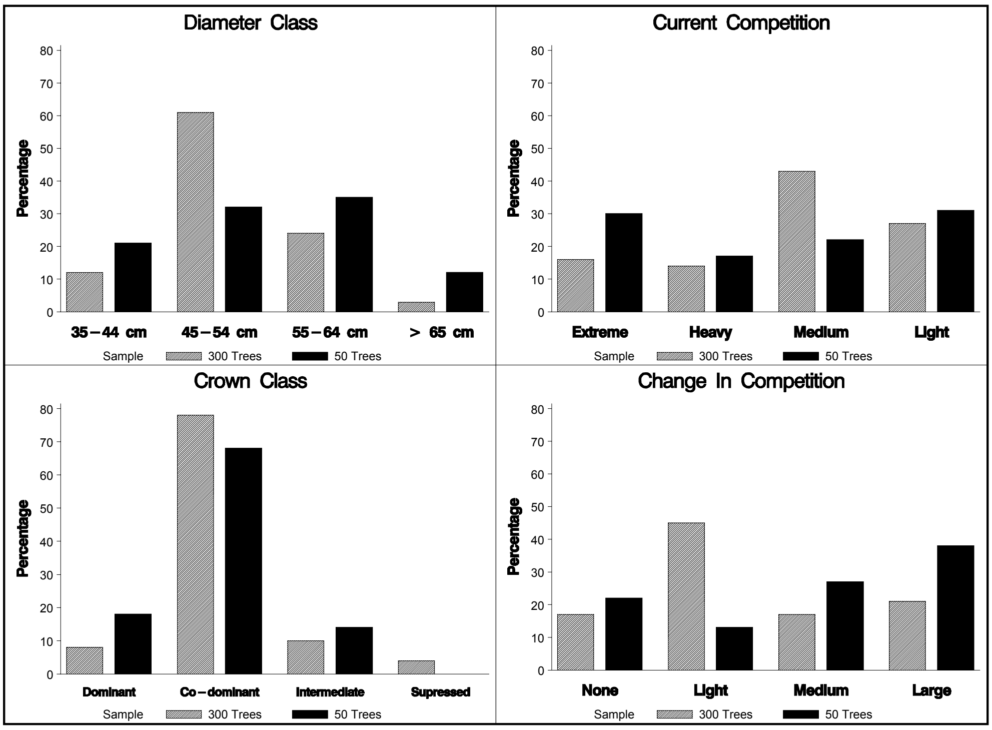

Figure 14: Comparisons of initial trees sampled (300 Trees) with trees actually selected for measurement (50 Trees) in Todtmoos

3.3.2 Standing Tree Measurements

The 50 trees selected for actual measurement within each stand were measured for several tree characteristics before being felled. Locations of all trees identified as competitors and recently cut stumps were recorded. For the purposes of this study, competitors were defined as those trees with a crown class equal to or higher than that of the subject tree. A number of previous studies have shown that the presence of understory trees has no significant effect on the growth of overstory trees (DALE 1975; KELTY et al. 1987). Further more, the definition of competitors, as used in this study, has been shown to improve the modeling of observed growth (LORIMER 1983). Species (*S*), diameter at breast height (*D*) to the nearest cm, total tree height (*H*) to the nearest 0.1 m and crown class (CC) were recorded for each subject tree. The crown classes recognized were dominant, co-dominant, intermediate and suppressed as defined by SMITH (1986). Relative height $\left(H/\overline{H}\right)$ and relative diameter $\left(D/\overline{D}\right)$ for all trees in the initial random sample were calculated by dividing total tree height or diameter by the arithmetic mean height or diameter. For each subject tree the height of the crown base to the nearest 0.1 m was measured and defined as the mean height where the lowest living branches connect to the stem in the four cardinal compass quadrants. Live crown ratio (*LCR*) was defined as the ratio of live crown length to total tree height. The height at the widest part of the crown (H_w) was also measured to the nearest 0.1 m.

The total crown projection area (*TCPA*) was calculated using 8 radii (measured to the nearest 0.1 m) that best described the shape of the total crown area (SPIECKER 1991c). A clinometer was used to sight the crown projection edge for all measurements. The crown radius (*CR*) was calculated from the theoretical average radius of *TCPA*. The exposed crown projection area (*ECPA*) was calculated in a similar way, but by using exposed radii instead of total crown radii. The exposed crown radius was taken to be that portion of the total radius estimated to be free from overlap from above by the branches of competing trees. The variable percent exposed crown projection area (%*ECPA*) was computed as the ratio of exposed to total crown projection area (COLE & LORIMER 1994). The number of unrestricted sides the crown was released on (*NUCS*), was estimated as the number of quadrants that a subject tree’s crown perimeter was not bordered by adjacent crowns of intermediate, co-dominant or dominant trees. This variable is analogous to crown release (LAMSON et al. 1990) but takes into account the fact that some trees, in particular unreleased trees may have some unrestricted crown perimeter due to natural mortality or other factors unrelated to release (refer to Figure 15).

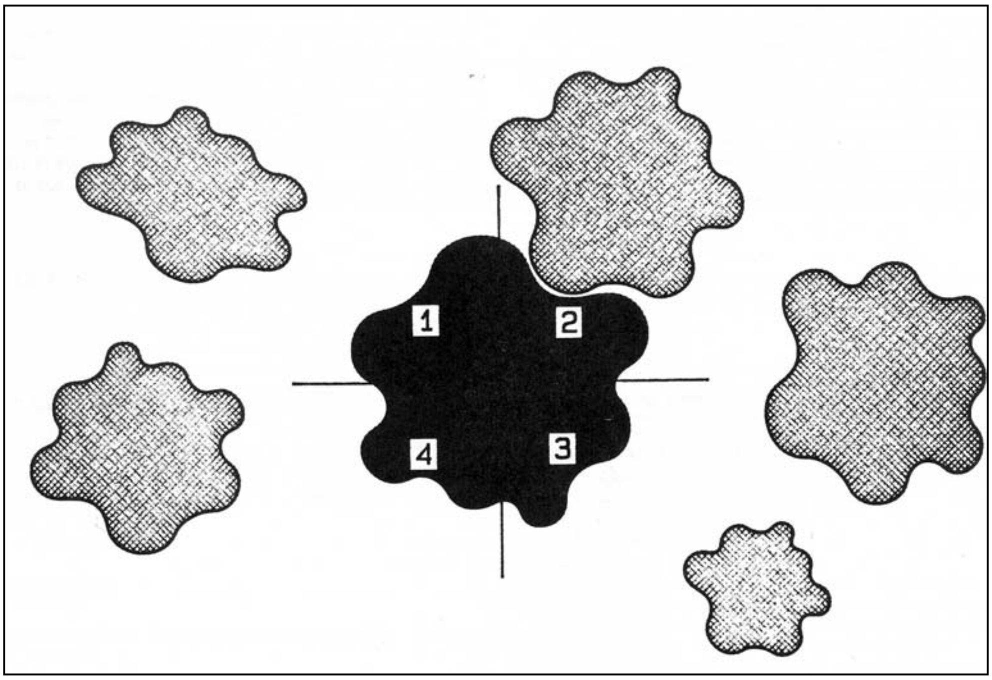

Figure 15: Schematic showing tree crown with free-to-grow quadrants. This tree crown has three sides that have an unrestricted perimeter

3.3.3 Felled Tree Measurements

On the felled subject trees four branches were removed from the canopy, namely those branches with the greatest influence on canopy width in each of the four cardinal compass quadrants. The height to the nearest 0.1 m and angle to the nearest degree of these branches from the stem were measured. To investigate differences in growth rates between gap and non-gap branches, each branch was classified by exposure. A branch with no overlap from above by a competitor tree crown was classified as a gap branch. Branches with any overlap by a competitor were classified as non-gap branches.

Additionally, one leader per tree, representing the terminal leader, was removed for height analysis. A stem disk was also removed at a height of 1.3 m from each tree for the laboratory measurement of radial increment. A wedge from the base of each tree, passing through the pith to the bark was removed and used to estimate the total age of the tree.

In the process of felling, the crowns of 30 trees were so severely damaged that they were not used for further analysis. Of the remaining 170 trees used in this study just under one third (31%) of the branches used for crown width and height increment analysis were damaged in felling. This damage was usually limited to the end of the branch. Of the damaged branches 56% were missing the last internode, 34% were missing the last two internodes and the last 10% were missing between three and five internodes.

3.4 DESCRIPTION OF THE LABORATORY METHODS

3.4.1 Diameter Measurement

Cross-sectional disks were air dried and sanded in the laboratory. On each disk, working outwards from the pith, the cumulative annual radial increments were measured every 45°. A tree ring analysis system with 0.01 mm precision was used. Individual-tree diameter measurements were estimated using the geometric mean of the eight radii (BIGING & WENSEL 1988). A master ring width chronology was created from 67 subject trees, whose growth rings were continuous around the stem and present for all radii. Nine "marker" growth periods (FRITTS 1976) were evident from this chronology: six slow-growth periods (1921, 1934, 1948, 1965, 1976, 1984) and three rapid-growth periods (1879, 1914, 1967). Slow-growth marker years matched known drought years (FISCHER & ROMMEL 1989; GÄRTNER & STOLL 1990). The master chronology was then used to correct for partial or missing rings in other sample trees during the period of interest from 1970 to 2001.

3.4.2 Internode Measurement

Detailed internode characteristics were measured on the subject trees and used to investigate crown development. Four branches, one at the widest part of the crown in each cardinal direction, and a terminal leader were transported to the laboratory. Using overall leaf angles as a guide, branches were repositioned in an approximate pre-felling orientation. For each of the identifiable internodes, the length to the nearest mm and angle deflections to the nearest degree from horizontal and from cardinal compass direction were measured (for more detailed information on the detection of internodes see ROLOFF (1984; 1986; 1988)). The two angle measurements were used to correct annual branch internode lengths to horizontal directional branch length increment in each cardinal direction (refer to Figure 16). The length and angle deflection from the vertical were measured in a similar manner for identifiable internodes on the terminal leader. The terminal leader internode lengths were corrected to vertical height increments using the single angle measurement.

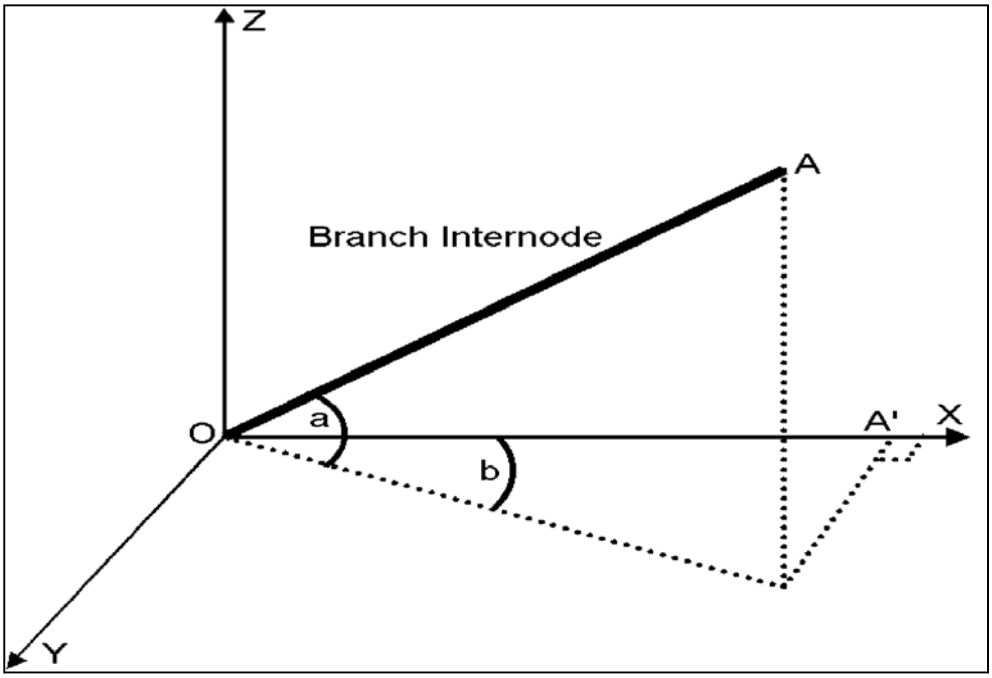

Figure 16: Branch angle correction for branch internode OA to horizontal cardinal OA' using the formula OA' = (OA)(cos a)(cos b)

3.4.3 Validation of Internode Methodology

3.4.3.1 Height Increment

The method for estimating the height increment using identified internodes was verified by taking a random sample of 60 branches and comparing the estimated number of internodes with the number of growth rings counted on a disk cut from the base of the branch. Figure 17 shows that there is a bias associated with the number of internodes identified versus the number of growth rings counted. The reason for this poor reconciliation is unknown, although it may be partly due to difficulties encountered in selecting the dominant terminal leader. Such difficulties were partially due to the lack of apical dominance in the advanced European beech trees sampled. The mean number of identifiable internodes per terminal leader branch was 18, the minimum was 8 and the maximum was 34.

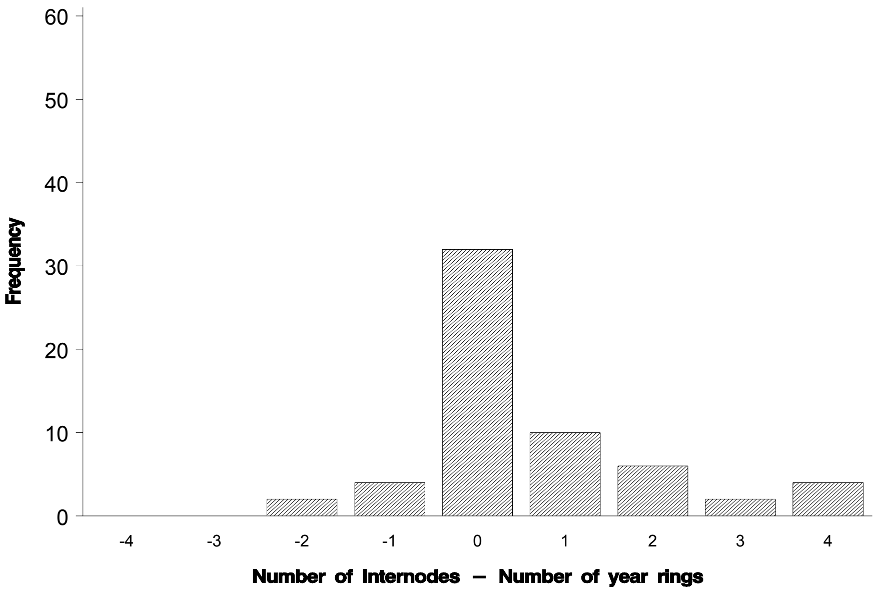

Figure 17: Bias in the estimation of the number of height internodes versus the number of year rings counted

3.4.3.2 Crown Radius Increment

The method for estimating the crown radius increment was also verified by taking a random sample of 60 branches back to the laboratory and comparing the estimated number of internodes with the number of growth rings counted from a disk cut from the branch. Figure 18 shows that there is only a small bias associated with the internode count versus the number of year rings observed. The mean number of identifiable internodes per crown radius branch was 23, the minimum was 8 and the maximum was 34.

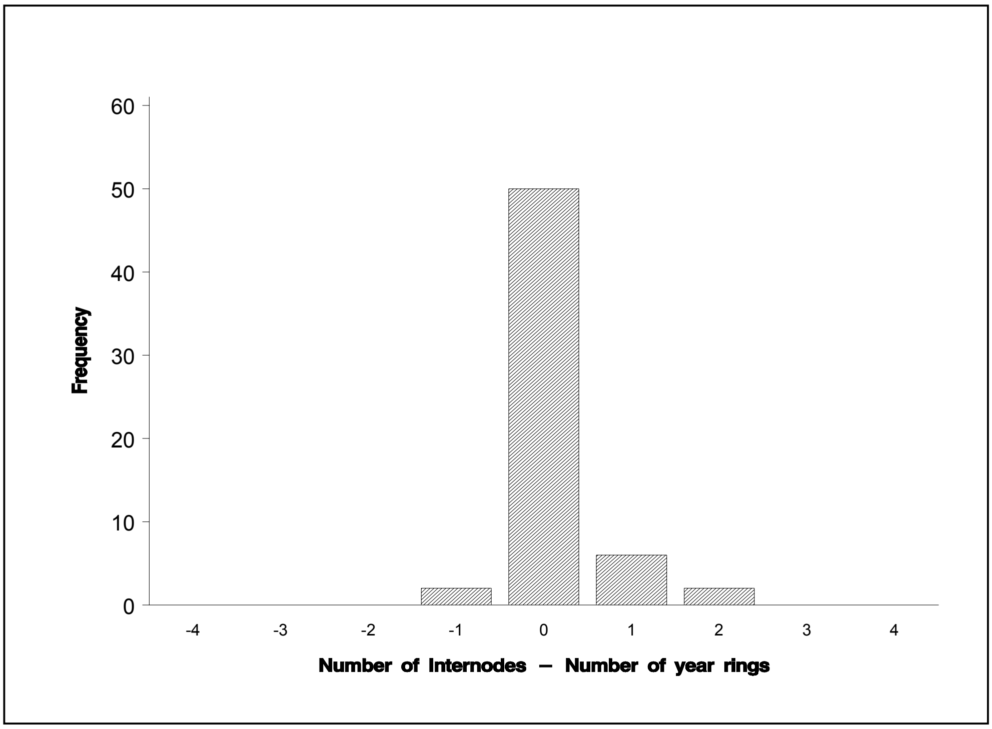

Figure 18: Bias in the estimation of the number of branch internodes versus the number of year rings counted.

The verification of the observed number of internodes with the year rings counted showed that the bias associated with crown width internodes was much smaller than that associated with the height internodes. The reason for the larger bias in the height internodes is unknown, but it may be due to any combination of the following factors: snow and ice damage; breakage of the apical tip; the lack of apical dominance in European beech and wind damage.

Both height and crown width branch internode identification was difficult in years when two dry summers occurred in succession. ROLOFF (1984) has previously noted this phenomenon, observing that in the second dry summer there was a tendency for no growth ring and/or an incomplete growth ring to form.

In both cases, it was decided that for the purposes of this study using the bud scar approach from ROLOFF was an acceptable methodology for identifying internodes and consequent annual branch extension.

3.5 DESCRIPTION OF THE DATA PREPARATION

3.5.1 Reconstruction of Growth Variables for Subject Trees

The size variables, diameter at breast height (*D*) and total height (*H*) of each tree were calculated by subtracting the observed annual growth increments from the current size of the tree. Bark thickness for all diameters was taken into account by using a regional double bark thickness equation (ALTHERR et al. 1974). The reconstruction of crown radius (*CR*) was obtained by subtracting the mean observed annual internode growth increments away from the theoretical average crown radius, which was calculated from the total crown projection area.

3.5.2 Reconstruction of Growth Variables for Competitor Trees

The corrections for competition trees were more complex than for the subject trees as growth increments were not measured on competitor trees. Species-specific regression equations were developed from the observed subject tree growth data from this study. For the species Norway spruce and silver fir, data from a parallel study in the BMBF project (A3) was used. The data was used to estimate the backdated diameter, as functions of current year values and time since release. The data was restricted to the calendar years 1980 onwards, as this was the earliest year of release in any of the study sites.

$$D_b = \gamma_0 + \gamma_1 D + \gamma_2 BY$$

Equation 4

where D_b = backdated diameter at breast height (cm);
BY = number of backdated years (years);
D = diameter at breast height (cm).

It was not possible to estimate the former height and crown radius of competitor trees using the method described above. Therefore, it was assumed that the height (*H*) and crown radius (*CR*) for most trees can be predicted using simple equations related to backdated diameter (*D*).

The equation used to estimate total height (*H*) was of the form:

$$\ln(H) = \gamma_0 + \gamma_1 D^{-1}$$

Equation 5

where H = individual total tree height (m);
D = diameter at breast height (cm).

The equation used to estimate crown radius (*CR*) was of the form:

$$CR = \gamma_o D^{\gamma_1}$$

Equation 6

where *CR* = crown radius (m);

D = diameter at breast height (cm).

All equations were fitted to the data using ordinary least squares (OLS) regression. The coefficients are given in Table 3.

Table 3: Regression equations used to estimate competitor tree stem and crown dimensions

Eq.	Model	$\bar{R}^2$	*F*
	European beech (n = 170)		
7	D_b = -0.237 + 0.967 (*D*) – 0.478(*YR*)	0.88	3214.2
8	*Ln*(*H*)= 3.212 –25.433/(*D*)	0.52	101.2
9	*Ln*(*CR*)= -4.121 + 1.726*Ln*(*D*)	0.66	66.6
	Norway spruce (n = 119)		
10	D_b = -0.537 + 0.986 (*D*) – 0.521(*YR*)	0.91	7856.2
11	*Ln*(*H*)= 3.816 –21.049/(*D*)	0.69	258.3
12	*Ln*(*CR*)= -3.424 + 1.626*Ln*(*D*)	0.27	43.5
	silver fir (n = 78)		
13	D_b = -0.943 + 0.992(*D*) – 0.585(*YR*)	0.92	7412
14	*Ln*(*H*)= 3.854 – 23.739/(*D*)	0.40	50.1
15	*Ln*(*CR*)= -4.438 + 1.885*Ln*(*D*)	0.34	39.1

Relative height $\left(H/\overline{H}\right)$ and relative diameter $\left(D/\overline{D}\right)$ were computed by dividing the backdated total height (*H*) or diameter (*D*) of the subject tree by its respective backdated site mean. It is assumed that the live crown ratio (*LCR*), percent exposed crown (%*ECPA*) and height at the widest part of the crown (H_w) for most advanced European beech trees would not have changed substantially since the year of release.

3.5.3 Reconstruction of Growth Variables for Cut Stumps

Stump data was collected on field trees from the four study sites. Solid wood stump diameter (D_s) was measured by inscribing the largest possible circle or ellipse (excluding bark) inside the flutes with a tape (refer to Figure 19). If the shape was elliptical, then the length of the long and short axes were geometrically averaged.

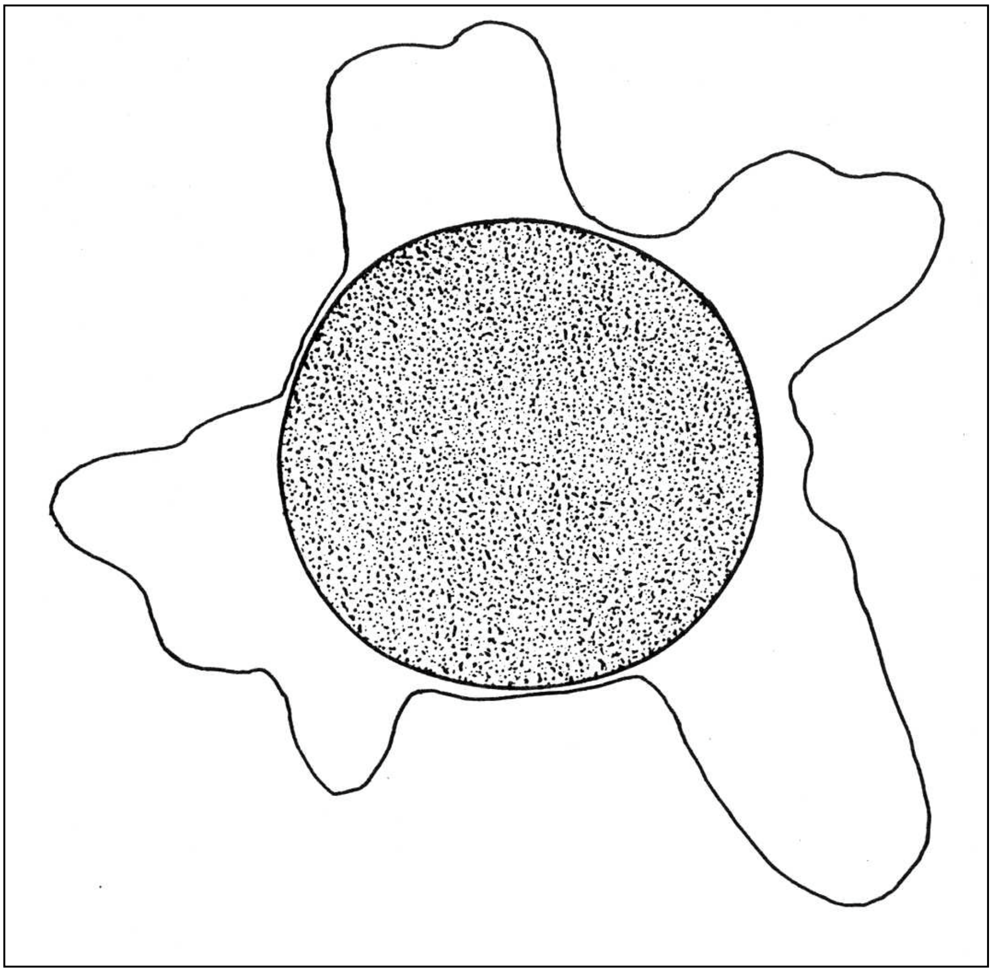

Figure 19: Schematic top view of European beech stump showing inscribed circle containing solid-wood diameter.

After examining scatter plots of D over D_s for different H_s, the following simple linear model was hypothesized for the relationship between D, D_s and H_s:

$$D = \gamma_0 + \gamma_1 D_s + \gamma_2 H_s$$

Equation 16

where D = diameter at breast height (cm);
D_s = diameter of stump (cm);
H_s = height of stump (cm).

This model was fitted for each species using ordinary least squares (OLS) regression. The coefficients and variances are given in Table 4.

Table 4: Coefficients for regression of tree diameter on stump diameter and height by species

Eq.	Species	N	γ_0	γ_1	γ_2	R^2	F
17	European beech	170	-0.559	0.686	0.143	0.67	32.8
18	Norway spruce	80	-0.861	0.963	0.067	0.82	45.8
19	Silver fir	67	-1.461	0.896	0.117	0.72	26.7
20	Combined (for other species)	317	-0.823	0.799	0.118	0.73	38.5

The total height (*H*) and crown radius (*CR*) for stump trees were predicted using the same equations as the competitor trees (refer to Table 3)

3.5.4 Reconstruction of Competition

The competition for each subject tree was quantified directly before and after release using the area potentially available (*APA*) index developed by Nance et al. (1988). This index has been found by Hahn (1995) to be highly correlated with the diameter increment of European beech. Competitors in this study were defined as only those trees with crown class equal to or higher than that of the subject tree. The definition of competitors in this way has been shown to improve the modeling of observed growth (LORIMER 1983).

It can be seen by Figure 20 that the sample tree 10 has been heavily released in two directions, the north and south. The location and size of the competitors and removed trees at the time of release, as shown in this diagram are used to calculate the constrained *APA* for each subject tree immediately before and after release using the previously explained Equation 1 and Equation 2 .

