## Master Thesis

# Growth Dominance and Gini-Index in even-aged and in uneven-aged forests 

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## Table of Contents

Table of Contents ..... i
Acknowledgements ..... iii
1 Abstract .....  1
1 Zusammenfassung ..... 2
2 Introduction ..... 3
2.1 Gini-index and Lorenz curve ..... 4
2.2 Deviation from equilibrium ..... 7
2.3 Growth dominance ..... 7
3 Hypotheses and Objectives ..... 12
4 Materials and Methods ..... 14
4.1 Plots ..... 14
4.2 Analysis ..... 16
4.2.1 Dataset ..... 16
4.2.2 Height curves ..... 16
4.2.3 Volume estimation ..... 17
4.2.4 Increment estimation ..... 17
4.2.5 Gini-index ..... 18
4.2.6 Growth dominance ..... 18
4.2.7 Variance of deviation from equilibrium ..... 18
4.2.8 Statistical methods ..... 19
5 Results ..... 20
5.1 Mean values ..... 20
5.2 Gini-index and growth dominance ..... 22
5.3 Gini-index and annual increment per ha ..... 24
5.4 Growth dominance and annual increment per ha ..... 27
5.5 Development of growth dominance-coefficients within stands ..... 30
5.6 Growth dominance, Gini-index and deviation from equilibrium ..... 33
5.7 Gini-index and growth dominance in uneven-aged stands ..... 35
5.8 Gini-index and growth dominance in even-aged stands ..... 36
5.9 Gini-index and growth dominance in mixed and pure stands ..... 37
6 Discussion ..... 39
6.1 Critical evaluation on the methods used ..... 39
6.2 General patterns of Gini-indices and growth dominance-coefficients ..... 39
6.3 Influence of the Gini-index on growth dominance ..... 40
6.4 Impacts on annual increment ..... 40
6.5 Growth dominance pattern ..... 41
6.6 Impact of the deviation from equilibrium. ..... 42
6.7 Final conclusion ..... 42
7 List of tables ..... 43
8 List of figures ..... 44
9 References ..... 47
Appendix ..... 51

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## 1 Abstract

The Gini-index is used as a parameter to assess the structural diversity of forest stands indicating whether a stand is homogeneous or heterogeneous. Growth dominance is a measure to identify growth patterns within stands being positive when larger trees proportionally have a greater share of stand growth than smaller trees, and negative when smaller trees proportionally have a greater share of stand growth than larger trees.
The study examined the influence of the Gini-index on growth dominance, using data of various stands which had been beforehand classified as even- or uneven-aged and mixed or pure. The influence of both parameters on annual increment per ha was also explored. Furthermore, the development of the growth dominance in the different stands was analysed to find specific development patterns.
A significant correlation between Gini-index and growth dominance was found. The results support the hypothesis that the more inhomogeneous a stand is, the more likely the so called "reverse" or negative growth dominance appears. Uneven-aged stand structures as well as a mixture of species led to a higher heterogeneity within stands and this caused low to negative growth dominance-coefficients indicating that smaller trees have a greater share of stand increment than they have of stand volume.
The relationships between Gini-index and annual increment on the one hand, and growth dominance and annual increment on the other hand, were complex: Adding the elevation as a variable led in uneven-aged stands to a significant correlation between Gini-index and annual increment as well as between growth dominance and annual increment. In contrast, in evenaged stands stand growth was mainly determined by stand age.
Patterns for the development of the growth dominance could not be identified; neither was a general pattern found nor could specific patterns for the different stand classes, species or elevation classes be detected. In this context, potentially a variety of factors such as species composition, management regime and environmental factors may influence the development of growth dominance within stands and therefore focusing on single parameters does not lead to specific patterns.

## 1 Zusammenfassung

Der Gini-Index dient als Parameter, um die Strukturdiversität innerhalb von Waldbeständen zu erfassen. Der Index zeigt an, ob ein Bestand homogen oder heterogen ist. Anhand der Wuchsdominanz können Wachstumsmuster innerhalb von Beständen identifiziert werden. Ist die Wuchsdominanz positiv, bedeutet dies, dass größere Bäume einen proportional größeren Anteil am Wachstum haben als kleinere Bäume. Negative Wuchsdominanzen bedeuten hingegen, dass kleinere Bäume ein proportional größeres Wachstum aufweisen als größere Bäume.
Anhand des Datenmaterials von verschiedenen Beständen, die zunächst nach den Kriterien von Bestandesstruktur und Mischung in gleichaltrige und ungleichaltrige Bestände sowie Misch- und Reinbestände eingeteilt wurden, wurde der Einfluss des Gini-Index auf die Wuchsdominanz untersucht. Außerdem wurde untersucht, ob ein Einfluss der beiden Parameter auf das Bestandeswachstum besteht. Des Weiteren wurde die Entwicklung der Wuchsdominanz in den einzelnen Beständen verfolgt und versucht, spezifische Entwicklungsmuster auszuscheiden.
Zwischen Gini-Index und Wuchsdominanz wurde ein straffer Zusammenhang festgestellt. Es konnte gezeigt werden, dass je inhomogener ein Bestand ist, desto wahrscheinlicher ist es, dass eine umgedrehte Wuchsdominanz auftritt; dies bedeutet, dass kleinere Bäume einen größeren Anteil am Bestandeszuwachs als am Bestandesvolumen haben. Sowohl eine ungleichaltrige Bestandesstruktur, wie auch eine Baumartenmischung, bewirkten eine größere Bestandesheterogenität, was wiederum niedrige bis negative Wuchsdominanzen zur Folge hatte.
Die Zusammenhänge zwischen Gini-Index und Zuwachs auf der einen Seite, und Wuchsdominanz und Zuwachs auf der anderen Seite, waren komplex: Erst mit der Seehöhe als zusätzlicher Variable konnte in den ungleichaltrigen Beständen gezeigt werden, dass sowohl Gini-Index als auch Wuchsdominanz einen signifikanten Einfluss auf den Zuwachs haben. In den gleichaltrigen Beständen wurde der Zuwachs hingegen hauptsächlich vom Bestandesalter bestimmt.
Ebenso konnten keine Muster für den Verlauf der Wuchsdominanz in den Beständen identifiziert werden, weder wurde ein einheitlicher Kurvenverlauf gefunden noch waren spezifische Muster für die verschiedenen Bestandesklassen, Baumarten oder Seehöhenstufen ersichtlich. In diesem Zusammenhang ist es wahrscheinlich, dass eine Vielzahl an Faktoren wie Baumartenzusammensetzung, Bewirtschaftung und Umweltfaktoren die Entwicklung der Wuchsdominanz beeinflussen und deshalb das Augenmerk nicht auf einzelne Parameter gelegt werden sollte.