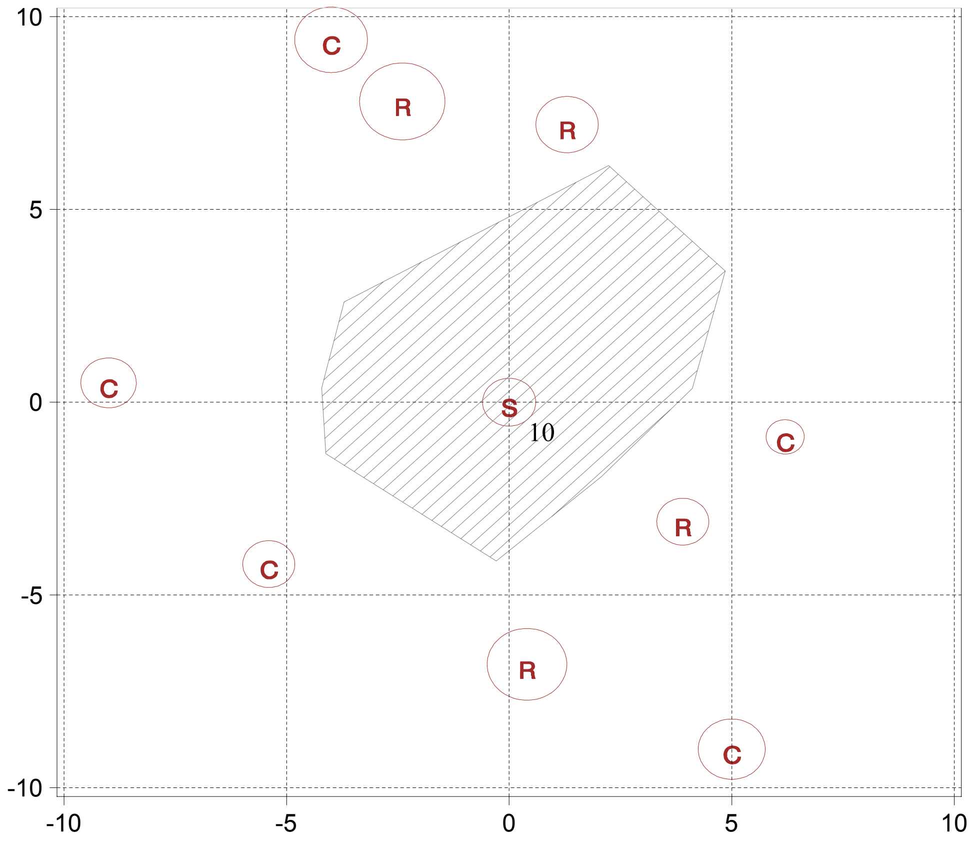

Figure 20: Schematic diagram of competition for sample tree 10 at study site Todtmoos. ‘S’ represents the sample tree. ‘C’ represents the competitor trees. ‘R’ represents the trees removed in the release in 1985. The circles representing the diameter of the trees are expanded in diameter by a factor of three to aid the viewing of the diagram.

3.6 DESCRIPTION OF DATA ANALYSIS

This section has been divided into six parts. The first four deal with the four null hypotheses relating to release response of basal area, height increment, crown expansion and gap simulation. The fifth section summarizes all analysis variables and the final section describes the general regression analysis method used in this study.

3.6.1 Basal Area Increment Release Response

A wide variety of methods are used in the literature to quantify response to release (NÄSLUND 1942; SUNDBERG 1971; MCWILLIAMS & BURK 1994). Two alternative approaches were used in this study to calculate the basal area increment response to release. One looks at the relative growth change after release, while the other focuses on the direct modeling of increment. The methodology of both approaches is described below.

3.6.1.1 Direct Analysis of Basal Area Increment Relative Rate Change after Release

The first approach examined the breast height stem disks of all subject trees for direct comparisons of increment rates before and after the year of release. Radial increment was measured on the eight axis of each subject tree disk for a period of 10 years prior to the treatment and compared with the growth rate for 10 years after treatment (or a minimum of 4 years from time of treatment for sites treated less than 10 years prior to sampling). The increments were then averaged and converted to mean basal area increment for each tree. Percent increment change after treatment was calculated using the following equation:

$$\%BAI = \frac{BAI_{after} - BAI_{before}}{BAI_{before}} \times 100$$

Equation 21

Where	$\%BAI$	=	percent basal area increment (%);
	BAI_{before}	=	10 year mean annual basal area increment before release ($cm^2.year^{-1}$);
	BAI_{after}	=	10 year mean annual basal area increment after release ($cm^2.year^{-1}$).

One advantage of this method is that actual changes in the increment rates of the same trees before and after treatment can be verified. However, other factors including aging, site productivity changes, extreme events (such as frost, drought, snow and storm damage, fire, insect or fungal diseases) or climatic fluctuations often cause a net change in increment over time in untreated European hardwood trees (SPIECKER et al. 1996). Changing weather conditions typically cause short and medium–term growth variations. However, the effects of extreme climatic events on increment may have an impact for up to several decades. Such an event may have an effect on the foliage, the root system and the water transportation system within a tree. It is extremely difficult to separate these effects from the increment trends which reflect the release of a tree.

However, it is possible to remove a component of the combined effect of these factors by creating a reference using unreleased trees. In this study there were 48 trees in total from all four sites that were not released. Before these trees were used to create a reference, a test was made to ensure that there are no excessive temporal effects on increment associated with the timing of release. This was done by comparing the percent change in basal area increment (for the 10 year period prior to release to the 10 year period directly after release) for the 48 trees for each separate time of release. As previously stated (refer to Table 1) the time of release for each study site was different. Figure 21 shows that there is slight temporal difference in the effect of the timing of the release on the mean percentage change. The first four time periods are not significantly different than from each other. However the last two time periods have a slightly higher change in percent basal area increment. There are some problems with comparing the last two release periods to the other time periods, as there is no data to calculate the 10 year period after release for the time periods 1994 and 1995. The average of the 4, 5 or 6 year period was used. It is unknown whether the observed difference is a real difference or an artifact of the shorter calculation period. Due to the difference between the last two periods and the first four periods, being similar to the confidence interval of the mean estimate for each time period, all time periods were compared to create a combined estimate of the percent change in basal area increment of the reference trees. It is acknowledged that combining the reference trees will slightly under or overestimate the reference growth depending on the study site and time of release but it is assumed that this error is an order of magnitude less than the actual change in increment of released trees and will have no practical effect. Given that the combined reference trees showed a 3.5% decline in basal area increment, a positive increase on released trees can be considered a slightly conservative estimate of the actual release-induced increment response.

Due to the reference trees behaving in a more or less similar way, the data analyses in the results section are based on a combined analyses using all four sites. Site-specific analyses in the results section are simply used to provide an indication of the likely variation encountered in the southern Black Forest and are not discussed in detail in this study.

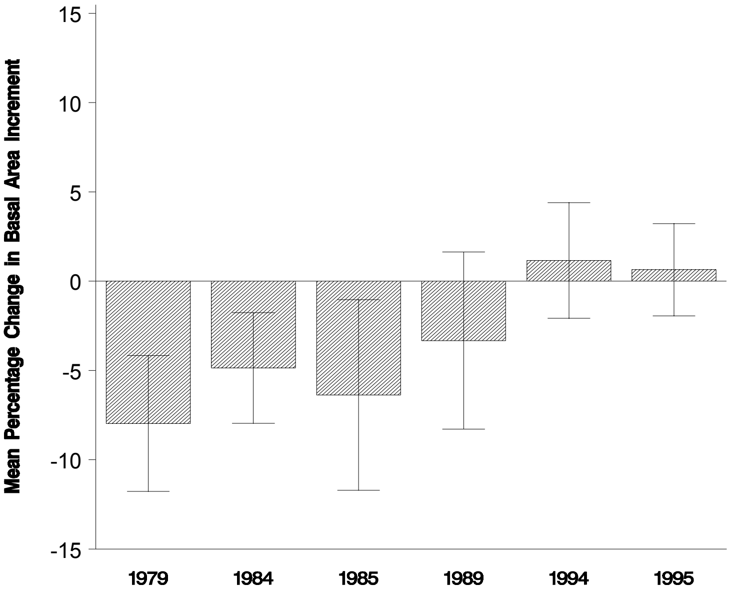

Figure 21: Mean percent change in basal area increment of unreleased trees for each time of release

3.6.1.2 Basal Area Response Based on Increment Model

The second approach used to evaluate the increment response was the development of regression equations which can predict annual increment given various independent variables. Predictive equations for annual basal area increment were based on the following model:

$$BAI = f(diameter, relative\ diameter, age, competition)$$

Equation 22

where *BAI* = 10 year mean annual basal area increment ($cm^2.year^{-1}$);
diameter = actual diameter at breast height (cm);
relative diameter = relative diameter;
age = age (year);
competition = some local competition variable.

Absolute tree diameter reflects a tree's overall stature and is assumed to be correlated with leaf surface area within a species. Relative diameter, the tree's size divided by the average mean size, represents the vertical stratification of trees in a stand and the effects of crown shading, even at low stocking levels. The local competition term is an indirect measure of the effect of stocking on competition for site resources, particularly competition for light among tree crowns.

Regression models of this type are easy to estimate and response to release can then be inferred by comparing the increment rates of trees of a given size under alternative management scenarios. From these comparisons, a percent increment change after treatment can be calculated. By using absolute basal area increment as the initial independent dependent variable rather than percent change, the interpretative problem in the first method caused by net changes in the reference trees is avoided.

Subject trees in the data set used in the model were well distributed among diameter classes from 35 cm to those in excess of 65 cm. Inspection of scatter plots verified that subject trees within this diameter range were well distributed across the spectrum of crown release levels. Observed increment rates from individual trees used to calibrate the model were based on a 4 to 10 year interval coinciding with the post-treatment period of treated trees. The subject trees were felled over a three-year period from 1999 to 2001, while the various sites were treated between 1980 and 1995. Therefore, the climatic period on which the increment rates in the model are based is the period 1980-2001.

The competition independent variables (indicating the level of crowding around subject trees) selected for potential prediction of the dependent variables were the following:

1. percent change in Area Potentially Available due to release (indicated as *%APA* in equations) calculated using the following equation:

$$\frac{APA_{after} - APA_{before}}{APA_{before}} \times 100$$

Equation 23

where APA_{before} = *APA* directly before release;
APA_{after} = *APA* directly after release;

2. residual Area Potentially Available immediately after release (APA_{after});
3. number of unrestricted crown sides (*NUCS*);
4. percent exposed total projection area (*%ECPA*);
5. live crown ratio (*LCR*).

3.6.2 Height Increment Release Response

The height increment response analysis was conducted in a similar manner to the basal area increment response analysis. Two alternative approaches were employed: the relative increment change after release and the direct modeling of height increment. An overview of each methodology is examined here.

3.6.2.1 Direct Analysis of Relative Height Increment Rate Change after Release

A direct comparison of height increment rates before and after the year of release was measured on the terminal leader. The height increment was measured on the axis of each subject tree terminal leader for a period of 10 years prior to the treatment and compared with the increment for 10 years after treatment (or a minimum of 4 years from time of treatment for trees treated less than 10 years prior to sampling). The increments were then averaged and converted to percent height increment change after treatment using the following equation:

$$\%HI = \frac{HI_{after} - HI_{before}}{HI_{before}} \times 100$$

Equation 24

Where $\%HI$ = percent height increment (%);
HI_{before} = 10 year mean annual height increment before release ($m.year^{-1}$);
HI_{after} = 10 year mean annual height increment after release ($m.year^{-1}$).

The mean percent height increment change was calculated for the 48 trees that were not released to test whether there were any temporal difference associated with the timing of the release. It is shown by Figure 22 that the reference trees behave very similarly with regard to the timing of the release and therefore can be combined to serve as a reference point. These reference trees averaged a negative 0.8% height increment decrease for all time periods, with 56% of trees exhibiting a declining basal area increment rate. Given that the reference trees showed a change of height increment of almost zero percent, a positive increase on released trees can be considered an accurate estimate of the actual release-induced height increment response.

Due to the reference trees behaving in a more or less similar way, the data analyses based on combined analyses using all four sites are presented in the results section. Site-specific analyses in the results section are simply used to indicate the likely variation encountered in the southern Black Forest and are not discussed in detail in this study.

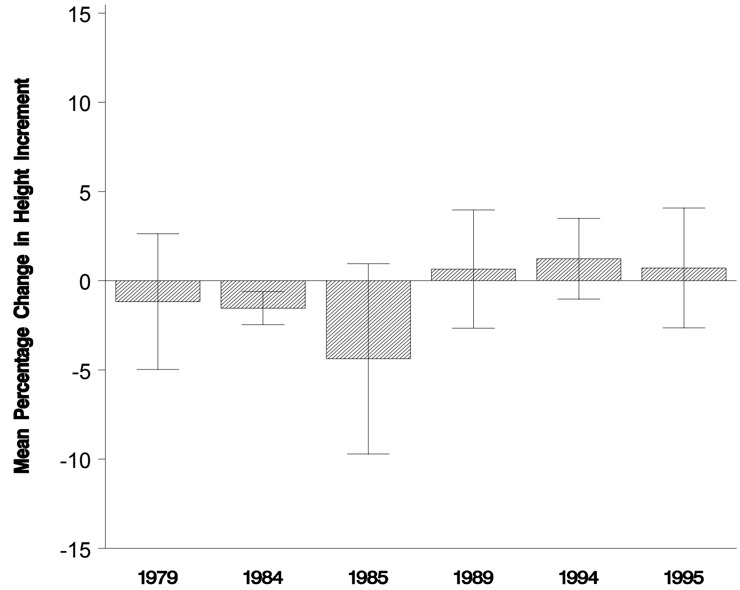

Figure 22: Mean percent change in height increment of unreleased trees for each time of release

3.6.2.2 Height Response Based on Increment Model

The second approach used to evaluate the height increment response was the development of regression equations to predict annual height increment given various independent variables. Predictive equations for annual height increment were developed based on the following model:

HI = f(height, relative height, age, competition)

Equation 25

where *HI* = annual height increment (cm.year^{-1});
height = total tree height (m);
relative height = relative height;
age = age (year);
competition term = some local competition variable*;

* The independent variables examined to quantify crowding were the same as those used in the basal area analysis.

It is common knowledge that height increment is a function of site conditions (ASSMANN 1961; MITSCHERLICH 1970; AVERY & BURKHART 1983; BORDERS et al. 1988; VANCLAY 1995), but it must be stated that the effect of site is at its greatest during the younger ages. The justification for not explicitly modelling site and combining advanced trees from different sites for further investigation of height increment was supported by the European beech top height curves for Baden Württemberg from SCHOBER (1969) (refer to Figure 23).

Due to the limited number of trees per study site (on average 42 trees), the trees from each study site were combined to provide an overall robust model based on 170 trees. The effect of pooling sites is shown in Figure 23. The site index curve of top height of 24.7 m at the base age of 100 years depicted in Figure 23 represents Todtmoos, the worst site class sampled in this study, while the site curve of 32.7 m represents Schopfheim, the best site class. It can be seen that the absolute difference in increment between these curves over the advanced age (80-220) range lies somewhere between 2 and 3 cm. This is the estimated maximum error associated with developing a model independent of site conditions. As the model developed lies somewhere in between these two site classes, it can be expected that the actual error is somewhat less than this. For the purposes of this study the statistical regression benefits of analysing a larger combined data set are assumed to outweigh the disadvantage of systematic errors in pooling the data.

Therefore, the data analyses for height increment presented in the results section are based on combined analyses using all four sites. Site-specific height increment equations in the results section are simply used to indicate the likely variation encountered in the southern Black Forest and are not discussed in detail in this study.

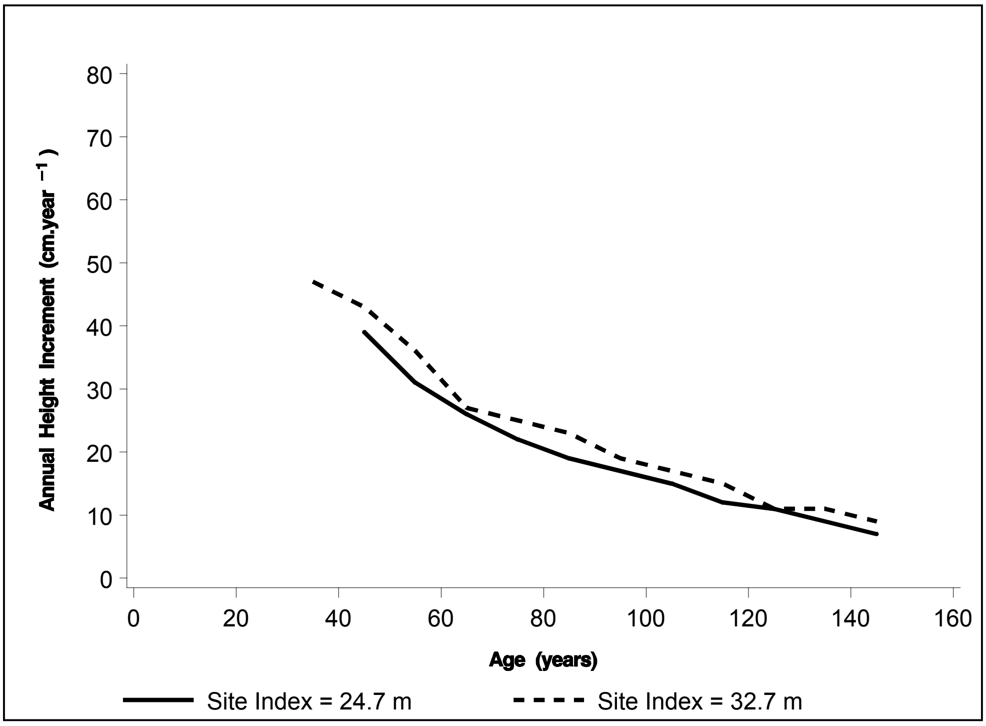

Figure 23: European beech height curves from two different site classes for Baden Württemberg from SCHOBER (1969).

3.6.3 Crown Expansion

It assumed that the overriding driver of crown expansion is competition. To investigate differences in increment rates between gap and non-gap branches, a measure of branch exposure was used. A branch with no overlap from above by a competitor tree crown was classified as a gap branch. Branches with any overlap by a competitor were classified as non-gap branches. Branches from all four study sites were combined for subsequent analysis. Site quality was not directly modeled as it is assumed that competition and age are the most important variables. In addition, as height increment was assumed to be rather independent of site quality for the advanced data set in this study, it was also assumed for the crown radius increment.

Mean annual whole tree lateral crown radius increment rates (*CRI*) were calculated as the average of the four radial crown radius increment rates for 10 years after release (n = 10 years per branch × 4 branches per tree = 40). Mean annual lateral extensions of individual branches (*BLI*) were computed as the average of the corrected lateral increment rate for 10 complete increment seasons after the year of release (n = 10 years per branch). The total span of years for which increment increments were used in the analyses was 1980 to 2000, inclusive.

The equation used to estimate mean annual whole tree lateral crown radius increment rates (*CRI*) was of the following form:

$$CRI = f(size,\ relative\ size,\ age,\ competition)$$

Equation 26

where *CRI* = 10 year mean annual whole tree lateral crown radius increment rate (cm.year^{-1});
size = actual initial size;
relative size = relative size (%);
age = age (year);
competition = some local competition variable.

The equation used to estimate mean annual lateral extensions of individual branches (*BLI*) was of the following form:

$$BLI = f(size,\ relative\ size,\ age,\ competition)$$

Equation 27

where *BLI* = 10 year mean annual branch length increment branches (cm.year^{-1});
size = actual initial size;
relative size = relative size (%);
age = age (year);
competition = some local competition variable;
branch exposure: measure of overlap from competitors.

As previously mentioned, during the process of felling, the crowns of some of the trees were damaged. Therefore, the internode data was missing for some of the branches. This missing data was handled by using a regression-based imputation methodology proposed by LITTLE & RUBIN (1987). In this type of imputation method, a regression model predicts the missing internode value based a) on the values of other internodes in the same year since release and b) on the overall relationships (correlation matrix) of the variables. Branches which have missing internodes were therefore given a predicted value based on the regression model applied to their covariate values. It must be noted that although this method is more objective than guessing and not as simplistic as mean substitution there are still some disadvantages. For example, the regression substitution may make the data fit together better than it actually should. The reason for this is that this method imputes only those values which are consistent with the other values in the same year. The imputed values using this method can also be too close to the mean, which results in reduced variance and deflated correlation. However, the advantages of this method were assumed to outweigh the disadvantages.

3.6.4 Gap Closure Simulations

The whole crown (*CRI*), directional (*BLI*) branch and annual height increment (*HI*) predictive equations developed in this study were used to further develop a relatively simple gap closure simulation model to study rates of canopy gap closure from lateral crown expansion and height increment within the gap. To limit complexity, all border trees and trees within a gap were assumed to be European beech, since this is the species investigated in this study. In the projection, a hypothetical circular gap of fixed size was used as the starting point. Gaps were set to one of five initial sizes (2.5 m, 5 m, 10 m, 15 m and 20 m) and were chosen to represent a gradient of canopy openings that might be created by crown release operations in transformation forests, although larger gaps might also be found under more drastic silvicultural treatments or normal disturbance regimes. It can be seen from Table 5 that these gap sizes extend further than the range of crown diameters of individual trees.

Table 5: Observed mean values for crown characteristics of study trees, used as initial values in the gap closure simulation

		Total height (m)		Crown radius (m)		*LCR*		H_w/H	
Crown Class	N	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
Intermediate	30	28.2	2.4	3.7	1.2	0.61	0.14	0.77	0.12
Co-dominant	99	31.6	3.2	4.2	1.4	0.60	0.11	0.76	0.12
Dominant	41	34.3	3.5	5.0	1.4	0.54	0.11	0.78	0.10

Four gap border trees, were placed along the cardinal axis from the gap center. The edge of each border tree crown radius facing the gap was located on the perimeter of the gap. Border tree crown classes were assigned in one of two configurations:

1) one intermediate, two co-dominant and one dominant tree; or
2) two intermediate, two co-dominant and no dominant trees.

These configurations were chosen to represent the typical proportions of crown classes expected in European beech stands in the southern Black Forest. The height and lateral crown radius increment predictive models were parameterized separately for three different percent exposed crown projection area classes (see 4.2.2 Height Increment Response Based on an Increment Model). It is acknowledged that the percent exposed crown projection area will change over time, especially after release. However, as there is no accurate way to estimate historical percent exposed crown projection area, for the purposes of the gap simulation in this study an assumption must be made about the percent exposed crown projection area class for each border tree. Since the crown class of the border trees are intermediate or higher and occur on the edge of a canopy gap, all border times were assumed to have percent exposed crown projection area greater than or equal to 75 for the life of the gap.

The following variables were assigned initial values for each border tree: total height (H), crown radius (CR) in the direction facing the gap, live crown ratio (LCR, represented as a proportion of total tree height) and height at the widest part of the live crown (H_w, represented as a proportion of total tree height, (H_w/H)). Initial values were assigned based on the observed mean of each variable for the respective European beech tree crown class as shown in Table 5, with sample sizes and their respective standard deviations. Border tree total height was incremented annually using the equation:

$$HI_b = 51.651 - 1.109(H) + 16.411(LCR)$$

Equation 28

where HI_b = annual height increment for border tree (cm.year^{-1});
H = total tree height (m);
LCR = live crown ratio (%).

The adjusted coefficient of multiple determination $\left(\overline{R}^2\right)$ for this regression equation was 0.35, with 80 degrees of freedom. The equation was based on Equation 68 developed in Chapter 4 (Table 13), but the non-significant variable LCR (p = 0. 22) was added to make it the same functional form as the crown radius increment equations. Consistent equations were necessary for multivariate regression analysis (described below for the stochastic simulations). Crown radius was incremented using equations developed in this study (refer to the results section 4.3 Crown Expansion). Live crown ratio (LCR) and H_w/H were found to be stable among European beech crown classes (Table 5), so the initial values assigned to these two terms were assumed to be constant for the life of the simulated gap. This assumption may be slightly unrealistic, as after release, LCR may be expected to increase as the crown base may stay at a constant height, especially in the direction of the gap, as the tree increases in overall height. Since both of these variables are proportions of total tree height, the absolute length of the foliated crown and the absolute height above the ground represented by LCR and H_w/H, respectively, increase with increasing tree height.

A single 4 m tall tree was arbitrarily located at the center of the simulated gap. A separate linear height increment equation was fitted to a subset of the data consisting of gap trees and intermediate crown class trees for use in predicting the development of trees in canopy gaps (refer to the results section 4.4 Gap Closure Simulation). This equation, shown below consists of a total height term and both first and second order relative height. The scatter diagram for these data is shown in Figure 24, where a strong non-linear pattern of height increment can be seen. The general trend is for increment rates to increase with height less than 1m to roughly 10m, then decrease rapidly as total height increases to 30 m. The range in relative heights in these data was 0.05 to 0.89.

$$HI_g = 12.581 - 0.130(H) + 98.541(H/\overline{H}) - 90.294(H/\overline{H})^2$$

Equation 29

where HI_g = annual gap tree height increment (cm.year^{-1});
H = total height (m);
$H/\overline{H}$ = relative height (%), computed as gap tree height divided by the mean total height of the surrounding canopy or by the four border trees in the simulator.

The adjusted coefficient of multiple determination $\left(\overline{R}^2\right)$ for this regression equation was 0.24, with 108 degrees of freedom.

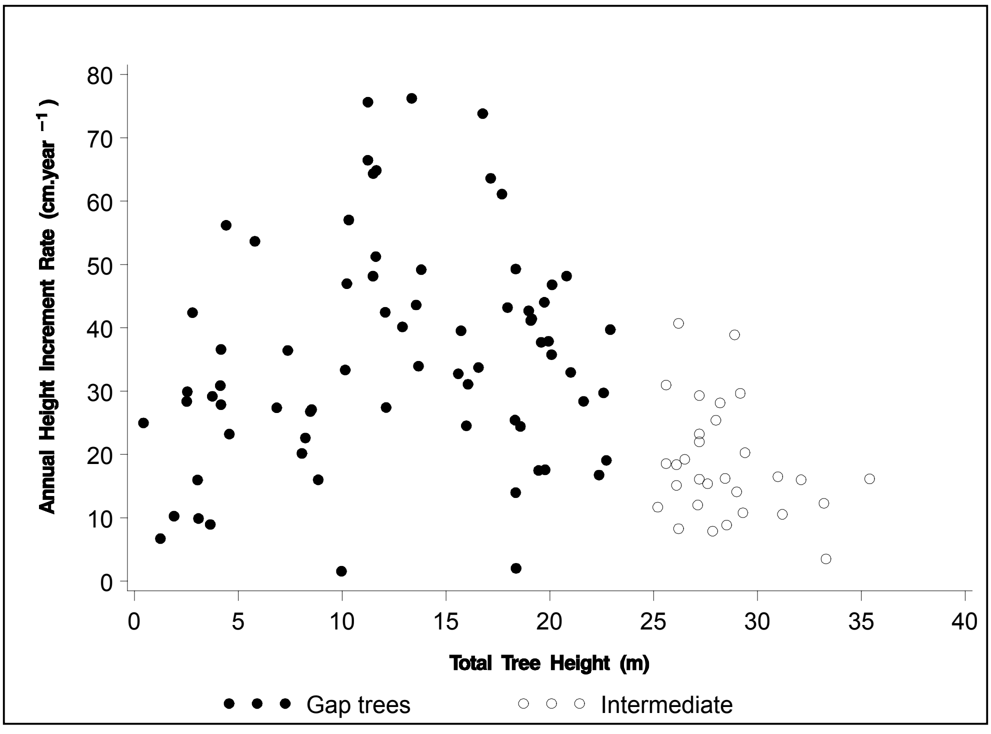

Figure 24: Annual height increment versus total tree height for gap and intermediate crown class trees

The simulation conditions of interest in this analysis are:

1. the number of years required for the border trees, either along the north-south or the east-west gap axis, to close the gap by lateral crown radius increment (the gap was assumed to be closed over when the distance between the crowns of opposing trees grew to within 0.5 m of one another); and
2. whether the gap tree grew to a height greater than or equal to the average height at the widest part of the crowns of the four border trees before condition 1 was met.

Three different forms of the simulation model were developed.

- Model 1 was a purely deterministic model using the (*CRI*) equations to predict lateral crown radius increment.
- Model 2 was also a purely deterministic model, but used directional branch length increment rate equations (*BLI*) rather than the whole crown equations (*CRI*), with the additional assumption that all four branches growing into the gap are gap branches.
- Model 3 used whole tree lateral crown radius increment equations (*CRI*) and has stochastic variation built into the projections.

Stochastic elements were included in Model 3 in several places. Border tree mean initial size terms (H, CR, LCR, H_w/H) were varied by adding a random number multiplied by the standard deviation of the mean for that variable as follows:

$$\overline{X} + s_{\bar{x}}^2 \times w$$

Equation 30

where $\overline{X}$ = mean border tree initial size
$s_{\bar{x}}^2$ = standard deviation of the mean
w = multivariate random number.

Random numbers were generated by a multivariate normal random number generator in SAS® which produced deviates distributed as N~(0, 1), and when constrained by the user, provided variance covariance structure, which in this case was the covariance matrix observed for these four variables for European beech trees of the same crown class. The random multivariate normal deviates fell roughly between -3 and +3 standard deviations.

The practical implication of using a constrained multivariate random number function was that the four initial values inputted into the increment projection model (H, CR, LCR, H_w/H) were realistic values from observed multivariate space. For example, the observed correlation coefficient from the data between total height and crown radius for trees was 0.82, which was a strong positive correlation. This shows that a tree with an above average total height will probably also have an above average mean crown radius. The use of unconstrained univariate normal deviates instead of the confined multivariate deviates can result in some cases in assigning an initial tree height that is above its mean, while the initial crown radius is substantially below its mean. This could have easily "created" a tree that is far outside the observed multivariate sample space for these variables, and is therefore not within the data space for which the regression models are calibrated.

Some correlation was present between predictor variables, even though an assumption of independence was made for these terms. The multivariate normal random numbers used in this projection maintained the approximate observed correlation structure between predictor variables. Predicted annual height and lateral crown radius increments were also subjected to stochastic variation, based on the formula:

$$\hat{Y}_o + s_{\hat{y}} \times \psi$$

Equation 31

where $\hat{Y}_0$ = the predicted annual increment to be added to the current size term;
$s_{\hat{y}}$ = the estimated standard deviation of the predicted value at an observed X_0 data vector;
ψ = a bivariate random normal deviate.

The estimated standard deviation for a predicted future response variable from a linear model was computed as:

$$s_{y_o} = s\frac{1}{\sqrt{(1 + X_i'(X'X)^{-1})X_i'}}$$

Equation 32

where s_{Y_0} = estimated standard deviation for a predicted response variable
s = the root mean squared error from the regression model,
X_i and X'_i = the observed predictor variable vector and its transpose, respectively, and
$(X'X)^{-1}$ = is the Xprime-X matrix from the regression model.

This formula was based on equation 5.2.1 from DRAPER & SMITH (1998) and extended to matrix notation. The rationale given above for the four-term initial size vector was extended to the two-level response vector generated in the model. In practical terms, it was expected that the annual height and the annual lateral crown radius increment on an individual tree would be correlated with one another and that random numbers, used to vary the predicted responses of these two values, should be singularly correlated. The variance and covariance terms were generated from a multivariate regression analysis.

Model 3 was run 100 times for each gap size-border tree configuration, from which averages of the number of years to gap closure and the frequency of gap tree success in reaching the canopy were computed. The relative positions of the four border trees around the simulated gap were assigned randomly at the beginning of each replication, in order to account for possible cumulative effects of the crown class of opposing border trees in the simulation.

As only one tree was simulated in each gap in Model 3, the observed percentage of gaps where the tree reaches the canopy is an estimate of how often a randomly chosen tree might reach the canopy in one increment period. This estimate should help to answer the question of whether the mean increment rate or some above average height increment rate is the limiting mechanism. Given that there are many trees in a typical gap, an equally interesting question is: how often might a gap be expected to be captured by one of the trees, rather than closed over from border tree expansion?

To investigate this question a second set of simulations was performed using Model 3 with identical border tree initial values and increment rates as the first stochastic simulation, but with a modification of the gap tree component. In this modified simulation, a single tree was again placed at the center of each gap, but was grown deterministically. It was assumed that if a tree was going to capture the gap space, it must be one of the fastest growers in the gap population and can thus be defined as a function of some confidence region about the tree height increment regression in Equation 29. The upper 90th percentile was chosen and resulted in a ten percent upper tail of the Student's-t distribution about the predicted height increment rate curve. The following equation was used:

$$\hat{Y}_o \pm (s)(t)_{(v,1-\frac{1}{2}\alpha)}\sqrt{\left\{1+\frac{1}{n}+\frac{(X_o-\overline{X})^2}{\Sigma(X_i-\overline{X})^2}\right\}}$$

Equation 33

where $\hat{Y}_0$ = the predicted growth increment from Equation 29 at a given X_0,

$\overline{X}$ = the mean X value;

s = the root mean squared error from the regression model;

t = the tabular t-value for the given degrees of freedom and joint confidence level, the formula within the brackets is the estimated standard deviation of a future predicted value (DRAPER & SMITH 1998 Eq. 5.3.4).

The joint confidence bands about a regression curve are divergent, widening as the observed X value diverges from its mean (DRAPER & SMITH 1998 Fig. 5.1). The use of Equation 33 in its entirety could lead to overestimates of gap tree increment at the smallest and largest X values because the upper confidence band is further away from its mean predicted value at extreme X values than it is at the mean X value. To make somewhat conservative estimates, it was further assumed parallel joint confidence bands about the regression curve by setting Xo equal to the mean, which causes the

$$\frac{(X_o-\overline{X})^2}{\Sigma(X_i-\overline{X})^2}$$

portion of Equation 33 to simplify to zero, and yields

$$Y_0 \pm (s)(t)_{(109,0.90)}\sqrt{\left\{1+\frac{1}{n}\right\}}$$

which simplifies to

$Y \pm 16.04$ cm.year^{-1}

with n = 110, s= $(160.71)^2$ and t = 1.295 for any predicted sapling height increment rate.

3.6.5 Summary of All Analysis Variables

Table 6: Summary of all variables used in analysis

Variable	Meaning	Unit
D	Diameter at breast height	cm
D_b	Backdated diameter at breast height	cm
D_s	Diameter of stump	cm
BA	Basal area	cm^2
H	Total height	m
H_s	Height of stump	cm
CR	Crown radius	m
CC	Crown class	1,2,3,4
H_w	Height at the widest point of the crown	m
A	Total tree age	years
$H/\overline{H}$	Relative height	%
$D/\overline{D}$	Relative diameter	%
H_w/H	Relative height at widest point of crown	%
LCR	Live crown ratio	%
$TCPA$	Total crown projection area	m^2
$ECPA$	Exposed crown projection area	m^2
$\%ECPA$	Percentage exposed crown projection area	%
$NUCS$	Number of unrestricted crown sides	0, 1, 2, 3 or 4
$\%BAI$	Percent basal area increment change	%
BAI	Annual basal area increment	cm^2year^{-1}
$\%HI$	Percent height increment change	%
HI	Annual height increment	$cm.year^{-1}$
CRI	Mean annual tree lateral crown radius increment rates	$cm.year^{-1}$
BLI	Mean lateral extensions of individual branches	$cm.year^{-1}$
HI_b	Annual border height increment	$cm.year^{-1}$
HI_g	Annual gap height increment	$cm.year^{-1}$

3.6.6 Regression Analysis

All statistical analysis was conducted using the Statistical Analysis System, SAS® (SAS INSTITUTE INC 1988; SAS INSTITUTE INC 2000). All model *f*-tests and parameters are significant at the p <0.05 unless otherwise stated. All models were selected on a basis of adjusted R-square $\left(\overline{R}^2\right)$ and the *f*-test. All Regression models were evaluated for lack of fit and homogeneity of variance by examining the residual plots (DRAPER & SMITH 1998) and were checked for unacceptable multicollinearity using a technique presented by CHATTERJEE (2000). Accordingly, if the sum of the inverted eigenvalues (computed for the correlation matrix, omitting the intercept parameter) is greater than five times the number of predictors, the model is judged to be highly multicollinear and is removed from further consideration.

Because of potential multicollinearity among predictor variables, a hypothesized equation was used as a starting point in the variable selection process, but was not used to constrain the final model structure. The linear regression assumption of the independence of observations was tested by refitting the selected regression models to randomly drawn subsets of subject trees. Results of these tests suggest that the use of moderate numbers of trees from each stand, both as subject trees and as competitors for other subject trees in the stand, did not create an autocorrelation problem. The subset data models had parameters with the same sign and similar magnitude as the full data set regressions. Predicted increment rates and coefficients of determination for the subset data models were all also consistently similar to those of the full data set.

The four sites sampled in this study have different site classifications. Unfortunately, these site classifications are heavily confounded with treatment, climate and temporal effects. Different treatments occurred in each of the stands, over different periods of time and under different climatic conditions. It is almost impossible to isolate these confounded effects without long-term replicated experimental trials. These trials would require; a) replication in space; b) replication in time of trees with similar age. Such a design is almost impossible. Within this study, site-specific analyses were conducted simply to examine the variation in release response encountered in the southern Black Forest. It is important to realize that these analyses do not reflect the influence of different site conditions on release response but rather some combination of site, treatment, climate and temporal interaction. These site-specific analyses are simply used to indicate the likely variation encountered in the southern Black Forest and are not discussed in detail in this study. The results from the combined analyses using all four sites are presented and discussed in more detail.

4 RESULTS

As stated in Chapter 1 the purpose of this study is to examine the release response of advanced European beech trees. Extensive data was collected from 170 such trees located in four different study sites in the southern Black Forest. A wide range of competition scenarios were incorporated into the study using a two stage sampling procedure. The following chapter discusses the results arising from the analysis of the data collected. The chapter has been divided into four sections corresponding to the four null-hypotheses relating to basal area increment release response, height increment release response, crown expansion and gap simulation.

4.1 BASAL AREA INCREMENT RELEASE RESPONSE

4.1.1 Direct Analysis of Relative Basal Area Increment Rate Change after Release

The responses of individual trees were analyzed to discover whether variation among trees in a stand could be partly explained by easily identifiable demographic characteristics. Specifically two separate measures of crowding, percent change in area potentially available *(%APA*) and the number of unrestricted crown sides (*NUCS*), were examined along with relative diameters $\left(D/\overline{D}\right)$ and initial diameter (*D*) to explain the percentage increase in basal area increment for individual trees

%BAI = f(diameter, relative diameter, age, %APA)

Equation 34

%BAI = f(diameter, relative diameter, age, NUCS)

Equation 35

These models were applied to trees from the four sites individually and combined (Table 7).

Table 7: Regression equations for predicting 10 year average percent increase in basal area increment for individual trees (*%BAI*) as a function of percent change in *APA* (*%APA*) or as a function of the number of unrestricted crown sides (*NUCS*)

Eq.	Study site	N	Model	$\bar{R}^2$	*F*
			As a function of *%APA*		
36	Bad Säckingen	40	*%BAI* = -10.786 - 21.483($D/\bar{D}$)+ 0.717(*%APA*)	0.23	25.7
37	Schopfheim	40	*%BAI* = 170.120 - 3.101(*D*) + 0.401(*%APA*)	0.25	31.3
38	St. Märgen	44	*%BAI* = 45.018 - 0.250(*D*) – 28.984($D/\bar{D}$) + 0.406(*%APA*)	0.28	18.5
39	Todtmoos	46	*%BAI* = 20.018 - 0.450(*D*) - 20.089($D/\bar{D}$) + 0,621(*%APA*)	0.25	17.5
40	Combined	170	*%BAI* = 58.396 – 1.228(*D*) + 0.548(*%APA*)	0.22	22.2
			As a function of *NUCS*		
41	Bad Säckingen	40	*%BAI* = 24.018 - 32.103($D/\bar{D}$) + 28.109(*NUCS*)	0.16	10.2
42	Schopfheim	40	*%BAI* = 10.089 - 0.328(*D*) + 18.988(*NUCS*)	0.15	6.6
43	St. Märgen*	44	*%BAI* = 28.024 - 0.249(*D*) – 21.984($D/\bar{D}$) + 28.015(*NUCS*)	0.19	7.2
44	Todtmoos	46	*%BAI* = 15.122 - 0.245(*D*) - 20.201($D/\bar{D}$) + 34.055(*NUCS*)	0.18	3.8
45	Combined	170	*%BAI* = 24.089 - 0.451(*D*) + 25.222(*NUCS*)	0.14	7.6

Note: Coefficients of all independent variables have *p* values < 0.05 except where noted.

* Coefficient for variable *NUCS* in this equation has a *p* value = 0.06.

Figure 25 shows that the correlation between percent change in basal area increment (*%BAI*) of the subject trees in all four study sites was significantly and positively correlated with percent change in *APA* (*%APA*). The 48 unreleased “reference trees”, with no change in *APA* at the time of release, can be seen on the left hand side of the graph. These unreleased trees had a basal area increment ranging from –60 to +71%, with an average of –3.4%. The variation encountered among the other trees was also quite high. The reason for this was that while some trees were released and responded well, others that were heavily released did not respond at all.

Initial diameter (*D*) and relative diameter $(D/\bar{D})$ of the subject trees were found to be negatively correlated with increment response when these variables were found to be significant (Table 7). Therefore, the largest trees in the stand showed a relatively smaller percentage increment increase. Increment response was also independent of tree age, whether or not relative diameter was included as an independent variable (*p* values for tree age in Table 7 ranged from 0.11 to 0.88).

It must be noted here that the adjusted coefficient of determination ($\bar{R}^2$) values for the percent change equations found in Table 7 are quite high for this type of equation form. If these equations were explaining level variation, i.e. basal area increment (*BAI*) then a $\bar{R}^2$ of 0.6-0.7 would probably represents an $\bar{R}^2$ of approximately 0.3 in the percentage form.

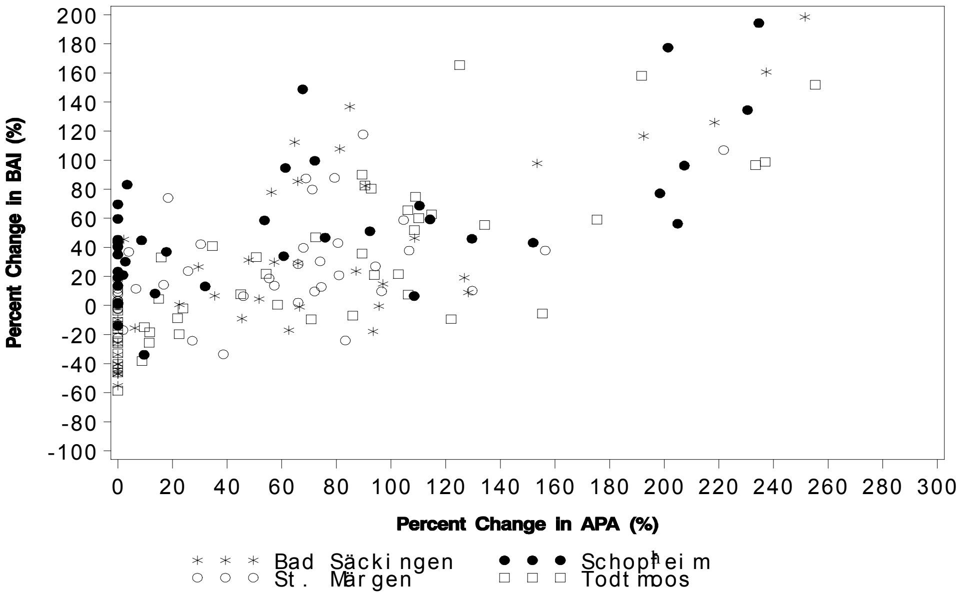

Figure 25: Percent change in basal area increment rate of individual canopy trees for the 4-10-year post-treatment period compared with increment of the same trees in the 10-year pre-treatment period

For a typical dominant tree in an 80-100 year old even-aged European beech stand with an initial diameter of 35 cm, the mean expected response is 43% for a 50% increase in *APA*, 70% for a 100% increase and 97% for a 150% increase in *APA* (Equation 40 in Table 7). Therefore, larger than average overstory trees showed a substantial increment response to treatment.

Percent change in basal area increment rate (*%BAI*) was less correlated with the number of unrestricted crown sides (*NUCS*) in comparison with percent change in *APA* (*%APA*). Adjusted coefficient of determination $\left(\overline{R}^2\right)$ values for the *NUCS* equations ranged from 0.14 to 0.19, whereas, the $\overline{R}^2$ values for the *%APA* were higher and ranged from 0.22 to 0.28.

4.1.2 Basal Area Response Based on an Increment Model

Log and inverse transformations of variables in each model were compared but since there was little evidence of heteroskedasticity in the residual plots, untransformed variables were used in the model fitting process. A simple basal area increment (*BAI*) model was developed with two separate measures of crowding:

$$BAI = f(diameter,\ relative\ diameter,\ age,\ APA_{after})$$

Equation 46

$$BAI = f(diameter,\ relative\ diameter,\ age,\ NUCS)$$

Equation 47

Absolute basal area increment was positively correlated with initial diameter (*D*) (and also positively correlated with relative diameter $\left(D/\overline{D}\right)$when that variable was significant) and APA_{after} (Table 8). Annual increment was also independent of tree age, whether or not relative diameter was included as an independent variable (*p* values for tree age in Table 8 ranged from 0.16 to 0.56).

Applying Equation 46 the resulting adjusted coefficient of determination $\left(\overline{R}^2\right)$ values for trees ranged from 0.35 to 0.54 depending on the study site. It is extremely difficult, if not impossible, to compare the adjusted coefficient of determination $\left(\overline{R}^2\right)$ for these equations and the percent change equations in Table 7. The form of the equations and error structure are totally different.

Table 8: Regression equations for predicting 10-year average annual basal area increment (*BAI*) as a function of APA_{after} or as a function of the number of unrestricted crown sides (*NUCS*)

Eq.	Study site	N	Model	$\bar{R}^2$	*F*
			As a function of APA_{after}		
48	Bad Säckingen†	40	$BAI = 3.045 + 0.281(D) + 10.891(D/\bar{D}) + 0.342(APA_{after})$	0.54	59.8
49	Schopfheim‡	40	$BAI = 2.989 + 0.269(D) + 11.131(D/\bar{D}) + 0.395(APA_{after})$	0.48	34.2
50	St. Märgen	44	$BAI = 4.022 + 0.303(D) + 0.126(APA_{after})$	0.40	29.8
51	Todtmoos	46	$BAI = -38.389 + 1.038(D) + 0.219(APA_{after})$	0.35	16.5
52	Combined	170	$BAI = 6.091 + 0.155(D) + 0.342(APA_{after})$	0.45	27.5
			As a function of *NUCS*		
53	Bad Säckingen	40	$BAI = 2.612 + 0.453(D) + 7.013(D/\bar{D}) + 5.937(NUCS)$	0.30	33.7
54	Schopfheim*	40	$BAI = -1.406 + 0.778(D) + 10.089(NUCS)$	0.26	21.6
55	St. Märgen	44	$BAI = 14.195 + 0.138(D) + 4.000(NUCS)$	0.28	18.8
56	Todtmoos	46	$BAI = -25.572 + 0.957(D) + 2.515(NUCS)$	0.22	9.3
57	Combined	170	$BAI = 18.881 + 0.191(D) + 6.085(NUCS)$	0.29	24.5

Note: Coefficients of all independent variables have p values < 0.05 except where noted.

† Coefficient for variable $\left(D/\bar{D}\right)$ in this equation has a p value = 0.06.

‡ Coefficient for variable $\left(D/\bar{D}\right)$ in this equation has a p value = 0.09.

* Coefficient for variable *NUCS* in this equation has a p value = 0.08.

The response of a 35 cm diameter tree was estimated using the basal area increment model (Equation 52 in Table 8) under various transformation management regimes for converting even-aged stands to more structured stands. Under these management scenarios, the expected increment of an untreated 35 cm diameter tree (with an APA_{after} of 30 m^2) is 21.81 cm^2year^{-1}. If a tree is treated to the conservative level of APA_{after} = 60 m^2, the predicted growth rate would be 32.07 cm^2year^{-1}, a 47% increase. For heavier treatments, increasing *APA* to 80 m^2 or 100 m^2, the predicted increment-rate increase would be 78% and 109% respectively.

The number of unrestricted crown sides (*NUCS*) was found to be positively correlated with basal area increment for all study sites (Equations 53 to 57 in Table 8), although it was only marginally significant for Schopfheim. In most cases this model had $\bar{R}^2$ values 12-24% points lower than comparable equations using APA_{after} as the variable to represent competition. Equation 57 in Table 8 predicts that a 35 cm diameter tree, which is initially restricted on all sides would experience a 23% increase in basal area increment, should 1 side be unrestricted, a 43% increase if two sides were unrestricted, a 71% increase if three sides were unrestricted and a 95% increase if all four sides were unrestricted.

The annual increment models for both APA_{after} and *NUCS* (Equation 52 and Equation 57) were validated by randomly removing approximately 1/3 (60) of the subject trees as a validation data set, and calibrating the model with the remaining 110 observations. This approach is similar to that used by MARTIN & EK (1984) and TECK & HILT (1991).

Observations of independent variables (size, relative size and competition sizes) for the 60 trees not used in model calibration were then entered into the model, and the predicted increment rate of these 60 trees was compared with the observed values from the initial 110 trees. Residual plots gave no indication that the model over-estimated or under-estimated growth across the range of tree diameters in the data set.

4.1.2.1 Long Term Basal Area Increment Projection after Release Treatment

Although the data indicates that heavy release can cause fairly dramatic basal area increment increases of 70-100%, the question of whether crown release treatments would be worthwhile in certain transformation cases depends on whether those trees in the stands selected for release are significantly larger and more stable than untreated trees. Such a positive transformation, which occurs over a period of decades, is necessary in order to compensate for the possible negative effects caused during crown release. The basal area increment models (Equation 52 and Equation 57 in Table 8) were used to forecast the time required for a 35 cm diameter tree (a typical dominant tree in existing even-aged European beech stands) to reach a 65 cm target under various initial treatment alternatives (Table 9). This target diameter of 65 cm was based on the Baden Württemberg state forest guidelines for mixed European beech forest (MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) 1999). These guidelines suggest that European beech trees in excess of 60 cm in diameter should be produced with this type of forestry system.

Table 9: Projected diameter of a dominant tree with an initial diameter of 35 cm under various APA_{after} and $NUCS$ conditions

APA_{after} (m^2) Eq. 52	Projected diameter (cm) Yr10	Yr30	Yr50	Years to reach 65 cm	mean radial increment ($mm.year^{-1}$)
20	38.2	43.7	49.1	101	1.48
40	39.3	46.7	53.7	85	1.76
60	40.4	49.6	57.9	69	2.17
80	41.5	52.4	61.7	58	2.58
100	42.5	55.0	65.4	49	3.06
NUCS Eq. 57					
0	39.4	46.9	54.0	84	1.78
1	40.3	49.5	57.7	69	2.17
2	41.3	52.0	61.3	53	2.83
3	42.2	54.3	64.6	51	2.94
4	43.1	56.6	67.7	45	3.33

Note: Treatments are assumed to occur at 10-year intervals

For simplicity, treatments were assumed to consistently occur at 10 year intervals to maintain the indicated level of APA_{after} or number of unrestricted crown sides ($NUCS$). However, treatments do not necessarily need to be that frequent to maintain the desired level of crown exposure. Lengthening the cutting cycle from 10 to 15 years will probably not affect the management, but longer cutting cycles could result in a slowdown of individual tree growth as the level of competition approaches the pre-release level.

If untreated trees, with a initial diameter of 35 cm, were maintained with an APA_{after} level of 40 m^2, Equation 52 (see Table 8) predicts that it would take 85 years for the tree to reach a 65 cm target diameter. The required time could be reduced to 49 years if heavy release was done to an APA_{after} of 100 m^2.

The second model, Equation 57 (see Table 8), which uses the number of unrestricted crown sides gave similar predictions. The time required for a 35 cm diameter tree to reach the target diameter ranged from 84 years, if the number of unrestricted crown sides (*NUCS*) is zero, to 45 years if *NUCS* was four (see Table 9).

4.1.2.2 Evaluation of Long-term Projections

Two approaches were used to evaluate the plausibility of the long-term projections in this study. For untreated trees, the long term projected cumulative diameter of a tree with an initial diameter of 35 cm was computed using the combined basal area increment model calibrated from the 4-10-year growth data (Equation 52) and by assuming an APA_{after} equal to that of the unreleased tree with 35cm diameter (APA_{after}= 30 m^2). This was compared with the total age-diameter regression for 130 dominant and co-dominant trees from this study, in order to incorporate the apparent long-term growth trend for the study sites into the evaluation. The age-diameter relationship in Figure 26 was based on 130 dominant-co-dominant canopy trees (open dots) from the study sites. The equation of the age–diameter trend was derived from a two parameter Schumacher's equation of the following form $D = e^{(4.688-110.069/A)}$. The projected growth trajectory (refer to Figure 26) for unreleased trees is similar to the actual long-term age-diameter trend among the sampled trees using the level of 30 m^2 $\mathrm{APA}_{\mathrm{after}}$ which corresponds to the average stocking level of an unreleased 35 cm diameter tree in this study. The model predicts that a 35 cm diameter tree will reach 65 cm in 93 years, whereas the age-diameter regression indicates an existing average difference of 116 years between 35 cm and 65 cm diameter trees. The implied mean radial increment is 1.6 mm.year^{-1} and 1.3 mm.year^{-1} respectively.

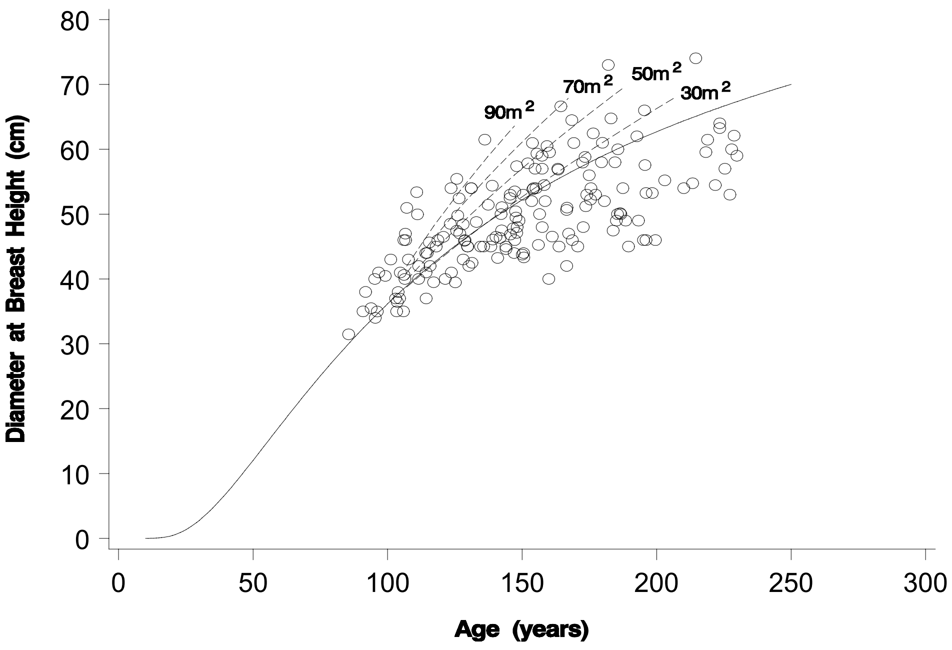

Figure 26: Growth projections of a 35 cm diameter canopy tree under various APA_{after} levels (broken lines), compared with the observed total age-diameter trend of canopy trees (solid line).

For released trees, the important question is whether the rapid increment rates predicted by the model can actually be sustained by overstory trees over a period of 50 years or more as Figure 26 implies. Based on crown release criteria (Equation 57 in Table 8), the predicted radial increment for a 35 cm diameter tree, given that the number of unrestricted crown sides is two, is 3.14 mm.year^{-1} in the first decade, declining to 2.25 mm.year^{-1} in the fifth decade, with an overall 50 year mean of 2.62 mm.year^{-1}.

A sample of 9 trees which contained sustained high radial increments over time periods in excess of 50 years, was selected from the total sample of 170 trees. These trees were divided into two age classes, those over 150 years and those between 80-150 years old (refer to Table 10). Selected trees between 80-150 years old sustained, on average, radial increments of 3.6 mm growth for an average duration of 55 years. The trees older than 150 years old were able to sustain an average growth of 3.3 mm for an average duration of 52 years. These results suggest that advanced European beech trees can sustain radial increment rates in excess of 3.5 mm for a number of decades under conditions of low competition.

Table 10: Observed long-term mean radial increments for felled sample trees

Age-Class	Mean radial increment (mm.year-1)	Mean no. of years.tree^{-1}	No. of trees
Trees 80 - 150 years old	3.6	54.8	4
Trees ≥ 150 years old	3.3	52.4	5

4.2 HEIGHT INCREMENT RELEASE RESPONSE

4.2.1 Direct Analysis of Relative Height Increment Rate Change after Release

The coefficients of determination between percent height increment change and single predictor variables is shown in Table 11. Predictor variables were classified into four categories corresponding to the four terms in Equation 25, although it is recognized that some of the variables may fall under more than one category. Almost all variables were found to be insignificantly correlated with percent height increment change after release for each study site and overall, all variables were found to be uncorrelated. The Pearson product moment correlation coefficient was used to show how strongly pairs of variables were related (DRAPER & SMITH 1998).

Table 11: Pearson product moment correlation coefficients between percent height increment change (%*HI*) and single predictor variables

Study Site	N	Absolute Size	Relative Size	Competition Terms				
		H	$H / \overline{H}$	*%APA*	APA_{after}	*NUCS*	*%ECPA*	*LCR*
Bad Säckingen	40	0.32*	0.35*	0.18	-0.28	-0.13	0.16	-0.15
Schopfheim	40	-0.15	-0.15	0.19	-0.19	0.01	-0.19	0.27
St. Märgen	44	0.24	-0.02	-0.32*	0.20	0.16	0.24	0.08
Todtmoos	46	-0.07	0.24	-0.02	-0.17	-0.13	-0.15	-0.17
Combined	170	0.03	-0.01	0.09	0.04	-0.05	0.09	-0.01

Note: * indicates coefficient of determination significant at the 0.05 percent level.

4.2.2 Height Increment Response Based on an Increment Model

Height increment was modeled in both a linear and non-linear form for investigations of border tree behavior in gap simulations. These models are not intended for general height increment investigations. The linear form was developed for use when assumptions about the distribution of errors on the fitted non-linear curves could make stochastic variation, based on observed variances, difficult in the gap simulation analysis.

4.2.2.1 Non-linear Height Increment Models

An examination of scatter plots of height increment versus total tree height suggested that a non-linear equation could be more accurate than an additive linear model for height increment predictions. A non-linear regression model of the general form

$$HI = \gamma_0 + \gamma_1 X_1 e^{\gamma_2 X_2}$$

Equation 58

where	HI	=	annual height increment ($cm.year^{-1}$)
	X_1	=	various combinations of total tree height, relative height and percent exposed crown projection area;
	X_2	=	various combinations of total tree height, relative height and percent exposed crown projection area;

was chosen on its ability to generate a family of curves that were concave downward and approached a low positive y-value at large x-values, a pattern suggested by the scatter plots.

The variables X_1 and X_2 were replaced by various combinations of total tree height (H), relative height $\left(H / \overline{H}\right)$ and percent exposed crown projection area ($\%ECPA$). Only these crown-based equations were used because the diameter, age and change in competition based variables (D, $D/\overline{D}$, age, APA_{after}, $NUCS$) accounted for less than 10% of the observed variation in annual height increment as single terms and were non-significant variables in the multiple-term equations.

The fact that the competition terms were not significant is not surprising. As previously mentioned several authors have found that height increment is somewhat insensitive to changes in stocking (DAHMS 1974; SCHMIDT et al. 1976; SEIDEL 1984). The most accurate non-linear annual height equations for each study site and a combined equation are presented in Table 12. It must be clearly stated that the height increment models developed within this study are only used to investigate the height increment behaviour of border trees for this study specific gap simulation and are not appropriate to be used as height increment model for general purposes.

Table 12: Best Non-linear Height Increment Equations

Eq.	Study Site	N	Equation	$\bar{R}^2$	F
59	Bad Säckingen	40	$HI = 0.641 + (2.572H + 2.432\%ECPA)\exp(-0.101H + 0.011\%ECPA)$	0.41	52.1
60	Schopfheim	40	$HI = 1..141 + (2.113H + 0.981\%ECPA)\exp(-0.098H + 0.014\%ECPA)$	0.48	60.7
61	Todtmoos	46	$HI = 36.031 + (-0.561H + 0.134\%ECPA)\exp(0.013\%ECPA)$	0.38	47.4
62	Combined	167	$HI = 0.561 + (2.780H + 2.360\%ECPA)\exp(-0.121H + 0.011\%ECPA)$	0.34	41.4

For the study sites Bad Säckingen, Schopfheim and Todtmoos, the best predictions of annual height increment regression were obtained by using initial height and percent exposed crown projection area as the independent variables in the non-linear models. A non-linear height increment model for the study site St. Märgen could not be to be fitted to yield significant *f*-values and retain significant parameters. These equations are only shown here to provide an indication of the variation of height increment in the southern Black Forest.

A non-linear regression equation, containing total height and exposed crown projection area was fitted for the combined data set, Equation 62 in Table 12. This combined increment model is independent of age (*p*-values for tree age in Table 12 ranged from 0.22 to 0.86). It is common knowledge that height increment is a function of age, but as previously shown by the top height curves in Figure 23, the effect of age is diminished the older the tree is. Therefore, as the trees analysed in this study are of an advanced age (between 80 years and 220 years) it is not surprising that age effect is not significant in the model.

Figure 27 is a 3-dimensional scatter plot of height increment and percent exposed crown projection area for the combined data set, which clearly shows that height increment is strongly influenced by total tree height and percent exposed crown projection area.

The response surface Figure 28 was generated using the non-linear regression Equation 62 in Table 12. Three outliers were removed from the data before the non-linear model was fitted. An outlier is defined as an observation which appear to be inconsistent with the remainder of the data set. The outliers were determined using the Cook's distance influence statistic (DRAPER & SMITH 1998).

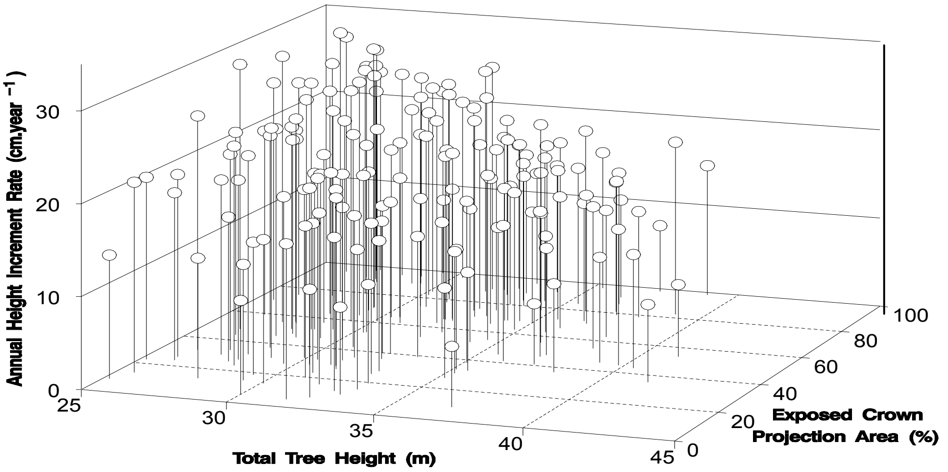

Figure 27: Three-dimensional scatter plot of annual height increment versus total height and percent exposed crown projection area

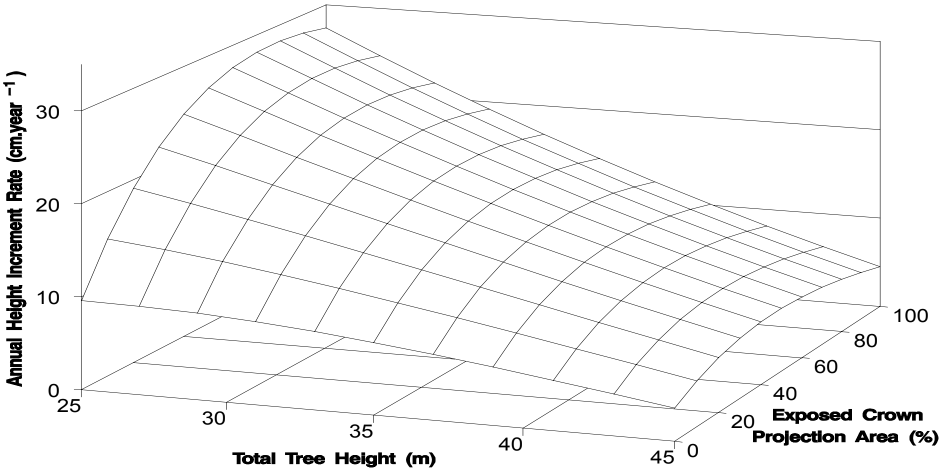

Figure 28: Predicted response surface of annual height increment versus total height and percent crown area

4.2.2.2 Linear Height Increment Models

A combined set of linear height increment prediction models were also developed for use when assumptions about the distribution of errors on the fitted non-linear curves could make stochastic variation, based on observed variances, difficult in the gap simulation analysis. Once again it must be stressed that these models are specifically constructed for investigating the height increment of border trees in gap simulation and are not intended for general use outside this study.

The non-linear patterns suggested by the data and the statistical significance of percent exposed crown projection area in the non-linear regression models prompted the partitioning of the data into sub-groups based on percent exposed crown projection area. The division of the data at 25% and 75% exposed crown projection area was based on observations of scatter plots and a somewhat arbitrary separation into groups. The separation of the data into three classes allows the data to be converted into a form where linear regression is appropriate.

A simple height increment (*HI*) model was developed for the three %*ECPA* classes with the following form:

$$HI = f(\mathit{height,\ relative\ height,\ age,\ competition})$$

Equation 63

In general, total tree height was found to be the variable most highly correlated with annual height increment. For the %*ECPA* > 75 group, height was the only significant variable (Table 13). Equations with total height as the only predictor variable are also provided for all subgroups, where a significant *f*-value was observed, both for comparisons and for use when only total height is available. These lower resolution models range in $\overline{R}^2$ from 0.17 to 0.49, provide more accurate predictions of height increment alone when other crown terms are not available.

Table 13: Best Linear Height Increment Equations

Eq.	Class	N	Equation	$\overline{R}^2$	*F*
64	%*ECPA* < 25	20	$HI = 43.434 - 1.043(H)$	0.07	15.1
65		20	$HI = 70.591 - 1.683(H) - 0.417(LCR)$	0.26	10.4
66	%*ECPA* 25 - 75	68	$HI = 44.941 - 0.892H$	0.16	20.7
67		68	$HI = 35.481 - 0.884(H) - 0.1505(LCR)$	0.29	41.2
68	%*ECPA* > 75	82	$HI = 55.562 - 1.105(H)$	0.21	29.1

4.3 CROWN EXPANSION

4.3.1 Directional Branch Length Increment Rates

As previously mentioned in the data analysis section, it is assumed that the major influence on crown expansion is competition. Comparisons of mean branch length increment between branch exposure classes were made within crown classes and within %*ECPA* classes using *t*-tests. Means between gap branches and non-gap branches within the intermediate and co-dominant crown class, were significantly different as were the means for the two branch exposure groups for the two *ECPA* classes %*ECPA* 25-75 and %*ECPA* >75. Conversely, differences between means for gap and non-gap branches within the dominant crown class and %*ECPA* < 25 class were not significantly different. In aggregate the means between gap and non-gap branches was found to be significantly at the 1% level of confidence.

Table 14: Summary of comparisons of mean branch length increment between branch exposure classes were made within crown classes and within %*ECPA* classes using individual *t*-tests

	Gap Branches			Non-gap branches			
Classes	N	Mean	s.d.	N	Mean	s.d.	*p*
Intermediate	43	13.5	0.5	77	6.6	0.4	<0.01
Co-dominant	141	8.4	0.3	255	5.5	1.2	<0.01
Dominant	58	7.9	1.1	106	7.6	1.8	n.s.
%*ECPA* ≤ 25	28	7.1	1.5	52	6.6	1.5	n.s.
25 ≤ %*ECPA* ≤ 75	96	12.1	0.9	175	5.0	0.9	<0.01
%*ECPA* ≥ 75	118	7.4	0.8	211	7.1	0.4	<0.01
Total	242	9.19	0.5	438	6.2	0.4	<0.01

4.3.2 Variation in Branch Length Increment Rates

To investigate why certain gap and non-gap mean branch length increment rates were not significantly different from one another in certain crown and percent exposed crown projection crown classes, the magnitudes and patterns of variation between branch length increment and whole-tree lateral crown radius increment within individual trees were compared. Figure 29 shows the magnitude of variation in observed individual branch length increment (*BLI*) over the range of observed mean whole-tree crown radius increment (*CRI*). In this figure, the horizontal reference line at y = 0 represents the mean whole-tree lateral crown radius increment. Each tree in the data set is represented by four points (branches) distributed vertically about their respective mean (whole-tree average). Branch length increment variation increases rapidly with increasing *CRI*, but becomes stable over a wide range of crown radius increment rates, with maximum branch length increment deviations of ± 25 cm.year^{-1}.

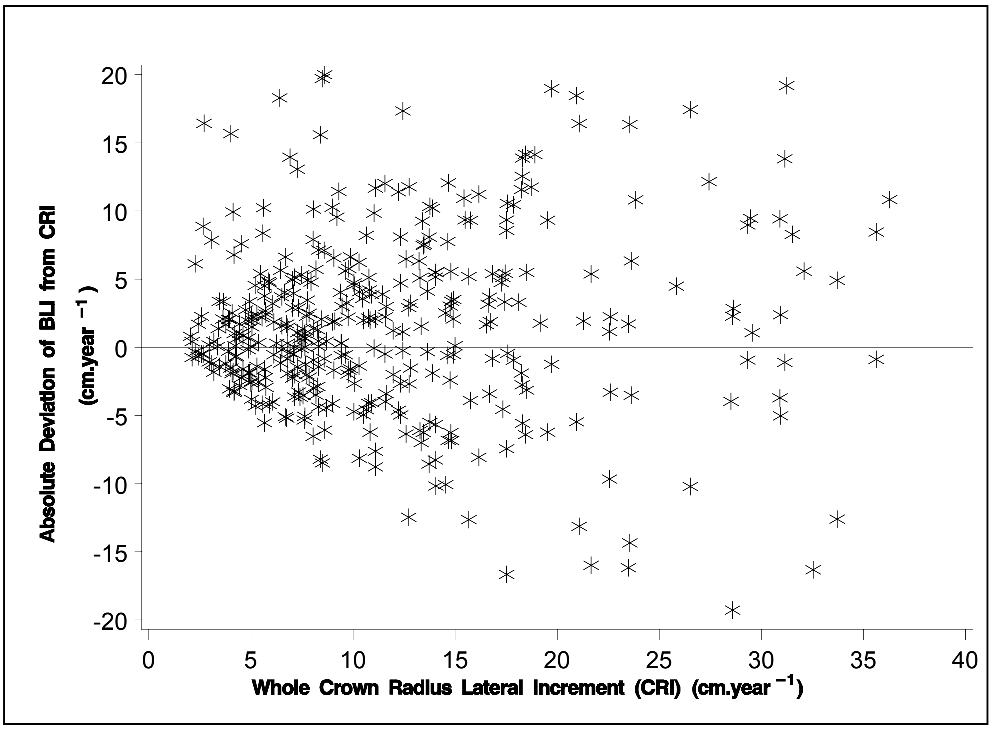

Figure 29: Scatter plot of absolute deviations of observed directional branch length increment from observed whole-tree crown radius increment for European beech

Figure 30 shows the frequency distributions of branch length increment deviation from whole-tree crown radius increment by percent deviation classes. That the histogram shows a positive skewness was due to the fact that a branch can grow at more than 100 % above its mean tree crown radius increment rate, but cannot grow at less than 100% below the whole-tree increment rate (i.e., a branch cannot be growing at less than 0 cm.year^{-1}).

The variance of branch length increment within trees suggested by this histogram is that branch length increment rates deviate frequently and significantly from their whole-crown average occur. This distribution suggests that a branch is equally likely to be growing 100% above or below its respective whole-tree means as it is to be growing near the mean.

TRIMBLE & TRYON (1966) found that branches growing north into a gap grow at a significantly greater rate than those growing in an eastern, southern or western directions. To test this hypothesis for the data, an analysis of variance was performed to establish whether significant differences in mean directional crown radius increment (*BLI*) among the four cardinal directions within each tree actually existed. For this purpose the trees were stratified by site and crown class. A randomized complete block design was used for this test, with compass direction main treatment effect and individual trees as the blocking factors (SNEDECOR & COCHRANE 1980). No statistical significance was detected for the effect of branch direction in any site-crown class combination in the data (p=0.07 to 0.82).

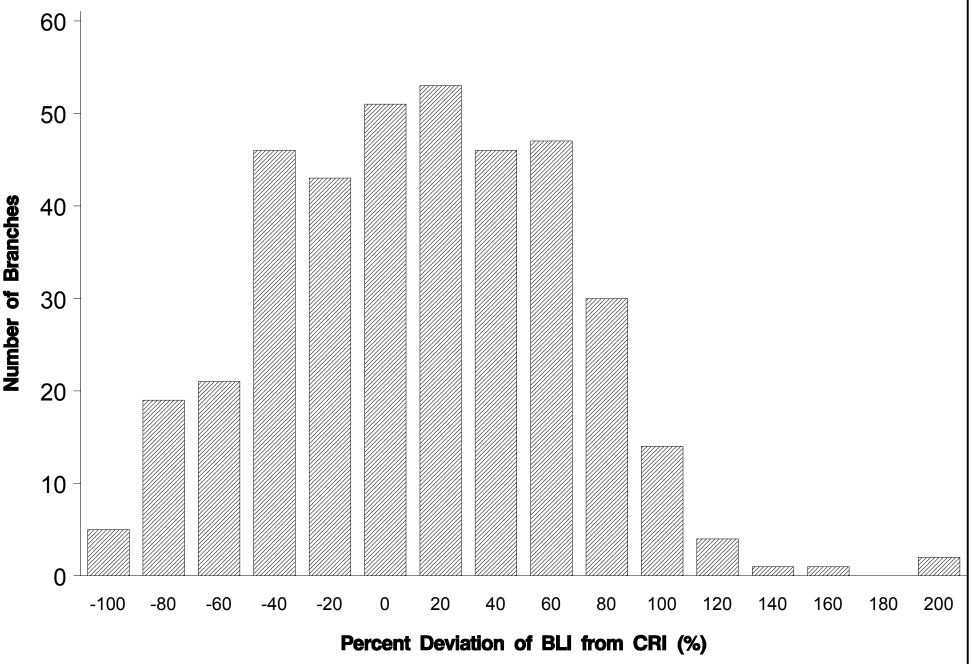

Figure 30: Frequency histogram of percent deviation of mean observed directional branch length increment from observed whole-tree crown radius increment by 10% deviation classes

4.3.3 Whole Tree Lateral Crown Radius Increment Equations

A simple whole tree lateral crown radius increment (*CRI*) model was developed for the three %*ECPA* classes with the following form:

CRI = f(height, relative height, age, LCR)

Equation 69

The results from regression analysis of overall crown radius increment are presented in Table 15. That the observed increment patterns and the linear regression equations for European beech lateral crown radius increment (*CRI*) and height increment (*HI*) are of the same model form (i.e. a function of *H* and *LCR*) is important for the gap closure simulations because multivariate models were needed to estimate the variance between predicted height and crown radius increments on a single tree (refer to section 4.2.2 Height Increment Response Based on an Increment Model).

Table 15: Whole-tree lateral crown radius increment (*CRI*) regression equations, fitted separately to %*ECPA* classes

Eq.	%*ECPA* Class	N	Model	$\bar{R}^2$	*F*
70	%*ECPA* < 25	20	$CRI = 5.1 - 0.22(H) + 8.12(LCR)$	0.14	32.4
71	%*ECPA* 25-75	68	$CRI = 13.3 - 0.27(H) + 12.01(LCR)$	0.33	42.7
72	%*ECPA* > 75	82	$CRI = 9.21 - 0.15(H) + 7.81(LCR)$	0.31	13.9

Absolute tree height was consistently the most highly, and always negatively, correlated predictor variable for *CRI* for %*ECPA* classes, accounting for 9-26% of the observed variation in lateral crown radius increment rate. The same negative correlation was observed between total height and annual height increment (refer to section 4.2.2 Height Increment Response Based on an Increment Model). Live crown ratio (*LCR*) was also a significantly correlated independent variable for the crown radius increment equations. It was always positively correlated with *CRI*. In the case of %*ECPA* < 25 the relative height was found to be significantly positively correlated with *CRI*.

The best predictive equations generated in the lowest %*ECPA* class had a considerably lower coefficient of determination than the corresponding higher %*ECPA* class equations. All models have highly significant *f*-values ($p < 0.01$ for all equations), suggesting that these equations can predict *CRI* more accurately than simply using the group mean.

4.3.4 Directional Branch Length Increment Equations

A simple whole tree lateral crown radius increment (*CRI*) model was developed for the three %*ECPA* classes with the following form:

BLI = f(height, relative height, age, competition)

Equation 73

The best predictive equations generated for advanced European beech directional branch increment (*BLI*) are presented in Table 16. Branch length, directional competition indices and a dummy variable for branch exposure class (gap or non-gap branches) were tested as independent variables in regression equations for all branches within each %*ECPA* class, but were generally found to be non-significant variables. To further investigate possible differences in increment trends between gap and non-gap branches, regression equations were fitted separately for gap and non-gap branch subsets.

As for whole-crown equations, total height and live crown ratio were the two independent variables most highly correlated with lateral branch length increment. The correlations were negative for total height and positive for *LCR* in all cases.

To examine the effect of separating gap branches from non-gap branches on predicted branch length increment rates the equations in Table 16 were used to predict branch length increment for a range of tree sizes within each %*ECPA* class. The gap branch equation consistently predicted larger increment rates than the non-gap branch equation over the range of tree sizes tested. Differences in predicted increment rates between branch exposure classes were largest for the %*ECPA* 25-75 class and smallest for the %*ECPA* >75 class. Within each %*ECPA* class, differences in predicted lateral growth rates for the two branch exposure classes decreased with increasing tree size. The equations presented in Table 16 behave logically in predicting faster increment rates for gap branches across the range of tree sizes, which suggests that these are real increment trends rather than spurious correlations due to overly fragmented data.

Table 16: Directional branch length increment (*BLI*) regression equations, with separate equations fit to whole-tree %*ECPA* class and individual branch exposure class.

Eq.	%*ECPA* Class Branch Exposure	N	Model	$\bar{R}^2$	*F*
	%*ECPA* < 25				
74	Gap branch	28	*BLI* = 10.11 –0.32(*H*) + 15.65(*LCR*)	0.08	11.2
75	Non-gap branch	52	*BLI* = 22.02 - 0.75(*H*) + 18.89(*LCR*)	0.23	33.5
	%*ECPA* 25-75				
76	Gap branch	96	*BLI* = 16.09 - 0.40(*H*) + 12.06(*LCR*)	0.36	50.7
77	Non-gap branch	175	*BLI* = 11.99 - 0.41(*H*) + 12.10(*LCR*)	0.33	27.9
	%*ECPA* > 75				
78	Gap branch	118	*BLI* = 4.88 – 0.27(*H*) + 19.27(*LCR*)	0.38	17.6
79	Non-gap branch	211	*BLI* = 15.17 – 0.45(*H*) + 17.09(*LCR*)	0.38	57.5

4.4 GAP CLOSURE SIMULATIONS

A summary of the gap closure simulations is provided in Table 17. Model 1 is a deterministic model using whole-tree lateral crown radius increment equations (*CRI*). Model 2 is a deterministic model using gap branch length increment equations (*BLI*). Model 3 is a stochastic model using whole-tree lateral crown radius increment equations (*CRI*) with 100 replications. Border tree codes show the numbers of intermediate, co-dominant and dominant European beech trees surrounding the gap.

As shown in Table 17 in the two deterministic models (1 and 2) the simulated 10 m diameter gaps did not close over from border tree lateral crown expansion in less than 50 years regardless of the border tree configuration. In the stochastic model (3), 10-17 % of the 10 m gaps did close over from border tree increment in less than 50 years, which suggests that knowledge of the mean lateral crown radius increment rates alone is not enough to accurately predict the outcome of border tree crown expansion into gaps. The mean number of years required for gap closure was not computed for Model 3 because 83% of the gaps in border tree configuration 1 (1 intermediate - 2 co-dominant - 1 dominant) did not close under 50 years and in 90% of the replications for configuration 2 (2 intermediate - 2 co-dominant – 0 dominant). Due to the simplifying assumptions involved in this simulation, the analysis was limited to 50 year projections.

Table 17: Summary of gap closure simulation results

			Model 1 Determin. CRI	Model 2 Determin BLI	Model 3 Stochastic, 100 reps CRI		
Gap Diameter (m)	Gap Area (m2)	Border tree config. (I-C-D)	Avg. no. of yrs to gap closure	Avg. no. of yrs to gap closure	Avg. no. of yrs to gap closure	% gaps closed in < 50 yrs	% 4.0 m tall trees that reach canopy	% gaps where 90th %ile 4.0 m tall tree reaches canopy
20	314	1 (1-2-1)	>50	>50	>50	0	75	100
20	314	2 (2-2-0)	>50	>50	>50	0	71	100
15	177	1 (1-2-1)	>50	>50	>50	7	56	100
15	177	2 (2-2-0)	>50	>50	>50	2	52	100
10	79	1 (1-2-1)	>50	>50	>50	17	40	83
10	79	2 (2-2-0)	>50	>50	>50	10	37	97
5	20	1 (1-2-1)	35	33	34	83	3	50
5	20	2 (2-2-0)	28	27	27	97	13	53
2.5	4.8	1 (1-2-1)	14	13	14	100	0	0
2.5	4.8	2 (2-2-0)	11	11	10	100	7	7

Random variation in initial border tree sizes and increment rates resulted in slightly more 10 m gaps closing with border tree configuration 1. Here there was only one intermediate tree, while configuration 2 had two intermediates (83% versus 90%). This result was somewhat unexpected as higher than average lateral crown radius increment were predicted for intermediate crown class trees.

The simulated 5 m diameter gaps closed in 33-35 years for gap configuration 1 for all three models and 27-28 years for configuration 2. Most of the gaps closed in less than 50 years (83-97 %) in the stochastic simulations. The simulated 2.5 m diameter gaps all closed in under 15 years, but these were very small gaps and may be more representative of typical canopy openings created in a thinning from below, where mostly poorer crown class trees are removed, than in single-tree selection cutting where larger crown class trees are often removed

Since intermediate crown class trees are predicted to have more rapid crown expansion rates than co-dominant or dominant trees, 5 m gaps with border tree configuration 2, with two intermediate and two co-dominant trees, tended to close in less years (= 20% faster) than gaps with configuration 1, consisting of one intermediate, two co-dominant and one dominant tree.

There were virtually no differences between the three different models in the gap closure results for gaps 5 m or smaller in diameter. As the stochastic variation in lateral crown radius increment rates is symmetric, the mean gap closure rate is the same for all three models. Additionally, with four border trees involved in each replication of the stochastic model, the probability is low that either pair of opposing border trees would both be growing greatly above or greatly below the mean enough times to systematically alter the average gap closure rate.

The standard errors of the means were examined to determine if the amount of replication (100) was adequate to accurately estimate the mean time to gap closure in Model 3. Standard errors for 100 runs of the model were less than 2 years for each gap size-border tree combination. The standard error of the mean time to gap closure dropped from 1.5 years to 1.1 years when the model was run 200 times for the 5 m gap with configuration 2. This small decrease in standard error caused by doubling the replication suggests that the estimated means would not differ greatly by using more than 100 runs for the other gap size border tree configurations.

The effect of using directional branch length increment equations versus whole-tree lateral crown radius increment could be seen by comparing the results of Models 1 and 2. Average gap closure in Model 2 (*BLI*) occurred only 0-2 years earlier than in Model 1 (*CRI*). The reasons for this lie in the fact that directional branch length increment rate equations predict crown expansion rates only slightly greater than the whole-tree rates and these differences decrease as gap and tree age increase. Based on this result, the stochastic model was not run using directional increment rates (*BLI*).

The gap tree height increment analysis from the stochastic simulations is also shown in Table 17. The first gap tree column under Model 3 indicates the predicted success rate of a single randomly selected tree under different gap conditions. Even in 10 m gaps in the stochastic model, which did not close by tree lateral crown radius increment in less than 50 years, only 40% of the 4 m tall trees growing at mean rates with stochastic variation, were predicted to reach the canopy in one sustained growth episode. Gap tree success dropped off sharply in 5 m diameter gaps, with only 3% and 13% of the trees respectively projected to reach the canopy with border configurations 1 and 2. Only 7% of simulated trees were successful in the smallest gaps with border tree configuration 2.

Model 3 included random variation in gap tree height increment, as well as in border tree size and increment rates. The successful trees in each predicted gap scenario represent the fastest growers, not those growing at the mean rate. This becomes clearly visible when Models 1 and 2 are compared with Model 3 in all three gap sizes. In the deterministic models, the 4 m tall trees, growing at mean predicted rates, did not reach the canopy in any of the gaps. Some trees in the stochastic models reached the gaps before they closed over from lateral increment of the border tree crowns.

The second gap tree column under Model 3 in Table 17 indicates the predicted frequency at which gaps will be captured by a tree before being closed by border tree lateral crown radius increment, if at least one tree in the gap is growing in the upper 90th percentile of predicted height increment rates. The mean annual height increment rates are calculated from a 10 year average to avoid the problem whereby an extremely fast increment in one year may be compensated for by an extremely slow increment in the following year. The model predicts that 83–97% of the 10 m diameter gaps will be captured by a tree before the gap is closed by border tree crown expansion. 50-53% of the 5 m diameter gaps are predicted to have gap trees successfully making it to canopy height. The results for 2.5 m gaps are identical to the individual tree success rate, which suggests that the fastest growing trees in the smallest gaps would still not reach the canopy before the gap closed as a result of lateral crown radius increment from above. These gap closure simulation results suggest that the primary process of gap closure changes from one of younger age classes, occupying the canopy opening the majority of the time in 10 m diameter gaps, to one of border tree crown expansion into 2.5 m diameter gaps.

4.5 SUMMARY OF RESULTS

Chapter 4 was organized into four main sections, each of which corresponds to each of the four null-hypotheses of the study. The analyses focused on the correlations between the independent variables (size, relative size, age and competition terms) and the dependent variables (basal area increment release response and height increment release response). All data were analyzed by least squares regression procedures and the level of confidence was set at 0.05. Using the model equations from this, a gap simulation study was conducted. The statistical findings provide support for the general aim of the study. In short, the analysis that crown release can be effective in increasing the development of advanced European beech trees in transformation forestry.

5 DISCUSSION

This chapter is divided into six sections. The first presents a discussion of the material and methodology. The second section discusses the results with respect to the four null-hypotheses relating to basal area increment release response, height increment release response, crown expansion and gap simulation. The third section discusses the practical implications of the results for forest practitioners. The fourth section discusses the limitations of the study. The fifth section discusses the further research opportunities following on from this study. The final section provides a summary of the study.

5.1 MATERIAL AND METHODS

Data were collected from four study sites in the Black Forest. The study sites were located at elevations ranging from montane to sub-montane. The altitude ranged from 550 to 1050 m. The general soil classification for all study sites is brown earth, derived from granite and sandstone rock. The sites were selected to represent a broad range of European beech ecosystems typical of the southern Black Forest. However, there was no attempt in this study to quantify the effect of different site quality on the release response. Although site-specific equations were provided in this study, only the mean trend of the data for all sites was discussed in any great detail. The variation in site quality was simply used to collect information on the possible range of release responses in the southern Black Forest. The study was conducted in this way to increase the external validity of the overall trends observed.

Each site was selected where thinning had occurred, from 5-21 years ago. This provided variation in the individual tree competition history. Unfortunately, due to the confounding between treatment intensity, treatment timing, site quality and climate, it is impossible to separate the effects with the data from this study. To answer questions about the interaction between site quality, climate and treatment, replicated long-term experimental studies are required. It was not the aim of this study to collect such a data set.

The overstory trees species included European beech, Norway spruce and silver fir. The mean canopy-age ranged from 110 to 130 years old, while the ages of individual trees selected for sampling ranged from 82 to 221 years old. Advanced European beech trees were selected for analysis in the study for several reasons. Firstly, there is a distinct lack of research investigating increased diameter and volume increment of released advanced European beech trees following release (ZIMMERLE 1936; ZIMMERLE 1938; ASSMANN 1965; JOHANN 1970; PREUHSLER 1981). Secondly, advanced European beech trees play an important role in the transformation process, in particular when it comes to the maintenance of perpetual cover in the upper story, stabilization of the stand, providing economic returns and providing structural diversity.

A two stage sampling procedure was adopted for the data collection process. In the first stage, using non-destructive measurements, the range of past and current competition scenarios within each study site was estimated from 300 trees. During the second stage, a smaller sample of 50 trees, uniformly representing the initial sample, were selected for further destructive measurements. This two stage sampling scheme was successful in ensuring a wide range of competition scenarios were intensively measured for modeling purposes.

Previous studies into the growth of European beech (DHÔTE 1990; HAHN 1995; DHÔTE 1996; BÖRNER 1997) have shown that this species is highly variable and plastic in growth. The retrospective study from BÖRNER (1997), which used a similar number of trees as was the case in this study (138 trees versus 170 trees), found that the results relating to growth response were not clear due to the high variation observed. He attributed this variation to three main causes:

1. the high unexplained error of competition measures
2. the error of the response estimator
3. the differences in the individual growth response behavior between trees

The two stage sampling scheme employed in this study attempted to limit the effect of the variation associated with these three effects identified by BÖRNER (1997) by ensuring the following:

1. Competition scenarios were uniformly sampled over a wide range. This provided a sound basis for subsequent regression equations. A broad range of competition is essential in ensuring that the variation explained by the competition index is of a greater magnitude than the random variation associated with the response estimator (refer to Figure 31).

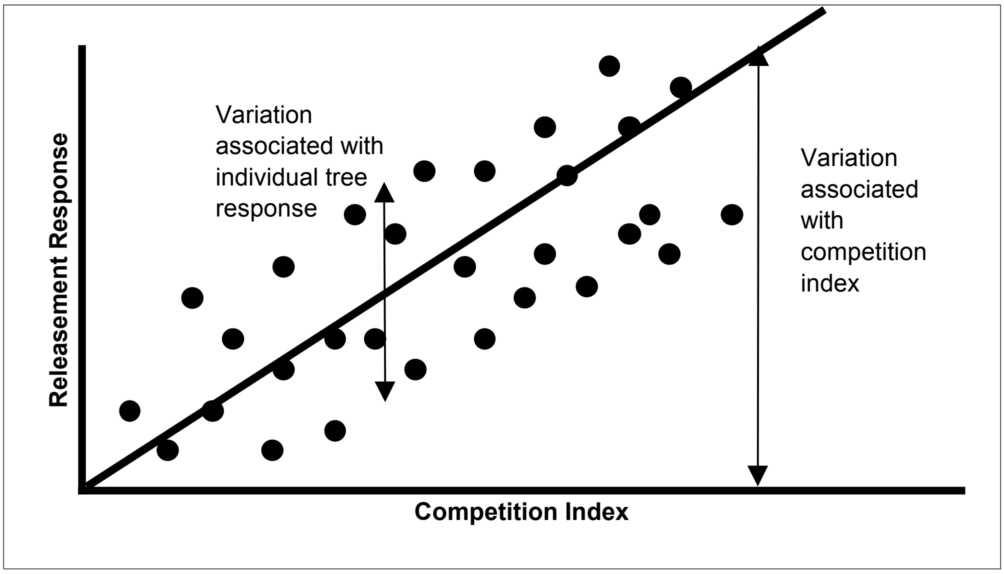

Figure 31: Schematic diagram representing the relative importance of the variation associated with competition index and release response

Figure 31 illustrates that if the competition index was sampled over a more narrow range then the variation associated with this index would be much smaller. If the sampled range was narrow enough, the effect of the competition index may not be significant in the regression analysis. This is one of the problems with regression techniques and illustrates why sampling extreme values is so important.

2. A simplistic release response was used in this study. The release response was defined as the ratio of the 10 year mean annual increment after release divided by the 10 year mean annual increment directly before release. This simple response index, calculated over a short time period (20 years) was used to reduce the variation associated with the estimator. A minimum of 10 reference trees per study site was also taken. This ensured that this ratio estimator was a stable and robust estimator of the base case where trees had not been released.
3. A minimum sample size of 40 trees per study site was taken for intensive measurements. This minimum sample size attempted to ensure that there was enough replication for each study site so that a valid mean release response for different competition scenarios could be predicted.

In the process of measuring the secondary sample 30 trees were damaged during the felling process. This left 170 remaining trees to test the posited hypothesis. Trees were measured for the radial increment, height increment and lateral branch increment for the 10 years before and the 10 years after release, using dendrochronology and branch internode analysis. The method of internode analysis, proposed by (ROLOFF 1988) was validated and found to be acceptable for the analysis of height and crown width increment in this study.

Competition at the time of release was reconstructed using backdating equations and stump diameters. The methodology for this reconstruction relied heavily on the ability to accurately date when the stumps were cut. This required the sampled study sites to have had release treatments occurring recently (5-21 years ago).

5.2 RESULTS

The first null-hypothesis dealt with changes in basal area increment due to heavy crown release. The *f*-test analysis from the fitted individual tree equations for predicted percent increase in basal area and actual annual basal area increment indicated that significant differences exist between released trees and non-released trees at the 0.05 level of confidence. Therefore, the first null-hypothesis was rejected. In other words, the data indicated a significant increase in the basal area increment of advanced European beech trees following release (**Null hypothesis rejected**).

The second null-hypothesis examined changes in height increment due to heavy crown release. The percent change in height increment was found to be uncorrelated with most measured variables. In addition, no change in competition variable could be successfully fitted to individual height increment equations. Based on the analysis of this data the second null-hypothesis was not rejected. In other words, the data failed to reveal significant changes in height increment due to heavy release (**Null hypothesis accepted**).

The third null-hypothesis compared the growth of gap branches versus non-gap branches. The *t*-test analysis for the overall comparison of gap branches versus non-gap branches indicated that significant differences for these branch exposure classes exists at the 0.05 level of confidence. Therefore, the null-hypothesis was rejected. In other words, the data indicated a significantly higher growth of gap branches than non-gap branches, as was predicted in the objective (**Null hypothesis rejected**).

The fourth null hypothesis examined whether a gap diameter of 10 m is sufficient in size, at the 0.05 level of confidence, to assure the recruitment of a 4 m high sapling into the canopy. The results of the deterministic and stochastic gap simulations showed that, to ensure a 4 m high sapling reaches the canopy before the gap is closed, diameters of greater than 10 m are required. Therefore, the fourth null-hypothesis was rejected. In other words, the data indicated that gaps significantly larger than 10 m were required to recruit 4 m high saplings into the canopy, as was predicted in the objective. (**Null hypothesis rejected**).

5.2.1 Basal Area Increment

Both a direct analysis of the basal area at 1.3 m increment rates of subject trees before and after treatment and comparisons of the post-treatment increment for treated and untreated trees indicate the basal area increment rates of advanced European beech can be increased by an average of 70-100% through heavy release. Under conditions of low competition even relatively old trees appear to be able to maintain rapid increment rates (>3.5mm radial increment/year) for long periods.

Surprisingly, once diameter (and relative diameter when significant) was fitted in the models, total tree age provided no additional predictive benefit. This is partially due to the strong correlation between diameter and tree age. In addition, this study was restricted to analyzing only advanced European beech trees (80-220 years old). If younger trees had been included in the study, total tree age may have been a more significant variable.

Regression results suggest that a 35 cm diameter tree with an increased *APA* from 30 to 80 m^2 would have a 78% mean increase in radial increment. This strong positive response to increased light intensities due to heavy crown release for European beech is not what would be expected from the traditional theory of growth responses in relation to shade tolerance (HORN 1971; BAZZAZ 1979). Evidence that shade-tolerant trees, which European beech is regarded as, reach asymptotic rates of photosynthesis or carbon gains at moderate light intensities, is, however, based largely on laboratory studies of young seedlings and may not be applicable to advanced canopy trees with large multi-layered crowns that are probably never fully light saturated (LARCHER 1995).

Models based on asymptotic response curves, such as JABOWA and FORET gap models, would predict little or no increase in growth rate attributable to changes in solar radiation following crown release of dominant shade-tolerant canopy trees, not only because of the underlying asymptotic equation, but also because competition for light in these models is assessed only in a vertical dimension above the top of a tree crown (BOTKIN et al. 1972; SHUGART 1984; BOTKIN 1993).

In addition, the results from DHÔTE'S (1990; 1996) individual tree model for European beech, predicted similar behavior for this shade-tolerant species. This model was based on eight long term experimental plots, comprising of 317 European beech trees. He hypothesized that this behavior can be explained by the phenomena that "the gross yield per unit area of a shade-tolerant species is almost independent of density (saturation), as long as the openings are not too large" (DHÔTE 1994).

As it can be seen, how much of the observed growth increase after crown release is attributable to changes in solar radiation versus other factors, such as changes in soil moisture and nutrient availability, is not well known for central European hardwood forests.

Growth models using detailed distant dependent individual tree measurements of competition, such as percent change in *APA* (%*APA*), and *APA* directly after release (APA_{after}), had less unexplained variation in this study than models using the number of unrestricted crown sides by competitors. It is suspected that this outcome partly reflects the greater difficulty in accurately reconstructing past crown competition levels compared with the more straightforward task of reconstructing past stem sizes. However, it is also likely that, among trees of equal crown exposure, growth may be additionally influenced by overall root competition and distance to the nearest competitors, factors better represented by *APA* measures.

Although model projections suggest 35 cm diameter trees can reach a 65 cm threshold within about 50 years, more detailed individual tree level models with mortality functions will be needed to accurately examine the effect of transformation processes on overall structure. Stands managed under transformation schemes, where individual trees are provided *APA* levels of over 100 m^2 for 50 years, might meet minimum structural standards of forest in the early stages of transformation. However, it will take much longer than 50 years for a significant proportion of the upper-canopy trees to reach a mean diameter of 60-65 cm, which is the aim of the state forest administration for steady state mixed forests located in the southern Black Forest (MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) 1993).

Although, the most dramatic responses are achieved through fairly heavy release, maintaining stands at relatively low stocking levels does not in practice require the repeated felling of a large proportion of trees after the first treatment, a point that is especially relevant for forest transformation management. Once density is reduced to the desired level, the percentage of canopy trees cut in subsequent treatments could be determined by the stand growth rate and treatment level.

5.2.2 Height Increment

Both a direct analysis of height increment rates of subject trees before and after treatment, and comparisons of post-treatment increment for treated and untreated trees, indicate that height increment rates of advanced European beech are independent of release.

For the combined data set from the four study sites there was no significant correlation between percent change in height increment and other measured variables. This result was not unexpected, as several studies have previously indicated that height increment is somewhat insensitive to changes in stocking, except at extremely low or extremely high stocking levels (DAHMS 1974; CARMEAN 1975; SCHMIDT et al. 1976; SEIDEL 1984).

For both the non-linear and linear post release height increment models, only combinations of total tree height (*H*), relative height $(H / \overline{H})$, live crown ratio (*LCR*) and percent exposed crown projection area (%*ECPA*) were used. Only these crown-based equations were used because the diameter, age and change in competition based variables (D, $D / \overline{D}$, *age*, APA_{after}, *NUCS*) accounted for less than 10% of the observed variation in annual height increment as single terms and were non-significant variables in the multiple-term equations. This result, as previously stated, tends to support the thesis that height increment is independent of crown release for the data collected in this study.

Height increment models were analyzed combining the four data study sites together independent of site. The justification for combining data from different site qualities was based upon the top height curves of SCHOBER (1969). It can be seen from Figure 32 that for trees of an advanced age that the relative importance of site quality is less as the age of the trees increases. As the data for the analyses in this study are limited to advanced trees with an minimum age of 80 years old and in general in excess of 120 years old the effect of pooling data from different sites is estimated from SCHOBER (1969) as being approximately 2-3 cm in the worst case.

Figure 32 also provides a possible explanation of why height increment from the data set for this specific study was found to be independent of age. It can be seen from the figure that the older the trees are the less effect age has on the height increment. The trees sampled in this study are of an age that corresponds with the flat area of the curves.

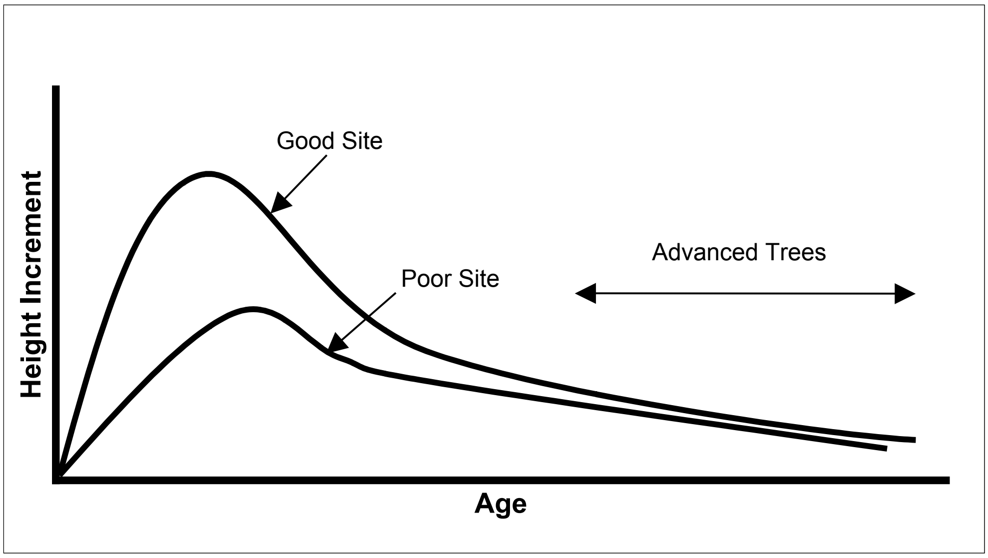

Figure 32: Schematic diagram of the theoretical height increment curves for two different site qualities (adapted from ASSMAN (1961))

The pooled non-linear advanced European beech height increment equation (Table 12), used to generate the response surface for annual height increment, total height and percent exposed crown projection area in Figure 28, provides some evidence supporting certain tree height increment theories. It has been shown that height increment rates of larger trees are somewhat insensitive to changes in stocking except at extremely low or extremely high stocking levels. This trend is explained in Figure 28 as a diminishing effect of release (increased %*ECPA* up to 50%) as tree height increases. For trees of all observed heights, height increment shows an asymptotic response as percent exposed crown projection area exceeds 50%. This might suggest that the terminal portion of advanced European beech tree crowns are light saturated at approximately 50% exposed crown projection area, although there is no evidence to suggest that the lower and internal portions of the crowns, or the crown as a whole, are at their light saturation points.

A continuous non-linear equation was developed for trees ranging in total height from 25-45 m. The combination of total height (crown-based initial size term) and percent exposed crown projection area (crown-based competition term) explained 34% of the total observed variation in the height increment rates.

In the present study, once percent exposed crown projection area was accounted for in the linear equations (by partitioning the data into low, medium and high %*ECPA* classes) total height explained from 7-29 % of the observed variation in height increment for the combined data set. The separation of data into subsets for the fitting of non-continuous linear equations imposes certain limitations on the resulting models. In cases where assumptions of linear regression are important, such as in stochastic simulations, where the distribution of errors about the predicted curve, or in situations where assumptions can be made about holding percent exposed crown projection area constant during a simulation, these linear equations provide the user with that option.

5.2.3 Crown Expansion

The mean lateral crown radius increment rates of 9.2 $cm.year^{-1}$ for all gap branches, and 13.5 $cm.year^{-1}$ for gap branches on intermediate crown class trees, are similar to increment rates reported for advanced European beech by GUERICKE (2001). The maximum observed lateral branch length increment rate for advanced European beech was 50.2 $cm.year^{-1}$, but this is not representative of the overall data set. The maximum advanced European beech increment rate of trees used in this study was similar to that of the 42.1 $cm.year^{-1}$ calculated by GUERICKE (2001). The estimated mean direct increment rates in this study are surprisingly similar to the indirect increment rates calculated by GUERICKE (2001), given the differences in location and stand histories among the studies. No strong evidence has been presented here, or in previous studies, to suggest that the particular crown radius increment estimation method employed in this study significantly biased the results.

Strong size-related trends in individual-tree increment rates are reflected in highly significant regression parameters for total tree height in predictive crown radius increment equations, and were previously reported for basal area and height increment relationships. This result suggests that the extrapolation of mean increment rates may not be suitable for long-term projections of gap related processes over periods of several years or several decades. Gap closure is a function of numerous size-related factors, such as border tree height and lateral crown radius increment, gap tree height increment and gap longevity. These size-related trends should be incorporated into forecasts of gap closure whenever possible.

The mean proportion represented by H_w/H for European beech was also very stable among all crown classes (Table 5), which suggests that the variable may be comparable for different total canopy heights. More research is needed to determine whether the proportional crown architectural variable H_w/H is similar to other southern Black Forest sites.

Since the crowns of forest grown hardwood trees can often become quite asymmetric it is important to understand the mechanisms of this asymmetrical crown development if individual-tree simulation models, capable of accurately predicting the small-scale spatial dynamics of uneven-aged stands, are to be developed. Results from this study suggest that the magnitude of the variation can be large, over 200% in some cases. However, most of this variation was uncorrelated with any of the measured variables in this study. Several lines of evidence suggest that such variation may be largely random. Results of an analysis of variance on gap versus non-gap branch length increment rates showed only weak trends that conform to the intuitive pattern, that gap branches grow at higher rates than non-gap branches.

Two hypotheses of lateral crown radius increment patterns have been presented in the literature that would explain the development of asymmetrical crowns in hardwood trees. One hypothesis, a release model, suggests that tree crowns respond to adjacent canopy openings with increased lateral crown radius increment rates for some time after gap formation. This accelerated increment response is outlined in RUNKLE (1982) and RUNKLE & YETTER (1987). A second hypothesis, one of crown shyness, proposes that the branches of a crown grow until the physical proximity of an adjacent crown somehow becomes limiting. In other words, asymmetric crown development simply may be due to the availability of growing space in a given direction. MITCHELL (1969) reported for white spruce that “branches facing potential competitors show a slight decline in the rate of growth immediately before the crowns make contact”. He further stated that branches just above the point of crown contact grew slightly yet significantly less than branches without direct spatial competitors. Experimental evidence in a lodgepole pine stand also tends to support the crown shyness mechanism for conifers (SMITH et al. 1990). They found that crown swaying and branch intermingling caused significant damage to adjacent crowns, with more crown abrasion and damage as total tree height increased. Little is known about this process in hardwoods. The actual crown expansion process in gap border trees is probably a combination of these two basic mechanisms. Evidence from this study seems to support the accelerated crown radius increment hypothesis for smaller trees with relatively poor overall crown positions. Larger trees in a more exposed position did not respond as well to release. The same patterns of asymptotic increment rate response, in relation to increasing percent exposed crown projection area, were seen for tree height increment rates.

5.2.4 Gap Model

A dramatic difference between the deterministic and stochastic gap closure models was seen for gap tree height increment rates and predicted success. On average, approximately 40 % of the simulated trees were predicted to reach a competitive canopy position, as defined by the average H_w/H of the four border trees, before border tree crown expansion closed the gap (Model 3). Whereas predicted mean tree increment rates indicated that no trees would be successful (Models 1 and 2). Growing trees at the upper 90th percentile growth threshold resulted in more than double the rate of gap tree success, with 83-97% of the simulated trees becoming part of the canopy. If it is assumed that there are 30 trees in a typical 10 m diameter gap, there will be an average of three gap trees growing at, or above, this threshold rate. A 10 m diameter gap is approximately 79 m^2, therefore 30 trees is equivalent to a tree density of just under 3800 trees/ha. A parallel study within the BMBF project (C2) has reported a mean density for 1 to 7 cm diameter trees of 17,616 $stems.ha^{-1}$ for stands with a wide range of stocking levels in the southern Black Forest. Based on these estimates, the assumption that there are at least three trees in the 90th percentile in a typical 10 m gap is fairly conservative.

The stochastic variation in initial border tree sizes and lateral crown radius increment rates in Model 3 resulted in up to 17% of 10 m diameter gaps being closed by lateral crown radius increment in under 50 years, while the mean was more than 50 years for the deterministic models (1 and 2). The critical gap diameter, where the primary gap closure process is predicted to change from border tree expansion to tree accession, lies somewhere between 2.5 m and 10 m . The largest gaps in the simulations were usually successfully occupied by the younger age-class trees, while the 2.5 m diameter gaps were closed over primarily by lateral expansion of the border trees.

5.3 PRACTICAL IMPLICATIONS

There were two major findings that can be derived from the study, which may have practical importance for forest managers; the basal area response of advanced European beech to release and the minimum gap size required for uneven-aged transformation. These two practical implications are briefly described here.

The Basal Increment Response of Advanced European Beech to Release

The direct analysis of basal area increment rates of subject trees before and directly after release, and the comparison of post-treatment increment rates for released and unreleased trees, generally supports the theory that the basal area increment of advanced European beech at a height of 1.3 m can be increased by an average of 70-100 % through heavy crown release.

This result has important implications for forest practitioners. The general transformation process has certain attributes of risk. Through careful crown release this risk may be reduced by increasing the growth and speeding up the stabilization of the advanced perpetual canopy cover trees.

Minimum Gap Size Required for Uneven-aged Transformation

The stochastic simulations of gap closure in this study generally support the use of canopy gaps greater than 10 m in diameter for transforming even-aged stands into more structured uneven-aged stands. One objective of creating such openings is to promote the growth of trees in gaps into competitive canopy positions. Gap sizes of roughly 10-15 m diameter were predicted to be successfully occupied by at least one fast growing tree in most cases. In addition, stand entry cycles of 10-20 years would allow for the successive release of trees in 10-15 m diameter gaps.

5.4 LIMITATIONS OF THE STUDY

While the present study has two major implications for forest practitioners, any conclusions drawn from this study must be tentative in nature. Section 1.6 in Chapter 1 has already outlined the major limitations of the research, certain conditions that were beyond the researcher's control. This section further discusses these limitations, especially with respect to aspects that became apparent during the progress of the research. Limitations have been divided into two categories, ones that directly affect the internal validity of the study and ones that affect the external validity of the study.

Internal Validity

Internal validity occurs when a researcher controls all extraneous variables and the only variable influencing the results of a study is the one being manipulated by the researcher. This means that the variable the researcher intended to study is indeed the one affecting the results and not some other, unwanted variables. The following are the main threats to the internal validity of the study:

Non-random selection

Due to the non-random selection of the trees in this study the applied statistical analysis conducted are not fully appropriate. All classical statistical and regression analysis assume that the observations are randomly selected. The sampling system used in this study might more appropriately be termed an "incidental sample", i.e. in which subjects were selected on the basis of availability. While this may be an inherent aspect of this kind of quantitative research it must be mentioned.

Spatial Auto-correlation

In addition, due to approximately 40 subject trees being taken from each study site, there is the possibility that the subject trees within a site are spatially auto-correlated. Spatial auto-correlation occurs when the measurements from adjacent trees are used as predictor variables for each other and from environmental variation within the stand. All classical statistical and regression analyses assume observations are independent. Therefore, the applied statistical analysis conducted within this study are not fully appropriate.

Ex-post facto

The analyses for this study are based on an *Ex-post facto* methodology rather than a controlled experimental design. Causation can only be tested when a researcher controls all extraneous variables and the only variable influencing the results of a study is the one being manipulated by the researcher. This is not the case in this study. Consequently, causation can not be attributable to any of the observed correlations within this study.

Confounding effect of site quality, treatment and climate

Another weakness associated with this study stems from the fact that site quality is heavily confounded with treatment, climate and temporal effects. The different treatments within each stand occurred over different periods of time and under different climatic conditions. It is impossible to isolate these confounded effects with the data from this study without long-term replicated experimental trials. Because of this confounding, each site has not been directly modeled within the data analysis of this study.

External Validity

The external validity of a study refers to the extent to which the results can be generalized to other studies. The following are threats to the external validity of this study:

Replication

Due to the limited amount of material (170 trees) involved, from a limited number of areas in the southern Black Forest (4 study sites), statements about whether the findings of this study can apply with equal validity to a larger population (the whole southern Black Forest) are speculative at best. To improve the external validity of the research within this project, the study needs to replicated over a range of sites.

Repeatability

The study was also restricted with regard to the individual characteristics of the selected trees. Since these data were gathered retrospectively within a relatively short period of time there is no method in the procedures to measure how these characteristics may be expected to change in the near future. In short, these retrospective descriptions may not be a reliable description of the sample in some future re-testing period.

5.5 SUGGESTIONS FOR FUTURE RESEARCH

This study presents a single tree level analysis of retrospective data derived from four stands in the southern Black Forest during the winters of 1999 to 2001. Some progress has been made towards answering the four main questions asked in the first chapter of this thesis. However, to obtain a thorough understanding of crown release as a tool for aiding the transformation of European beech forests, a considerable amount of research remains to be done. Through recognition of the limitations of this current research project, the following are suggested as a range of subsequent research, both exploratory and confirmatory, that could refine the understanding of crown release of European beech in transition:

1. expansion of the results to the stand level;
2. replication of the study;
3. examination of the release response over time;
4. examination of the release response of younger trees.

Expand the Results to the Stand Level

To accurately examine the effect of transformation processes on overall structure, it is recommended that more detailed individual tree level models with mortality functions be developed. However, there are some limitations associated with this approach: permanent plot data rarely contain the detailed measurements necessary for formulating such models and the cost of obtaining such detailed data tends to restrict the application of such models to research, rather than practical applications. Therefore, to facilitate the extension of this research into practice these individual models should be aggregated to the stand level. It also tends to be only at the distant independent stand level that results are utilized by forest practitioners. This aggregation to the stand level requires the spatial elements of the analysis to be replaced with some non-spatial stand measures.

Replication of the Study

As mentioned earlier, the combined four study site focus of this study may limit the application of results to the whole southern Black Forest. An important extension of this study would thus be to conduct similar analysis using data from different sites to see whether the same results are achieved. This type of replication would add robustness and allow the effect of site on the release response of advanced European beech to be investigated. This type of research would greatly enhance the external validity of this study.

Trends in the Release Response over Time

The release response estimator in this study has been calculated assuming that the response is a simple ratio over a 10 year period. However, it can be hypothesized that the biological affect of releasing is not a simple ratio, but begins at zero and increases to some maximum, then diminishes and approaches a pre-released condition. This hypothesised response has two particular attributes that would be interesting to investigate. Firstly, when does the release response peak and secondly, how long does the response last. These two attributes provide interesting insight into the required frequency of intervention to ensure maximum growth rates.

Examine the Effect of Release Response on Younger Trees

This study has focused on investigating the release response of advanced European beech. No attempt has been made to quantify the response of young trees. It may be useful to extend this type of analysis to younger trees to investigate whether tree age is an important variable for quantifying release response. As previously stated tree age was not found to be a significant variable in this study, but this may be a consequence of restricting the sampling to advanced European beech trees only. Therefore, incorporating younger trees into this type of research may increase the understanding of the effect of age on the crown release of European beech as a tool in aiding the transformation process.

6 SUMMARY

This study makes some contributions to the understanding of crown release of European beech as a tool to aid the transformation of stands in the southern Black Forest. The study looked at several factors, which could be related to the growth reaction of a tree responding to release. These factors included the current level of competition to which the tree is subjected, change in competition levels, tree size and tree age. The dependent variables modeled in this study included diameter increment at breast height, height increment and crown radius increment. The following objectives provided the main focus of the study:

1. to demonstrate that the basal area increment response of advanced European beech trees to release is correlated with initial tree size, relative tree size, tree age and local competition terms;
2. to demonstrate that the height increment response of advanced European beech trees to release is correlated with initial tree size, relative tree size, tree age and local competition terms;
3. to demonstrate that the crown expansion of branches in gaps is greater than that of branches overlapped by competitors;
4. to demonstrate the appropriate gap size for transformation processes using gap simulation.

Chapter 2 is a review of the literature relevant to the study. The analysis of the literature relating to the history of European beech in the southern Black Forest, and the role of close-to-nature forestry within this area, indicates that this species has an important part to play in transformation forests.

The literature also revealed many issues of concern in respect to previous studies of close-to-nature forestry, in terms of methodology and analysis, and the appropriateness of comparisons to current silvicultural systems. Although, there have been numerous studies comparing close-to-nature forestry to even-aged systems, little research into quantifying the transformation from even-aged forestry to close-to nature forestry has been conducted.

Further analysis of the literature revealed the importance of advanced European beech trees in the transformation process, particularly their role in maintaining perpetual cover in the upper story, stabilizing the stand, and in providing economic returns and structural diversity.

The literature on quantifying the growth response following release was also reviewed. A definition for growth response was developed from the literature. A comparison of the benefits of individual tree-level versus stand-level investigations was discussed. This was important in determining what type of variables were appropriate for this study. A short annotated bibliography of competition indices suitable for individual tree investigations was created from the literature. Special focus was applied to the Area Potential Availability index (*APA*), as HAHN (1995) had previously found it to be a suitable index for modeling European beech growth.

The literature analysis also summarizes the data collection methods appropriate for transformation researchers. Due to the lack of long-term experiments focusing on the silvicultural aspects of transformation, the advantages and disadvantages of *Ex-post facto* studies were examined. In particular, the use of analytical methods for the reconstruction of radial increment, height increment and crown width increment, such as dendrochronology and internode analysis, were reviewed.

The specific null-hypotheses (NH) posited for testing in the study were as follows:

NH1) There is no significant difference, at the 0.05 level of statistical confidence, in the basal area increment of advanced European beech trees during the period from before to after heavy release;

NH2) There is no significant difference, at the 0.05 level of statistical confidence, in the height increment of advanced European beech trees during the period from before to after heavy release;

NH3) There is no significant difference, at the 0.05 level of statistical confidence, in the increment of an exposed branch to that of an unexposed branch for advanced European beech trees;

NH4) A gap diameter of 10 m is insufficient in size, at the 0.05 level of statistical confidence, to assure the recruitment of a 4 m high gap tree into the canopy.

Study sites were established in four European beech stands in the southern Black forest, that had been subjected to a range of cutting intensities over the last 25 years. The sites were located on fresh brown earth. Species composition was primarily European beech, Norway spruce and silver fir in the overstory, with European beech and Norway spruce dominating the understory.

A two stage sampling procedure was used for the data collection. In the first stage, using non-destructive measures, the range of past and current competition scenarios within each of the four study sites was estimated from 300 trees per site. During the second stage, a smaller sample of 50 trees per study site, uniformly representing the initial sample, were selected for destructive measurement. This two stage sampling scheme was successful in ensuring a wide range of competition scenarios. In the process of measuring this secondary sample, 30 trees were damaged during the felling process. The remaining 170 tree were analyzed using dendrochronology and branch analysis to test the posited hypotheses.

The results section was broken into four parts, associated with the four hypotheses. The first section deals with changes in basal area increment due to heavy crown release. Advanced European beech was found to increase by an average of 70-100% through heavy release. Under conditions of low competition even relatively old trees appear to be able to maintain a rapid growth rate for long periods. Equations predicting the percent change and annual increment of basal area were developed as a function of *APA* directly after release and the number of unrestricted crown sides (*NUCS*).

The second section of the results chapter relates to the effect of release on height increment. For the combined data set from the four study sites, there was no significant correlation between percent change in height increment and other measured variables. Linear and non-linear height increment equations were developed using initial height (*H*), live crown ration (*LCR*) and percent exposed crown projection area (*%ECPA*).

A non-linear annual height increment equation, using initial height and percent exposed crown area, was developed that explained 34 % of the total observed variation in European beech trees across a wide range of tree sizes and competitive positions within the canopy. Height increment was found to be independent of age. This seems to be due to the advanced age of the trees sampled.

The third part of the results section focuses on the lateral crown radius increment rates of European beech canopy trees following selective cutting. There was a great deal of variation in mean branch length increment within individual tree crowns, ranging from –100% to +200% of the mean whole-crown radial increment. Predictive equations were developed for mean crown radius increment. Total height was the single most important independent variable for prediction.

The final part of the results section focused on gap closure simulations. Gap closure simulations using four equally spaced European beech trees around circular gaps of 2.5, 5.0, 10, 15 and 20 m diameter, with a centrally located European beech tree, suggested that the projections of the gap closure process, based only on mean lateral crown radius increment and tree height increment rates, may not represent the actual process very well. Deterministic simulations for the 10 m diameter gaps, with border tree crown expansion and tree height increment rates estimated by the equations developed, indicated that trees would not reach the crown contact of the four border trees in under 50 years. Simulations using stochastic variation based on variance patterns predicted that 37 to 40 % of randomly selected trees could reach the canopy before the gap closed over due to lateral crown expansion. Predictions made with the 90th percentile predicted tree growth rate, believed to be a conservative estimate of the fastest growing trees in the gap, indicated that 83 to 90 % of the 10 m diameter gaps have at least one successful tree that reached the height of border tree crown contact before lateral crown radius increment from the border trees closed the gap and overtopped the trees. The increment rates, predictive equations and stochastic simulations presented in this study suggest that gap diameters of 10-15 m, are appropriate for the efficient conversion of even-aged stands to uneven-aged stands, and are large enough to permit some gap trees to reach the competitive canopy positions within periods of suppression.

The main aim of the research in this study was to explore crown release of European beech as a tool to aid the transformation of stands in the southern Black Forest. The research hypothesis, which spawned from this, covered the three main tree growth attributes; basal area, height and crown width, and their importance to gap closure simulation.

Although some of the specifics of the analyses are lost when generalizations are made, taken all together, the results suggest the following broad conclusions:

- basal area increment of advanced European beech can be increased by up to 100% by heavy crown release;
- height increment of advanced European beech is little affected by crown release;
- on average, branches growing in gaps have an annual lateral expansion rate 3 cm greater than branches not grown in gaps;
- minimum canopy gaps of 10 m in diameter are required to recruit 4 m gap tree into the canopy.

7 ZUSAMMENFASSUNG

Diese Untersuchung möchte zu einem besseren Verständnis der Wachstumsreaktionen von Buchen beitragen. Dabei soll mit dem vorliegenden Konzept eine Hilfestellung zum Umbau von Waldbeständen im Südschwarzwald vorgelegt werden. Die Untersuchung erstreckt sich auf verschiedene Einflussfaktoren, die jeweils einen potenziellen Einfluss auf die Wachstumsreaktionen von älteren Buchen nach Freistellung haben können. Zu diesen Faktoren zählen der augenblickliche Konkurrenzstatus des Baumes, die Veränderung des Konkurrenzsituation, die Dimension des Baumes und das Baumalter. Als abhängige Variablen standen im Zentrum der Untersuchung das Durchmesserwachstum in Brusthöhe, das Höhenwachstum und die horizontale Veränderung des Kronenradius. Folgende Zielsetzungen wurden im Rahmen dieser Untersuchung angestrebt:

1. es soll überprüft werden, ob der Grundflächenzuwachs älterer Buchen im Zusammenhang steht mit der ursprünglichen Baumdimension, der relativen Baumdimension, dem Baumalter und den lokalen Konkurrenzverhältnissen;
2. es soll überprüft werden, ob die Reaktion des Höhenzuwachses älterer Buchen auf Freistellung im Zusammenhang steht mit der ursprünglichen Baumdimension, der relativen Baumdimension, dem Baumalter und den lokalen Konkurrenzverhältnissen;
3. des weiteren soll überprüft werden, ob das Längenwachstum von in Bestandeslücken hinein wachsenden Ästen größer ist als dasjenige von Ästen, die durch benachbarte Bestandesbäume beschattet werden;
4. schließlich soll ein Modell zur Berechnung Mindestgrößen für Verjüngungslücken vorgestellt werden.

Im Kapitel 2 erfolgt ein Literaturüberblick zum Themenkomplex der vorliegenden Untersuchung. Aus der Analyse der Literatur zur Geschichte der Rotbuche im Südschwarzwald und der augenblicklichen Bedeutung naturnaher Forstwirtschaft in diesem geographischen Raum ist ersichtlich, dass dieser Baumart eine wichtige Position bei der Überführung von Beständen zukommt.

In der bisherigen Literatur werden sehr zahlreich Problemstellungen diskutiert, die in engem Zusammenhang mit einer naturnahen Waldbewirtschaftung gesehen werden müssen, wie zum Beispiel spezielle wachstumskundliche Analysemethoden oder auch vergleichende Gegenüberstellungen verschiedener Waldbausysteme. Trotz dieser zahlreichen Vergleiche verschiedener Formen naturnaher und altersklassenweiser Forstwirtschaft, liegen bislang nur wenig Forschungsarbeiten vor, die sich über einen quantitativen Ansatz mit der Überführung altersklassenweiser Wälder hin zu naturnahem Waldaufbauformen beschäftigen.

Darüber wurde im Verlauf der Literaturstudie die herausragende Rolle älterer Buchen deutlich, insbesondere wegen ihrer Dominanz in der Kronenschicht, der Bestandesstabilität, der wirtschaftlichen Ertragserwartungen aber auch zum Aufbau struktureller Diversität.

Zudem wurde die Literatur gesichtet, die sich mit der Analyse von Wachstumsreaktionen beschäftigt. Anhand bisheriger Untersuchungen wurde zunächst der Begriff der Wachstumsreaktion definiert. Zudem erfolgte ein Vergleich der Vorteilhaftigkeit einzelbaumorientierter gegenüber bestandesweisen Untersuchungsansätze. Dies stellte eine wichtige Grundlage für die Entscheidung über die zu erhebenden Wachstumsgrößen dar. Zusätzlich wurde ein kurze Bibliographie von Konkurrenzindizes vorgestellt, die für einzelbaumorientierte Untersuchungen in Frage kommen. Eine besonderer Schwerpunkt lag dabei beim *APA*-Index (Area Potential Available index), der auch von HAHN (1995) in einer früheren Arbeit als geeigneter Indikator zur Modellierung des Wachstums der Buche verwendet wurde.

Die Literaturübersicht fasst darüber hinaus bisherige Methoden der Datengewinnung zusammen, die im Zusammenhang mit der Überführung verwendet wurden. Aufgrund der wenigen langfristigen Versuchsanordnungen zur Untersuchung wachstumskundlicher Aspekte der Überführung, erfolgte zusätzlich auch eine eingehende Diskussion von Vor- und Nachteilen von *Ex-post facto* Untersuchungsansätzen. Insbesondere verschiedene analytische Methoden für die Rekonstruktion des Durchmesser- und Höhenwachstums, sowie des Kronenradius, wie dendrochronologische Methoden oder die Vermessung von Knospenschuppennarben wurden hinsichtlich ihrer Brauchbarkeit für die vorliegenden Zielsetzungen einer kritischen Betrachtung unterzogen.

Folgende Nullhypothesen (NH) lagen den Auswertungen zu Grunde:

NH1) Es besteht kein signifikanter Unterschied (Irrtumswahrscheinlichkeit von $\alpha = 0{,}05$) zwischen dem Durchmesserzuwachs älterer Buchen vor und nach einer starken Freistellung;

NH2) Es besteht kein signifikanter Unterschied (Irrtumswahrscheinlichkeit von $\alpha = 0{,}05$) zwischen dem Höhenwachstum älterer Buchen vor und nach einer starken Freistellung;

NH3) Es besteht kein signifikanter Unterschied (Irrtumswahrscheinlichkeit von $\alpha = 0{,}05$) zwischen dem Astlängenwachstum älterer Buchen von nicht beschatteten und beschatteten Kronenästen;

NH4) Eine Bestandeslücke von 10 m reicht nicht aus (Irrtumswahrscheinlichkeit von $\alpha = 0{,}05$), um das Emporwachsen in die Kronenschicht einer 4 m hohen Buche zu ermöglichen.

Es wurden temporäre Untersuchungsflächen in vier Buchenbeständen im Südschwarzwald angelegt, die in den vergangenen 25 Jahren unterschiedlichen Durchforstungsintensitäten ausgesetzt waren. Die Untersuchungsflächen stockten auf frischen Braunerden. Die Baumartenzusammensetzung war führende Buche mit Fichte und Tanne im Herrschenden und mit überwiegend Buche und Fichte im Unterstand.

Die Datenaufnahme erfolgte in einem zweistufigen Verfahren. In der ersten Stufe wurde in einer nicht-destruktiven Erhebung das Niveau der früheren und aktuellen Konkurrenzsituation innerhalb der vier Untersuchungsflächen für insgesamt 300 Einzelbäume geschätzt. In der zweiten Stufe wurden 50 Bäume je Untersuchungsfläche repräsentativ für die Spannweite der ersten Stufe ausgewählt. Mit dieser zweistufigen

Vorgehensweise konnte eine breite Spanne unterschiedlicher Konkurrenzsituationen erfasst werden. Im Zuge die nachfolgenden Fällarbeiten wurden 30 Bäume beschädigt, sodass lediglich 170 Buchen für die Überprüfung der Nullhypothesen zum Dicken- und Höhen- und Astlängenwachstum zur Verfügung standen.

Die Ergebnisse wurden entsprechend den Nullhypothesen in vier Teile untergliedert. Im ersten Abschnitt wird die Dynamik des Grundflächenzuwachses im Zusammenhang mit starken Freistellungen untersucht. Im Mittel zeigte sich bei den älteren Buchen eine Anstieg des Grundflächenzuwachses um 70 – 100 % nach einer starken Freistellung. Bei geringer Konkurrenz scheinen sogar ältere Buchen über längere Zeit hinweg eine hohes Zuwachsniveau aufrecht halten zu können. Es wurden Funktionsgleichungen entwickelt, mit denen die prozentualen Veränderungen und der jährliche Grundflächenzuwachs als vom *APA* direkt nach der Freistellung abhängige Variablen und der Anzahl der konkurrenzfrei wachsenden Kronensektoren geschätzt werden konnte (*NUCS*).

Der zweite Abschnitt behandelt den Zusammenhang zwischen Freistellung und Höhenwachstum. Für die Gesamtdaten der vier Untersuchungsflächen konnte keine signifikante Korrelation zwischen der prozentualen Veränderung des Höhenzuwachses und anderen Variablen gefunden werden. Es wurden in der Folge lineare und nicht-lineare Gleichungsmodelle entwickelt mit der Ausgangshöhe des Baumes vor der Freistellung (*H*), der relativen Kronenlänge (*LCR*) und dem prozentualen Anteil der schirmfreien Kronenprojektionsfläche (*%ECPA*) (eine Variable, die die relative Position des Baumes in der Kronenschicht und den nach oben frei exponierten Teil der Krone erfasst).

Mit der nicht-linearen Modellgleichung, bestehend aus der Ausgangshöhe des Baumhöhe vor der Freistellung und dem prozentualen Anteil der schirmfreien Kronenprojektionsfläche, konnten 34 % der Gesamtstreung des Höhenwachstums der Buche für eine weite Spanne von Baumdimensionen und Konkurrensituationen erklärt werden..

Der dritte Abschnitt behandelt die Veränderung des Kronenradius von Buchen nach einzelstammweisen Nutzungen. Zwischen den einzelnen Bäumen konnte eine große Variation des Astlängenwachstums festgestellt werden, die sich von – 100 % bis + 200 % des mittleren allseitigen Kronenradius erstreckte. Es fanden sich mehrere Hinweise, dass ein wesentlicher Anteil dieser Streuung der einzelnen Astlängenzuwächse Zufallseffekte darstellt. Für das Wachstum des mittleren Kronenradius wurden geeignete Modellgleichungen aufgestellt. Die Baumhöhe war dabei jeweils die wichtigste unabhängige Variable.

Im letzten Abschnitt der Ergebnisse werden Simulationen zum Zusammenwachsen von Bestandeslücken durchgeführt. Im Zuge dieser Simulationen mit vier konzentrisch um Lücken von 2,5, 5,0, 10, 15 sowie 20 m Durchmesser - mit einer nachwachsenden Buche im Zentrum - und im gleichem Abstand zueinander angeordneten älteren Buchen zeigte sich, dass Vorhersagen zum Bestandesschluß allein mit den Variablen Zuwachs des mittleren horizontalen Kronenradius und Höhenwachstum den aktuellen Wachstumsprozess möglicherweise nicht ausreichend gut wiedergeben.

Mit den deterministischen Simulationansätzen für 10 m breite Bestandeslücke wurde deutlich, dass ein Kronenkontakt der vier Randbäume nicht innerhalb der nächsten 50 Jahre stattfindet. Stochastische Simulationsansätze auf der Basis der zuvor ermittelten

Reststreuung ergaben, dass 37 bis 40 % zufällig ausgewählter Buchen die Kronenschicht erreichen, bevor die Bestandeslücke durch die seitliche Kronenexpansion der vier Nachbarbäume geschlossen ist. Vorhersagen anhand von 90 % Perzentilen des Höhenzuwachses als konservativer Schätzer des am schnellsten in einer Lücke emporwachsenden Baumes zeigten, dass 83 bis 90 % der 10 m breiten Bestandeslücken mindestens eine Buche aufweisen, die erfolgreich in die Lücke der älteren Buchen hineinwachsen kann, bevor der Kronenschluss und damit eine vollständige Überschirmung eingetreten ist. Diese aus den Modellgleichungen abgeleiteten Wachstumsabläufe legen nahe, dass Bestandeslücken von 10 bis 15 m für eine Überführung von gleichaltrigen Beständen in ungleichaltrige Bestände breit genug sind, um einigen Buchen in der Bestandeslücke das Emporwachsen in die Kronenschicht der Altbuchen zu ermöglichen.

Das Ziel dieser Untersuchung war die Analyse des Kronenexpansionsvermögens von Buchen als Hilfestellung zum Umbau von Waldbeständen im Südschwarzwald. Die daraus abgeleiteten Untersuchungsansätze beziehen sich auf die drei zentralen Wachstumsgrößen Grundfläche, Baumhöhe und Kronenbreite und auf deren Bedeutung für Simulationen zum Zusammenwachsen von Bestandeslücken.

Obgleich mit allgemeinen Aussagen einige spezifische Ergebnisse der vorliegenden Arbeit unberücksichtigt bleiben, können dennoch folgende Leitlinien mit weitgehender Gültigkeit formuliert werden:

- das Grundflächenwachstum älterer Buchen lässt sich mit starken Freistellungen auf bis zu 100 % des Ausgangwertes steigern;
- das Höhenwachstum älterer Buchen ist nur in geringem Maße beeinflusst durch Freistellungen;
- im Mittel weisen Äste, die in Bestandeslücken hineinwachsen um 3 cm größere Längenzuwächse auf als Äste, die nicht in Bestandeslücken hinein wachsen;
- bei 4 m großen Buchen stellen Bestandeslücken von 10 m Breite für ein Emporwachsen in die Kronenschicht einen Minimalwert dar.

8 RESUMÉ

Cette étude contribue à mieux comprendre l'impact du détourage des hêtres comme une aide à une irrégularisation des peuplements de Forêt Noire du Sud. Cette étude a pris en considération plusieurs facteurs qui peuvent être mis en relation avec le rendement des houppiers en fonction du détourage. Ces facteurs incluent le niveau actuel de compétition auquel l´arbre est soumis, la variation des niveaux de compétition, la taille et l´âge de l´arbre. Les variables dépendantes modélisées dans cette étude incluent la croissance en diamètre à la hauteur de 1.30 m, la croissance en hauteur ainsi que la croissance radiale. La présente étude était axée sur les objectifs suivants

1. Démontrer que l'accroissement de la surface terrière de hêtres destinés à être détourés est fonction de la taille initiale de l´arbre, de sa taille relative, de son âge ainsi que de son statut social
2. Démontrer que l'accroissement en hauteur de ces hêtres est également corrélé avec sa taille initiale, sa taille relative, son âge ainsi que son statut social
3. Démontrer que l´expansion des branches de la couronne dans des espacements est supérieure à celle de branches recouvrantes des compétiteurs;
4. Evaluer la taille de l´espacement idéal pour le processus de transformation en utilisant une simulation d´espacement.

Le chapitre 2 est une revue de la littérature se rapportant à cette étude. L´analyse de cette littérature qui traite de l´histoire du hêtre dans la Forêt Noire du Sud et du rôle d´ une gestion forestière plus proche de la nature dans cette région, indique que cette espèce a un important rôle à jouer dans la transformation des forêts.

Cette approche bibliographique fut aussi très instructive au sujet des pratiques forestières plus proches de la nature, en termes de méthodologie et d´ analyse ainsi qu'au sujet de la pertinence de comparaisons des systèmes de gestion sylvicole actuels. Bien que de nombreux travaux aient procédé à une comparaison entre des peuplements gérés d'après d'une sylviculture douce et des peuplements équiennes, peu de recherches furent consacrées à une quantification de la transformation de ces derniers vers des peuplements à structure proche de la nature.

Une analyse poussée de la littérature a mis en évidence l´importance des hêtres âgés dans les processus de transformation, en particulier leur rôle dans le maintien d´ une couverture d´ étage supérieur, stabilisant le peuplement et présentant un intérêt économique tout en assurant une diversité de structure.

La littérature concernant la quantification de la croissance en hauteur en fonction du détourage a également été examinée La fonction de réponse de la croissance a été calculée sur la base de cette approche bibliographique. Les avantages respectifs d'une approche au niveau individuel de l´arbre et au niveau d´ un peuplement ont été confrontés. Ceci était important pour déterminer quels types de variables étaient à considérer pour cette étude. Une brève bibliographie annotée des indices de compétition se prêtant pour des études au niveau individuel a été réalisée. Un intérêt particulier a été porté sur l´indice de surface potentiel de disponibilité (*APA*) que Hahn (1995) avait montré comme étant un indice valable pour la modélisation de la croissance des hêtres.

L´analyse bibliographique résume aussi les méthodes de collecte des données dont peuvent s'inspirer des chercheurs impliqués dans une démarche d'irrégularisation des peuplements. En raison du manque d´ expériences à long- termes sur les aspects de la transformation de la sylviculture, on a examiné les avantages et les désavantages d´ études *Ex-post facto*. En particulier, l´utilisation de méthodes analytiques pour la reconstruction de la croissance radiale, la croissance en hauteur et l'accroissement en diamètre de la couronne telle la dendrochronologie et l'approche internode ont été passées en revue.

Les Hypothèses (NH) qu'on se proposait de valider étaient les suivantes:

NH1) Il n´ y a pas de différences significatives au seuil de 0.05 de confiance entre l'accroissement de la surface terrière de hêtres avant et après les opérations de détourage;

NH2) Il n´ y a pas de différences significatives au seuil de 0.05 de confiance dans l'accroissement en hauteur des hêtres entre la période comprise avant et après le détourage;

NH3) Il n´ y a pas de différences significatives au seuil de 0.05 de confiance entre l'accroissement en longueur d´une branche de hêtre exposée et celui d'une branche non exposée;

NH4) Un espacement de 10 m de diamètre est insuffisant, au seuil de 0.05 de confiance, pour assurer le recrutement dans la canopée d´ un jeune arbre de 4 mètres de hauteur.

Les sites d´ étude ont été sélectionnés dans quatre peuplements de hêtres du sud de la Forêt Noire qui avaient fait l'objet de coupes intensives durant 25 ans. Les sites étaient localisés sur des substrats à sols bruns frais. L'étage supérieur était dominé par des hêtres, de l´épicéa et du sapin alors que la strate inférieure était composée de hêtres et d´épicéa.

Une procédure de collecte de données en deux étapes a été utilisée. Dans la première étape, on a appréhendé pour les quatre sites les scénarios de concurrence passés et actuels en faisant appel à des techniques non destructives, l'échantillonnage retenu étant de 300 arbres par site. Pendant la seconde étape, un nombre réduit de 50 arbres par site représentatif de l´échantillon initial a été sélectionné pour des mesures destructives. Cette procédure de collecte de données en deux étapes a permis d'obtenir un large éventail de scénarios de compétition. Lors de la collecte de ces seconds échantillons, 30 arbres ont été endommagés par l´abattage. Les 170 arbres restants ont été analysés par dendrochronologie et analyse de la branchaison pour tester les hypothèses à valider.

La section traitant des résultats a été divisée en quatre parties, associées aux quatre hypothèses. La première partie traite des variations d'accroissement de la surface terrière suite au détourage. Il a été montré que les hêtres âgés ont affiché une croissance moyenne de 70-100% après le détourage. Dans des conditions de faible compétition, même des arbres relativement âgés semblent en mesure de pouvoir soutenir une vitesse rapide de croissance pendant de longues périodes. Les modèles prédisant le pourcentage de variation et le changement annuel de la surface terrière ont été développés à partir de l'*APA* directement après détourage et du nombre non limité de côtés des couronnes(*NUCS*).

La seconde partie des résultats porte sur l´effet du détourage sur l´augmentation de taille. Pour la combinaison des donnés provenant des quatre sites d´ étude, il n´y avait pas de corrélations significatives entre le pourcentage de variation en croissance en hauteur et d´ autres variables mesurables. Les équations linéaires et non linéaires de croissance en hauteur ont été développés en utilisant la taille initiale (*H*), la part des couronnes en vie (*LCR*), et le pourcentage de la surface de projection de la couronne exposée (*%ECPA*).

Une équation non linéaire de croissance en hauteur utilisant la taille initiale et le pourcentage de la surface de la couronne exposée a été développée. Elle explique 34% de la totalité de la variation chez les hêtres pour un large éventail de tailles d´ arbres et de statuts de compétition dans la canopée. La croissance en hauteur était très prononcée dès lors que le pourcentage de la surface de la couronne exposée (une variable donnant la position d´ un arbre dans la canopée et son exposition aux rayonnements directs) augmente pour les arbres avec moins de 50% de la surface de la couronne exposée. Toutefois l´augmentation était plus forte pour les plus petits arbres.

La troisième partie des résultats traite de l'accroissement latéral en diamètre de la couronne des hêtres de la canopée après une coupe sélective. On a relevé de fortes variation parmi les accroissements en diamètre des couronnes des arbres, de l'ordre de – 100% à +200% par rapport à la croissance moyenne du diamètre des couronnes . Bien des évidences ont suggéré qu´ une part substantielle de la variation observée pour la croissance en longueur des branches était fortuite. Des modèles prévisionnels ont été développés pour la croissance radiale moyenne de la couronne. La hauteur totale était la seule variable intervenant de manière notable dans ce modèle. La dernière partie des résultats traite des simulations de la fermeture des espacements. Les simulations de fermeture des espacements basées sur quatre hêtres équidistants dont les espaces disponibles ont respectivement 2,5 5 10 15 et 20 m de diamètre par rapport à un hêtre central font apparaître que les projections du processus de fermeture de l´espacement qui se réfèrent uniquement à la croissance radiale moyenne de la couronne et la croissance en hauteur des arbres, ne reflètent pas correctement le processus. Les simulations pour les espacements de 10 m de diamètre pour lesquels on a estimé l'expansion de la couronne des arbres contigus ainsi que leur taille en appliquant les modèles proposés indiquent que les couronnes des quatre arbres contigus ne se toucheraient pas avant 50 ans.. Les simulations utilisant les variations stochastiques basées sur les profils de variance suggèrent que 37 à 40% des arbres sélectionnés au hasard peuvent atteindre la canopée avant la fermeture de l´espacement consécutive à l´extension latérale de la couronne. Les prédictions se rapportant à une croissance en hauteur au seuil des90 % considéré comme s'appliquant aux arbres à la croissance la plus rapide indiquent que 83 à 90% des espacements de 10 m comportaient au moins un arbre atteignant la hauteur de contact avec la couronne voisine avant que la croissance radiale de la couronne des arbres voisins ne ferme l´espacement et ne dépasse les arbres. Les taux de croissance, les modèles prévisionnels et les simulations stochastiques présentées dans cette étude suggèrent que des espacements de diamètre 10-15 m peuvent être adoptés pour une conversion efficace des peuplements équiennes en des peuplements à classes d'âge variable. Ils sont suffisamment importants pour permettre à quelques arbres des trouées d´être concurrentiels au sein de la canopée au cours des périodes de détourage???

L'objectif prioritaire de la présente étude était d'appréhender la contribution du détourage chez le hêtre comme un moyen d'aide à l'irrégularisation des peuplements du Sud de la Forêt Noire. L´hypothèse de recherche qui y est associée relève des trois principaux paramètres de croissance: la surface terrière, la hauteur et la largeur de la couronne ainsi que leur rôle respectif pour la simulation de fermeture des espacements.

Bien que certaines spécificités des analyses soient masquées quand on procède à des généralisations, on peut tirer les conclusions générales suivantes:

- L'accroissement de la surface terrière du hêtre peut-être augmenté de 100% par détourage;
- La croissance en hauteur du hêtre est peu affectée par le détourage
- En moyenne, les branches poussant dans les espacements ont une expansion latérale annuelle de 3 cm supérieure à celles poussant ailleurs;
- Des espacements minimaux de 10 m de diamètre de canopée sont nécessaire pour recruter pour la canopée des arbres à espacement de 4 m.

9 REFERENCES

ABETZ, P.; UNFRIED, P. (1984): Fichten-standraumversuche im Forstbezirk Riedlingen/Donau. Allgemeine Forst- und Jagdzeitung 155, 89-110

ADAMS, W. R. (1935): Studies in tolerance of new England forest trees XII: Effect of thinning in plantations on some of the physical factors of the site and in the development of young Northern White Pine (*Pinus strobus* L.) and Scotch Pine (*Pinus silvestris* L.). Dissertation: Yale School of Forestry, New Haven. 156p.

ALBERT, M.; GADOW, K. v. (1999): Strukturparameter als Kontrollinstrumente für Überführungsvorhaben. In: HANEWINKEL, M. (eds.): Überführung von Altersklassenwäldern in Dauerwälder. 14-37

ALEXANDER, R. A.; EDMINSTER, C. B. (1977): Regulation and control of cut under uneven-aged management. USDA Forest Service, Research Paper RM-182, Fort Collins, CO. 7p.

ALMEDAG, I. S. (1978): Evaluation of some competition indexes for the prediction of diameter increment in planted white spruce. Information Report FMR-X-108. Canadian Forestry Management Institute, Ottawa. 39p.

ALTHERR, E. (1971): Wege zur Buchenstarkholzproduktion. Festschrift zur 15. Hauptversammlung des Baden-Württembergischen Forstvereins. 127p.

ALTHERR, E.; UNFRIED, P.; HRADETZKY, J.; HRADETZKY, V. (1974): Statistische Rindenbeziehungen als Hilfsmittel zur Ausformung und Aufmessung unentrindeten Stammholzes Teil I: Kiefer, Buche, Hainbuche, Esche und Roterle. Mitteilungen der Forstlichen Versuchs und Forschungsanstalt Baden-Württemberg, 61. 137p.

ASSMANN, E. (1961): Waldertragskunde. BLV Verlagsgesellschaft, München. 490p.

ASSMANN, E. (1965): Der Zuwachs im Verjüngungsstadium. Zentralblatt für das gesamte Forstwesen 82, 193-217

AVERY, T. E.; BURKHART, H. E. (1983): Forest measurements. 3rd Edition. McGraw-Hill Book Co, New York, NY. 331p.

BAUER, E. (1962): Der Soonwald im Hunsrück : Forstgeschichte eines deutschen Waldgebietes. Dissertation: Albert-Ludwigs-Universität, Freiburg. 250p.

BAUER, F. W. (1921): Entwicklung der Waldwirtschaft in den Gemeindewaldungen des oberen Kinzigtales (Schwarzwald) im Laufe des 19. Jahrhunderts - Ein Beitrag zur Geschichte des Waldbaus. Dissertation: Albert-Ludwigs-Universität, Freiburg. 56p.

BAZZAZ, F. A. (1979): The physiological ecology of plant succession. Annual Reviews Ecology and Systematics 10, 351-371

BELCHER, D. W.; HOLDAWAY, M. R.; BRAND, G. J. (1982): A description of STEMS - the stand and tree evaluation and modeling system. USDA Forest Service, General Technical Report NC-79, St. Paul, MN. 18p.

BELLA, I. E. (1971): A new competition model for individual trees. Forest Science 17, 364-372

BIEHL, H. (1996): Die Laubholzplenterwälder in Nordwest-Thüringen. Allgemeine Forstzeitschrift 51, 492-494

BIGING, G. S.; DOBBERTIN, M. (1992): A comparison of distant-dependent competition measures for height and basal area growth of individual conifer trees. Forest Science 38, 695-720

BIGING, G. S.; WENSEL, L. C. (1988): The effect of eccentricity on the estimation of basal area and basal area increment of coniferous trees. Forest Science 34, 621-633

BORDERS, B. E.; BAILEY, R. L.; CLUTTER, M. L. (1988): Forest growth models: parameter estimation using real growth series . In: EK, A. R.; SHIFLEY, S. R.; BURK, T. E. (eds.): Forest growth modelling and prediction. Proceedings of IUFRO Conference. USDA Forest Service General Technical.Report NC120, 660-667

BOREL, W. (1929): Guide pour l'application du contrôle aux futaies jardinées. Jacques & Demontrond, Besacon. 104p.

BOTKIN, D. B. (1993): Forest dynamics: an ecological model. Oxford University Press, Oxford. 309p.

BOTKIN, D. B.; JANAK, J. F.; WALLIS, J. R. (1972): Some ecological consequences of a computer model of forest growth. Journal of Ecology 60, 849-872

BÖRNER, M. (1997): Zu Wachstum und Wachstumsreaktion der Rotbuche (*Fagus sylvatica* L.) nach Freistellung im fortgeschrittenen Alter. 3, Lincom Europa. 197p.

BRANDL, H. (1992): Die Entwicklung der Durchforstung in der deutschen Forstwirtschaft. Allgemeine Forst- und Jagdzeitung 163, 61-70

BROSINGER, F.; ROTHE, A. (2002): Die bayerische Staatsforstverwaltung erneuert ihre Waldbaugrundsätze. AFZ/Der Wald 57, 167-169

BROWN, G. S. (1965): Point density in stems per acre. New Zealand Forest Research Notes 38. New Zealand Forest Service, Forest Research Institute, Wellington, New Zealand. 11p.

BRUCIAMACCHIE, M.; GRANDJEAN, G.; JACOBÉE, F. (1994): Installation de régénérations feuillues dans de petites trouées en peuplements irréguliers. Revue Forestière Française 6, 639-653

BUONGIORNO, J. (2001): Quantifying the implications of transformation from even to uneven-aged forest stands. Forest Ecology and Management 151, 121-132

CANNELL, M. G. R.; MORGAN, J. (1990): Theoretical study of variables affecting the export of assimilates from branches of *Picea* . Tree Physiology 6, 257-266

CARMEAN, W. (1975): Forest site quality evaluation in the United States. Advances in Agronomy 27, 209-269

CHANG, M.; AGUILAR, J. R. (1980): Effects of climate and soil on the radial growth of loblolly pine (*Pinus taeda* L.) in a humid environment of the southeastern U.S.A. Forest Ecology and Management 3, 141-150

CHATTERJEE, S.; HADI, A. S.; PRICE, B. (2000): Regression analysis by example. Third Edition. John Wiley & Sons, Inc., New York. 359p.

CLUTTER, J. L.; FORTSON, J. C.; PIE, L. V.; BRISTER, G. H.; BAILEY, R. L. (1983): Timber management: a quantitative approach. John Wiley & Sons, New York. 333p.

COATES, K. D.; BURTON, P. J. (1997): A gap-based approach for the development of silvicultural systems to address ecosystem management objectives. Forest Ecology and Management 99, 339-356

COLE, W. G.; LORIMER, C. G. (1994): Predicting tree growth from crown variables in managed northern hardwood stands. Forest Ecology and Management 67, 159-175

CUTTER, B. E.; LOWELL, K. E.; DWYER, J. P. (1991): Thinning effects on diameter growth in black and scarlet oaks as shown by tree ring analysis. Forest Ecology and Management 43, 1-13

DAHMS, W. G. (1974): Tree growth and water use response to thinning in a 47-year-old lodgepole pine stand. USDA Forest Service Research Note PNW-194. 14p.

DALE, M. E. (1975): Effect of removing understory on growth of upland oak. USDA Forest Service Research Paper NE-321. 10p.

DALE, V. H.; DOYLE, T. W.; SHUGART, H. H. (1985): A comparison of tree growth models. Ecological Modelling 29, 145-169

DANIELS, R. F. (1976): Simple competition indices and their correlation with annual loblolly pine tree growth. Forest Science 22, 454-456

DANIELS, R. F.; BURKHART, H. E. (1975): Simulation of individual tree growth and stand development in managed loblolly pine plantations. Publication FWS-5-75, Virginia Polytechnic Institute and State University, Blackburg. 69p.

DAUME, S.; ROBERTSON, D. (2000): A heuristic approach to modelling thinnings. Silva Fennica 34, 237-249

DHÔTE, J. F. (1990): Modèles de la dynamique des peuplements forestiers: articulation entre les niveau de l'arbre et du peuplement. Applications à la sylviculture des hêtraies. Dissertation: Laboratoire de Biométrie. Université C. Bernard-Lyon I, Lyon. 256p.

DHÔTE, J. F. (1994): Hypothesis about competition for light and water in even-aged beech (*Fagus silvatica* L.). Forest Ecology and Management 69, 219-232

DHÔTE, J. F. (1996): A model of even-aged beech stands productivity with process-based interpretations. Annales des Sciences Forestieres 53, 1-20

DIETERICH, H.; HAUFF, R. (1980): Die Bedeutung der Pollenanalyse für die forstliche Standortskunde in Baden-Württemberg. Forstwissenschaftliches Centralblatt 99, 120-128

DOBLER, D.; HOHLOCH, K.; LISBACH, B.; SALIARI, M. (1988): Trieblängen-Messungen an Buchen - Anwendung der Methode von A. Roloff im Forstbezirk Reutlingen. Allgemeine Forstzeitschrift 43, 811-812

DRAPER, N. R.; SMITH, H. (1998): Applied regression analysis. 4th. John Wiley & Sons Inc., New York. 706p.

DUDEK, A.; EK, A. R. (1980): A bibliography of worldwide literature on individual tree based forest stand growth models. Staff Paper Series 12, University of Minnesota, Department of Forest Resources

DUNKEL, K.; ELSASSER, P.; OESTEN, G.; ROEDER, A. (1994): Wertschätzung des Waldes aus der Sicht der Waldbesucher - Ergebnisse einer Zielgebietsbefragung im Pfälzerwald. In: OESTEN, G.; ROEDER, A. (eds.): Zur Wertschätzung der Infrastrukturleistungen des Pfälzerwaldes. Trippstadt: Mitteilungen aus der Forstlichen Versuchsanstalt Rheinland-Pfalz. 1-72

DUNNING, D. (1922): Relation of crown size and character to rate of growth and response to cutting in western yellow pine. Journal of Forestry 20, 377-389

ERDMANN, G. G. (1986): Developing quality in second-growth stands. In: MROZ, G. D.; REED, D. D. (eds.): Proceedings of a conference on the Northern Hardwood Resource: Management and Potential, 18-20 August 1986. Michigan Technology University, Houghton, 206-222

FISCHER, H.; ROMMEL, W. D. (1989): Jahrringbreiten und Hohentrieblängen von Buchen mit unterschiedlicher Belaubungsdichte in Baden-Württemberg. Allgemeine Forstzeitschrift 11, 264-265

FRANCOIS, T. (1938): La composition théorique normale des futaies jardinées de Savoie. Revue des eaux et forêts 76, 1-18

FRANK, R. M. (1973): The course of growth response in released white spruce - 10 year results. USDA Forest Service Research Paper NE-258

FRANKLIN, J. F. (1989): Towards a new forestry. American Forestry 95, 37-44

FREISE, C.; SPIECKER, H. (1999): Konkurrenzfreies Wachstum der Buche. AFZ/Der Wald 54, 1346-1349

FRIEND, A.; HAFLEY, W. (1989): Climatic limitations to growth of Loblolly pine (*Pinus taeda* and *Pinus echinata*); a dendroclimatological approach. Forest Ecology and Management 26, 122-

FRITTS, H. C. (1966): Growth rings of trees: their correlation with climate. Science 154, 973-979

FRITTS, H. C. (1976): Tree rings and climate. Academic Press, London. 567p.

GAYER, K. (1886): Der gemischte Wald, seine Begründung und Pflege, insbesondere durch Horst- und Gruppenwirtschaft. Verlag von Paul Parey, Berlin. 168p.

GÄRTNER, R.; STOLL, G. (1990): Weiserjahre in Baden-Württemberg: Fichte, Tanne, Kiefer und Buche. Allgemeine Forstzeitschrift 45, 1163-1167

GOFF, N. L.; OTTORINI, J.-M. (1993): Thinning and climate effects on growth of beech (*Fagus sylvatica* L.) in experimental stands. Forest Ecology and Management 62, 1-14

GOLTZ, H. v. (1991): Strukturdurchforstung der Fichte. Allgemeine Forstzeitschrift 13, 677-679

GRISEL, F.; GADOW, K. V. (1995): Naturgemäßer – naturnaher – ökologischer Waldbau – Begriffsbestimmungen, Konzepte und Richtlinien, Anwendungsbeispiele. Internal report. Institute of Forsteinrichtung, University of Göttingen. 20p.

GUERICKE, M. (2001): Untersuchungen zur Wuchsdynamik von Mischbeständen aus Buche und Europ. Lärche (*Larix decidua*, Mill.) als Grundlage für ein abstandsabhängiges Einzelbaumwachstumsmodell. Dissertation: Göttingen University. 220p.

HAHN, D. (1995): Entscheidungshilfen für die Steuerung des Dickenwachstums von Buchen (*Fagus sylvatica* L.): Entwicklung und Aufbau auf der Grundlage eines distanzabhängigen Einzelbaum-Konkurrenzmodells. Dissertation: Albert-Ludwigs-Universität, Freiburg. 225p.

HAMILTON, G. J. (1969): The dependence of volume increment of individual trees on dominance, crown dimensions and competition. Forestry 42, 133-144

HANEWINKEL, M. (1996): Konzept zur Überführung einschichtiger Fichtenwälder in stufige Dauerwälder. Arbeitsbericht Nr. 23-96, Institut für Forstökonomie, Universität Freiburg. 60p.

HANEWINKEL, M. (1998): Plenterwald und Plenterwaldüberführung - Modellstudien zu planungstechnischen, waldbaulichen und ökonomischen Aspekten am Fallbeispiel des Wuchsgebietes Schwarzwald. Dissertation: Universität Freiburg, Schriften aus dem Institut für Forstökonomie der Universität Freiburg, Band 9. 252p.

HANEWINKEL, M.; PRETZSCH, H. (2000): Modelling the conversion from even-aged to uneven-aged stands of Norway spruce (*Picea abies* L. Karst.) with a distance-dependent growth simulator. Forest Ecology and Management 134, 55-70

HARI, P.; SIRÉN, G. (1972): Influence of some ecological factors and the seasonal stage of development upon the annual ring width and radial growth index. Research Notes, 40 Royal College of Forestry, Department of Reforestation, Stockholm. 22p.

HARPER, J. L. (1977): Population biology of plants. Academic Press, New York. 892p.

HARRISON, W. C.; BURK, T. E.; BECK, D. E. (1986): Individual tree basal area increment and total height equations for Appalachian mixed hardwoods after thinning. Southern Journal of Applied Forestry 10, 99-104

HASEL, K. (1985): Forstgeschichte - Ein Grundriß für Studium und Praxis. Parey, Hamburg. 285p.

HAUFF, R. (1961): Nachwärmezeitliche Pollenprofile aus Baden-Württembergischen Forstbezirken. In: Mitteilungen des Vereins für Forstliche Standortskunde und Forstpflanzenzüchtung. 66-78

HAUFF, R. (1969): Nachwärmezeitliche Pollenprofile aus Baden-Württembergischen Forstbezirken IV. Folge. In: Mitteilungen des Vereins für Forstliche Standortskunde und Forstpflanzenzüchtung. 29-48

HAUFF, R. (1978): Nachwärmezeitliche Pollenprofile aus Baden-Württembergischen Forstbezirken V. Folge. In: Mitteilungen des Vereins für Forstliche Standortskunde und Forstpflanzenzüchtung. 53-67

HAUTOT, A. (1992): Croissance en diamètre et développement du frêne et du mersier au stade juvénile dans différentes conditions expérimentales de plantation. Dissertation: Diplôme d'Études Approfondies. Biologie Forestière, Université de Nancy, Nancy France.p.

HEGYI, F. (1974): A simulation model for managing jack-pine stands. In: FRIES, J. (eds.): Growth Models for Tree and Stand Simulation. Royal College Forest Department, Forest Yield Research Resource Note No. 30, Stockholm, Sweden, 74-90

HELLIWELL, D. R. (1997): Dauerwald. Forestry Oxford 70, 375-379

HIBBS, D. E. (1982): Gap dynamics in a hemlock-hardwood forest. Canadian Journal of Forest Research 12, 522-527

HILEY, W. E. (1959): Conifers: South African methods of cultivation. Faber and Faber, London. 123p.

HILT, D. E. (1985): OAKSAM: an individual-tree growth and yield simulator for managed, even-aged, upland oak stands. USDA Forest Service Research Paper NE-562, Broomall, PA. 21p.

HOLMES, M. J.; REED, D. D. (1991): Competition indices for mixed species northern hardwoods. Forest Science 5, 1338-1349

HORN, H. (1971): Adaptive geometry of trees. Princeton University Press, Princeton, N.J. 146p.

HUNT, F. M. (1968): Tree growth and soil moisture changes following thinning of eastern white pine. Dissertation: Ph.D. thesis, University of Massachusetts, Amherst, MA.p.

HUSCH, B. (1959): Height growth of white pine in relation to selected environmental factors on four sites in southeastern New Hampshire. Agricultural Experimental Station University of New Hampshire Technical Bulletin No. 100.

INOSE, M. (1982): Tree growth model based on crown competition in Todomatsu (*Abies sachalinensis*). I. The relationship between crown development and volume increment., 318. 127p.

INOSE, M. (1985): Tree growth model based on crown competition in Todomatsu (*Abies sachalinensis*). II. Estimation of the diameter increment and bark thickness. Bull For For Prod Res Inst, 334. 20p.

JOHANN, K. (1970): Ergebnisse strukturanalytischer Untersuchungen in näturlich verjüngten Fichtenbeständen. Forstwissenschaftliches Centralblatt 89, 228-251

KELTY, M. J.; GOULD, Jr. E. M.; TWERY, M. J. (1987): Effects of understory removal in hardwood stands. Northern Journal of Applied Forestry 4, 162-164

KERR, G. (1999): The use of silvicultural systems to enhance the biological diversity of plantation forests in Britain. Forestry 72, 192-205

KLÄDTKE, J. (1999): Zuwachsreaktionen schwächerer Bäume. Forschungsbericht 1999 der FVA Freiburg. 28p.

KOCH, N. E.; SKOVSGAARD, J. P. (1999): Sustainable management of planted forests: some comparisons between central Europe and the United States. New Forests 17, 11-22

KONNERT, M.; SPIECKER, H. (1996): Beeinflussen Nutzungen einzelner Bäume die genetische Struktur von Beständen? AFZ/Der Wald 51, 1284-1291

KORPEL, S. (1982): Degree of equilibrium and dynamical changes of the forest on example of natural forests of Slovakia. Acta Facult.Forest.Zvolen 24, 9-31

KORPEL, S. (1985): Die Urwälder der Westkarpaten. Fischer, Stuttgart and Jena and New York. 310p.

KÖNIG, G. (1849): Die Waldpflege aus der Natur und Erfahrung neu aufgefasst. Becker'sche Verlags-Buchhandlung, Gotha. 313p.

KRAMER, H. (1988): Waldwachstumslehre. Verlag Parey, Hamburg und Berlin. 374p.

KREMSER, W. (1990): Niedersächsische Forstgeschichte: Eine integrierte Kulturgeschichte des nordwestdeutschen Forstwesens. Rotenburger Schriften Sonderband 32. Rotenburg/Wümme: Heimatbund. 965p.

LAMSON, N. I.; SMITH, H. C.; PERKEY, A. W.; BROCK, S. M. (1990): Crown release increases growth of crop trees. USDA Forest Service Research Paper NE-635. 8p.

LARCHER, W. (1995): Physiological plant ecology. 3rd Ed. Springer-Verlag, Berlin. 519p.

LÄHDE, E.; LAIHO, O.; NOROKORPI, Y. (1999): Diversity-orientated silviculture in the Boreal Zone of Europe. Forest Ecology and Management 118, 223-243

LEOPOLD, A. (1936): Deer and Dauerwald in Germany. I. History. Journal of Forestry 34, 366-375

LITTLE, R. J. A.; RUBIN, D. B. (1987): Statistical Analysis with Missing Data. New York: John Wiley. John Wiley & Sons, New York. 278p.

LIU, J.; BURKHART, H. E.; AMATEIS, R. L. (1995): Projecting crown measures for Loblolly pine trees using a generalised thinning response function. Forest Science 41, 43-53

LORIMER, C. G. (1983): Tests of age-independent competition indices for individual trees in natural hardwood stands. Forest Ecology and Management 6, 343-360

MACARTHUR, R. H.; MACARTHUR, J. W. (1961): On species diversity. Ecology 42, 594-598

MADGWICK, H. A. I.; TAMM, C. O.; FU, M. Y. (1986): Crown development in young *Picea abies* stands. Scandinavian Journal of Forest Research 1, 195-204

MANTEL, K. (1990): Wald und Forst in der Geschichte. Schaper Verlag, Alfred Hannover. 517p.

MAO-YI, F.; TAMM, C. O. (1985): Predicting branch and needle growth od spruce from easily measurable tree parameters. Acta Ecologia, Ecologia Plantarum 6, 347-363

MARTIN, G. L.; EK, A. R. (1984): A comparison of competition measures and growth models for predicting plantation red pine diameter and height growth. Forest Science 30, 731-743

MCWILLIAMS, E. R. G.; BURK, T. E. (1994): Evaluation of eight forest fertilizer response estimators by means of a simulation study. Canadian Journal of Forest Research 24, 107-119

MINCKLER, L. S. (1957): Response of pole-sized white oak trees to release. Journal of Forestry 55, 814-815

MITCHELL, K. J. (1969): Simulation of the growth of even-aged stands of white spruce. Bulletin 75, School of Forestry, Yale University. 48p.

MITCHELL, K. J. (1975): Dynamics and simulated yield of Douglas-fir. Forest Science Monograph, 17. 39p.

MITSCHERLICH, G. (1952): Der Tannen-Fichten (Buchen)-Plenterwald: eine ertragskundliche Studie. Schriftenreihe der Badischen Forstlichen Versuchs- und Forschungsanstalt, 8. 42p.

MITSCHERLICH, G. (1970): Wald, Wachstum und Umwelt. Band 1: Form und Wachstum von Baum und Bestand. 142, Sauerländer´s Verlag, Frankfurt am Main

MLINŠEK, D. (1996): From clear-cutting to close-to-nature silviculture system. IUFRO News, 25, 4. International Union of Forest Research Organizations. 8p.

MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) (1965): Jahresbericht der Landesforstverwaltung Baden-Württemberg.

MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) (1993): Ernährung, Landwirtschaft und Forsten Baden-Württemberg. Naturnahe Waldwirtschaft. 32p.

MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) (1994a): Forsteinrichtungsstatistik 1981-90 für die öffentlichen Waldungen in Baden-Württemberg. 372p.

MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) (1994b): Jahresbericht der Landesforstverwaltung Baden-Württemberg.

MLR (MINISTERIUM FÜR LÄNDLICHEN RAUM) (1999): Richtlinie Landesweiter Walden wicklungstypen. Ministerium Ländlicher Raum - Baden Württemberg, Stuttgart. 32p.

MOORE, J. A.; BUDELSKY, C. A.; SCHLESINGER, R. C. (1973): A new index representing individual tree competition status. Canadian Journal of Forest Research 3, 495-500

MORGAN, J.; CANNELL, M. G. R. (1988): Support costs of different branch design: effects of position, number, angle and defection from laterals. Tree Physiology 4, 313-

MOSANDL, R. (1984): Löcherhiebe im Bergmischwald - Ein waldbauökologischer Beitrag zur Femelschlagverjüngung in den Chiemgauer Alpen. Forstliche Forschungsberichte München, Nr. 61. 317p.

MOSANDL, R. (1991): Die Steuerung von Waldökosystemen mit waldbaulichen Mitteln - dargestellt am Beispiel des Bergmischwaldes. Mitteilungen aus der Staatforstverwaltung Bayerns, herausgegeben vom Bayerischen Staatsministerium für Ernährung Landwirtschaft und Forsten, 46. Heft Munich. 246p.

MÖLLER, A. (1922): Der Dauerwaldgedanke. Sein Sinn und seine Bedeutung. Springer Verlag, Heidelberg. 84p.

MUNRO, D. D. (1974): Forest growth models - a prognosis. In: FRIES, J. (eds.): Growth models for tree and stand simulation. Royal College Forest Department, Forest Yield Research Resource Note No. 30, Stockholm, Sweden, 7-21

MÜLLER-WESTERMEIER, G. (1996): Klimadaten von Deutschland Zeitraum 1961 - 1990: (Lufttemperatur, Luftfeuchte, Niederschlag, Sonnenschein, Bewölkung). Selbstverlag des Deutschen Wetterdienstes, Offenbach am Main. 431p.

MÜLLER, T.; OBERDORFER, E. (1974): Die potentielle atürliche Vegetation von Baden-Württemberg. Beihefte zu den Veröffentlichen der Landesstelle für Naturschutz und Landschaftspflege Baden-Württemberg, 6. 46p.

NANCE, W. L.; GRISSOM, J. E.; SMITH, W. R. (1988): A new competition index based on weighted and constrained area potentially available. In: EK, A. R.; SHIFLEY, S. R.; BURK, T. E. (eds.): Forest growth modelling and prediction. General Technical Report NC-120. USDA Forest Service, North Central Experiment Station, 134-142

NÄSLUND, M. (1942): Die Reaktionsfähigkeit des alten nordländischen Fichtenwaldes nach Durchhauung. Medd. från statens skogsförsökanst, 33 (1). 212p.

NEWNHAM, R. M. (1966): Stand structure and diameter growth of individual trees in a young Red Pine stand. Bi-m. Research Notes Department Forest Canada, 22, 4. 5p.

NIEDERSÄCHSISCHE LANDESREGIERUNG (1991): Niedersächsisches Programm zur langfristigen ökologischen Waldentwicklung in den Landesforsten. Hannover. 50p.

NIPKOW, T. (1995): Ein synoptischer Verfahrensansatz zur naturschutzfachlichen Gebietsbewertung auf der Basis multivariater Analysemethoden. Schriftenreihe des Instituts für Landespflege der Universität Freiburg. Heft 20. 156p.

OLIVER, C. D. (1981): Forest development in North America following major disturbances. Forest Ecology and Management 3, 153-168

OPIE, J. E. (1968): Predictability of individual tree growth using various definitions of competing basal area. Forest Science 14, 314-323

OTTO, H. J. (1989): Langfristige ökologische Waldbauplanung für die Niedersächsischen Landesforste. Aus dem Walde, Band 1. Heft 42. Mitteilungen aus der Niedersächsischen Landesforstverwaltung, Hannover. 434p.

PETRINI, S. (1932): Der lanforser Bestand-ein schwedischer Versuch mit WAGNER-Hieb und natürlicher Verjüngung. Forstwissenschaftliches Centralblatt 54, 425-455

PLOCHMANN, R. (1992): The forests of central Europe. A changing view. Journal of Forestry 90, 12-16

PREUHSLER, T. (1981): Ertragskundliche Merkmale oberbayerischer Bergmischwald-Verjüngungsbestände auf kalkalpinen Standorten im Forstamt Kreuth. Forstwissenschaftliches Centralblatt 100, 313-345

PRODAN, M. (1949): Normalisierung des Plenterwaldes? In: Schriftenreihe der Badischen Forstlichen Versuchs- und Forchungsanstalt, 7-21

PUTZ, F. E.; PARKER, G.; ARCHIBALD, M. (1984): Mechanical abrasion and inter-crown spacing. American Midland Naturalist 112, 24-28

REININGER, H. (1976): Schlagweiser Hochwald oder Zielstärkennutzung? Allgemeine Forstzeitung Wien 87, 627-638

REININGER, H. (1987): Zielstärken-Nutzung oder die Plenterung des Altersklassenwaldes. Österreichischer Agrarverlag. 163p.

ROACH, B. A. (1974): Selection cutting and group selection. Miscellaneous Report 5. Applied Forestry Research Institute, State University of New York, Syracuse. 9p.

ROLOFF, A. (1984): Nur zwei trockene Sommer oder mehr? Der Forst- und Holzwirt 14/15, 364-366

ROLOFF, A. (1986): Morphologische Untersuchungen zum Wachstum und Verzweigungssystem der Rotbuche (*Fagus sylvatica* L.). Mitteilung Deutsche Dendrologische Gesellschaft, 76. 47p.

ROLOFF, A. (1988): Morphologie der Kronenentwicklung von *Fagus sylvatica* L. (Rotbuche) unter besonderer Berücksichtigung neuartiger Veränderungen. II Strategie der Luftraumeroberung und Veränderungen durch Umwelteinflüsse. Flora 180, 297-338

ROMMEL, W.-D. (1990): Die Flößerei auf dem Kocher: insbesondere die Versorgung der Salinen Hall und Friedrichshall und ihre forstwirtschaftliche Auswirkung auf das Limpurger Land vom Ausgang des Mittelalters bis zur Industrialisierung. Dissertation: Forstwissenschaftlichen Fakultät Freiburg, Freiburg. 193p.

RUNKLE, J. R. (1982): Patterns of disturbance in some old-growth mesic forests of eastern North America. Ecology 63, 1533-1546

RUNKLE, J. R.; YETTER, T. C. (1987): Treefalls revisited: gap dynamics in the southern Appalachians. Ecology 68, 417-424

SAS INSTITUTE INC (1988): SAS/GRAPH® User's Guide, Release 6.03 Edition. Sas Institute, Cary, NC. 549p.

SAS INSTITUTE INC (2000): SAS/STAT® User's Guide, Version 8, Volumes 1, 2, and 3. Sas Institute, Cary, NC. 3884p.

SCHABEL, H. G.; PALMER, S. L. (1999): The Dauerwald: its role in the restoration of natural forests. Journal of Forestry 97, 20-25

SCHAEFFER, A.; GAZIN, A.; D'ALVERNY, A. (1930): Sapinières; le jardinage par contenance (méthode du contrôle par les courbes). Presse Universitaire de France, Paris. 100p.

SCHEIFELE, M. (1986): Zur Geschichte der Flößerei in Süddeutschland. Allgemeine Forst- und Jagdzeitung 157, 13-17

SCHMIDT, M.; SCHÜTZ, J.-P.; GADOW, K. (1997): Strukturanalyse in vier Plenterüberführungsbeständen. Schweizerische Zeitschrift für Forstwesen 148, 335-352

SCHMIDT, W. C.; SHEARER, R. C.; ROE, A. L. (1976): Ecology and silviculture of western larch forests. USDA, Technical Bulletin 1520. 96p.

SCHNITZLER, A.; BORLEA, F. (1998): Lessons from natural forests as keys for sustainable management and improvement of naturalness in managed broadleaved forests. Forest Ecology and Management 109, 293-303

SCHOBER, R. (1969): Buchenertragstafeln. In: Hilfstabellen für die Forsteinrichtung. Landesforstverwaltung Baden-Württemberg,

SCHÜTZ, J.-P. (1981): Que peut apporter le jardinage à notre sylviculture? Schweizerische Zeitschrift für Forstwesen 132, 218-242

SCHÜTZ, J.-P. (1989a): Der Plenterbetrieb - Vorlesungunterlagen zur Vorlesung Waldbau III und zu SANASILVA Fortbildungskursen. ETH Zurich. 54p.

SCHÜTZ, J.-P. (1989b): Zum Problem der Konkurrenz in Mischbeständen. Schweizerische Zeitschrift für Forstwesen 140, 1069-1083

SCHÜTZ, J.-P. (1989c): Zum Problem der Konkurrenz in Mischbeständen. Schweizerische Zeitschrift für Forstwesen 140, 1069-1083

SCHÜTZ, J.-P. (1992): Die waldbaulichen Formen und die Grenzen der Plenterung mit Laubbaumarten. Schweizerische Zeitschrift für Forstwesen 143, 442-460

SCHÜTZ, J.-P. (1994): Geschichtlicher Hergang und aktuelle Bedeutung der Plenterung in Europa. Allgemeine Forst- und Jagdzeitung 165, 106-114

SCHÜTZ, J.-P. (1999a): Close-to-nature silviculture: is this concept compatible with species diversity? Forestry 72, 359-366

SCHÜTZ, J.-P. (1999b): Conditions of equilibrium in fully irregular, uneven-aged forests: The state-of-the-art in European plentar forests. In: EMMINGHAM, W. H. (eds.): Proceedings of the IUFRO Interdisciplinary Uneven-aged Management Symposium September 1997. Oregon State University, Corvallis, 455-467

SCHÜTZ, J.-P. (1999c): Die Plenterung und ihre unterschiedlichen Formen - Skript zur Vorlesung Waldbau II und Waldbau IV.

SCHÜTZ, J.-P. (1999d): Praktische Bedeutung der Überführung für die Umsetzung der Plenteridee. In: HANEWINKEL, M. (eds.): Überführung von Alterklassenwälder in Dauerwälder. 1-13

SCHÜTZ, J.-P. (1999e): The Swiss experience: More than one hundred years of experience with a single-tree-selection management system in mountainous mixed forest of spruce, fir, and beech. In: EMMINGHAM, W. H. (eds.): Proceedings of the IUFRO Interdisciplinary Uneven-aged Management Symposium September 1997. Oregon State University, Corvallis, 21-34

SCHÜTZ, J.-P. (2001a): Der Plenterwald und weitere Formen strukturierter und gemischter Wälder., Parey, Berlin. 207p.

SCHÜTZ, J.-P. (2001b): Opportunities and strategies of transforming regular forests to irregular forests. Forest Ecology and Management 151, 87-94

SCHÜTZ, J.-P.; GRUNDER, K.; MANDALLAZ, D. (1986): Die Vitalität von Weißtannen und ihre Abhängigkeit von bestandesstrukturellen, ertragskundlichen, ernährungskundlichen und waldbaulichen Variablen. Forstwissenschaftliches Centralblatt 105, 406-420

SEIDEL, K. W. (1984): A western larch-Engelmann spruce spacing study in eastern Oregon: results after 10 years. USDA Forest Service, Research Note PNW-409. 6p.

SHUGART, H. H. (1984): A theory of forest dynamics: the ecological implications of forest succession models. Springer-Verlag, New York. 278p.

SJOLTE-JØRGENSEN, J. (1967): The influence of spacing in the growth and development of coniferous plantations. International Review of Forest Research 2, 43-94

SMITH, D. M. (1962): The practice of silviculture. John Wiley and Sons, New York. 598p.

SMITH, D. M. (1986): The practice of silviculture. 8th. John Wiley, New York. 527p.

SMITH, F. W.; LONG, J. N.; SAMPSON, D. A. (1990): The mechanical abrasion hypothesis of crown shyness: a direct test in *Pinus contorta* forests. Bulletin of the Ecological Society of America 71, 327-328

SMITH, H. C.; MILLER, G. W. (1991): Releasing 75- to 80-year-old Appalachian hardwood sawtimber trees: 5-year D.B.H. response. In: MCCORMICK, L. H.; GOTTSCHALK, K. W. (eds.): Proceedings of the 8th Central Hardwood Forest Conference, University Park, Penn. USDA Forest Service General Technical Report NE-148. 402-413

SNEDECOR, G. W.; COCHRANE, W. G. (1980): Statistical Methods. 7th ed. Iowa State University Press, Ames, Iowa. 507p.

SPATHELF, P. (1997): Seminatural silviculture in Southwest Germany. The Forestry Chronicle 73, 715-722

SPATHELF, P. (1999): Orientierungshilfe zur Prognose und Steuerung des Wachstums von Fichten (Picea abies (L.) Karst) und Tannen (Abies alba Mill.) in Überführungswäldern mit Hilfe der relativen Kronenlänge. 4, Freiburger Forstliche Forschung

SPIECKER, H. (1986): Das Wachstum der Tannen und Fichten auf Plenterwaldversuchsflächen des Schwarzwaldes in der Zeit von 1950 bis 1984. Allgemeine Forst- und Jagdzeitung 157, 152-164

SPIECKER, H. (1991a): Growth variation and environmental stresses: long-term observations on permanent research plots in southwestern Germany. Water, Air, and Soil Pollution 54, 247-256

SPIECKER, H. (1991b): Zur Dynamik des Wachstums von Tannen und Fichten auf Plenterwald-Versuchsflächen im Schwarzwald. Allgemeine Forstzeitschrift 46, 1076-1080

SPIECKER, H. (1991c): Zur Steuerung des Dickenwachstums und der Astreinigung von Trauben- und Stieleichen (*Quercus petraea* (Matt.) Liebl. und *Quercus robbur* L.). Schriftenreihe der Lanesforrstverwaltung Baden-Württemberg. 72. 155p.

SPIECKER, H.; MIELIKÄINEN, K.; KÖHL, M.; SKOVSGAARD, J. P. (eds.) (1996): Growth trends in European Forests; studies from 12 countries. Springer-Verlag, Berlin. 372p.

SPIECKER, H. (2000): The growth of Norway spruce (*Picea abies* [L.] Karst.) in Europe within and beyond its natural range. In: HASENAUER, H. (eds.): Forest Ecosystem Restoration - Ecological and Economical Impacts of Restoration Processes in Secondary Coniferous Forests, Proceedings of the International Conference held in Vienna, Austria 10.-12. April, 2000. Wien. 247-256

SPIECKER, H. (2001): Changes in wood resources in Europe with special emphasis on Germany. World Forests, Markets and Policies. In: PALO, M.; UUSIVUORI, J.; MERY, G. (eds.): World Forests Volume III, Kluwer Academic Publisher. 425-436

SPRUGEL, D. G.; HINCKLEY, T. M.; SCHAAP, W. (1991): Theory and practice of branch autonomy. Annual Reviews Ecology and Systematics 22, 309-334

STAEBLER, G. R. (1965): Effect of controlled release on growth of individual Douglas-fir trees. Journal of Forestry 54, 567-568

STERBA, H.; ZINGG, A. (2001): Target diameter harvesting - a strategy to convert even-aged forests. Forest Ecology and Management 151, 95-105

STOKES, M. A.; SMILEY, T. (1968): An introduction to tree-ring dating. University of Chicago Press, Chicago, IL. 73p.

SUNDBERG, R. (1971): On the estimation of pollution-caused growth reduction in forest trees. The IASPS symposium on statistical aspects of pollution problems, Boston 1971. 42p.

TECK, R. M.; HILT, D. E. (1991): Individual-tree diameter growth model for the northeastern United States. USDA Forest Service, Research Paper NE-649, Broomall, PA. 11p.

THOMASIUS, H. (1988): Stabilität natürlicher und künstlicher Waldökosysteme sowie deren Beeinflußbarkeit durch forstwirtschaftliche Maßnahmen. Allgemeine Forstzeitschrift 43, 1037-1043, 1064-1068

TRENKLE, H.; RUDLOFF, H. v. (1981): Das Klima im Schwarzwald. In: LIEHL, E.; SICK, W. D. (eds.): Der Schwarzwald: Beiträge zur Landeskunde. Konkordia, Bühl/Baden, 59-100

TRIMBLE, G. R.; TRYON, E. H. (1966): Crown encroachment into openings cut in Appalachian hardwood stands. Journal of Forestry 64, 104-108

TRUHLÁR, J. (1995): Results of conversions to the selection forest in the Masarykuv Les Training forest enterprise. Lesnictví-Forestry 41, 97-107

TRUHLÁR, J. (1997): Silviculture in Biological Conception., Mendel University of Agriculture and Forestry in Brno, Faculty of Forestry and Wood Technology. 186p.

(UBW) UMWELTMINISTERIUM BADEN WÜRTTEMBERG (1995): Bewertung der Böden nach ihrer Leistungsfähigkeit. Luft Boden Abfall. 31p.

VANCLAY, J. K. (1994): Modelling forest growth and yield: Applications to mixed tropical forest. CAB International, England. 312p.

VANCLAY, J. K. (1995): Growth models for tropical forests: a synthesis of models and methods. Forest Science 41, 7-42

VOLZ, K.-R. (1995): Zur ordnungspolitischen Diskussion über die nachhaltige Nutzung der Zentralressource Wald. Forst und Holz 50, 163-170

WAN RAZALI, M.; RUSTAGI, K. P. (1988): Development of a generalized growth model for mixed tropical forests of peninsular Malaysia. 167-174

WEIDENBACH, P.; KARIUS, K. (1993): Plenterwälder und Dauerbestockungen in Baden-Württemberg. Allgemeine Forstzeitschrift 48, 54-57

WILLIAMSON, R. L. (1966): Thinning response in 110-year-old Douglas-fir. U.S. Forest Service Pacific Northwest Forest and Range Experiment Station Resource Note 36. 7p.

WILLIS, K.; MCELWAIN, J. (2002): The evolution of plants. Oxford University Press, London. 352p.

ZIMMERLE, H. (1936): Die Plenterwald Versuchsflächen in Württemberg. In: Schriftenreihe der Württembergen Mitteilungen Forstlichen Versuchs- und Forschungsanstalt. 92-210

ZIMMERLE, H. (1938): Zuwachsuntersuchungen bei der Fichte im Fürstl. Forstbezirk Härtzfeldhausen. Allgemeine Forst- und Jagdzeitung 114, 341-351