## 2 Introduction

Even- and uneven-aged stands differ in many ways. One difference is that even-aged stands normally have a beginning and end point; such stands are characterized by constant changes within stand development. For uneven-aged stands on the other hand, a continuous functioning is characteristic as well as only small variations in stand characteristics (O’Hara et al., 2007).
Usually one just has to look at the diameter distribution of a stand to know, whether it is an even- or an uneven-aged stand. Table 2.1 shows two typical diameter distributions, on the left side an even-aged and on the right side an uneven-aged stand.


Figure 2.1: Two typical diameter distributions from the plots of this study. The numbers of trees in the dbh-classes are total values, not values per hectare. The left diameter distribution is one of the distributions of plot \# 100200, an even-aged stand. On the right side is a diameter distribution of plot \# 1015001, an uneven-aged stand.

The processes that take place during stand development reflect the growth of individual trees, which is determined by resource availability, resource acquisition and the efficiency of resource use (Binkley, 2009). Tree age and tree size as well as social class play a crucial part within these processes (Binkley et al., 2002).
In an even-aged stand, where all trees naturally are of approximately the same age, the size of the trees and their diameter at breast height $1.3 \mathrm{~m}(\mathrm{dbh})$ is a reflection of their social class. Consequently, suppressed trees are small, dominant trees are large. In an uneven-aged stand, the situation usually turns out to be more complex: The size of the dbh of a tree compared to the other trees in the stand is more a function of age than of social class. Within such a stand, there is a great variety of dbh-classes, whereas in an even-aged stand, the diameter distribution is much narrower.

A very interesting question is how stand structure determines the growth of the individual trees and of the stand itself. Giving an answer to this question by using the Gini-index and the growth dominance as parameters is the main goal of this study.

### 2.1 Gini-index and Lorenz curve

There exist many different methods to assess the diversity in forest stands (Neumann and Starlinger, 2001). In advance, there probably has to be pointed out that there exist also different kinds of diversity itself (Neumann and Starlinger, 2001), as for example species diversity and structural diversity (Sterba, 2008). Both types can be expressed by specific indices. For example, a simple index to assess species diversity in a forest stand is the number of species. However, there are also more complex ones like the Shannon-Index (Shannon, 1949) or Pielou's segregation index (Pielou, 1961). In contrast, structural diversity indices, for example, are the standard deviation and the Clark-Evans-index (Clark and Evans, 1954). Apart from grouping the diversity indices according to the type of diversity they measure, they can also be categorized as indices, which are spatially explicit, and such, which are spatially inexplicit (Sterba and Zingg, 2006). Spatially explicit indices, like the Pielou-index, allow assessing the microstructure within stands (Neumann and Starlinger, 2001); for most of these indices the distances between individual trees and at least their nearest neighbour is necessary. Spatially inexplicit indices, however, do not need this information and give rather an overview of the stand as a whole.

Nevertheless, and despite their differences, all of these indices have the same objectives, which are to describe stands in a verifiable and objective way as well as to make diversity measurable and comparable (Sterba and Zingg, 2006).

This study focuses on a spatially inexplicit index for measuring structural diversity, namely the Gini-index, which is closely connected to and derived from the Lorenz curve. Originally, these were developed by Lorenz (1905) and Gini (1912) respectively for economics and used for example to illustrate the income distribution within the population of a country. In forestry, they are used to analyse the structure of a stand and serve as parameters either for the homogeneity or the heterogeneity of stand structures (Stöcker, 2002).
For the calculation of the Gini-index adapted to forest stands, first of all the trees within a stand have to be sorted by their diameters in ascending order (compare example in Table 2.1); then the relative tree number and the relative basal area or relative volume are calculated. Subsequently, the relative tree number as well as the relative basal area (relative volume) have to be cumulated step by step. The Lorenz curve can be gained by plotting the cumulated relative number of trees on the $x$-axis and the corresponding cumulated relative basal area or volume on the y-axis (Lee et al., 1999, see example in Figure 2.2). If each tree had the same share of basal area (volume) as of tree number, then the Lorenz curve would be identical with the $45^{\circ}$ line in Figure 2.2. This would mean that the basal areas (volumes) in the stand were distributed in the same way as the stem numbers indicating that all trees had the same dbh or volume. However, the individual basal areas and volumes of the trees in a stand normally
differ more or less widely and as a consequence, the Lorenz curve deviates from the $45^{\circ}$ line. The extent of this divergence thus is a parameter for the variability of tree sizes in a forest stand. To record this deviation quantitatively, the area below the Lorenz curve is calculated as the sum of trapezoids of different size. The Gini-coefficient is the area between the $45^{\circ}$ line and the Lorenz curve - the so called Lorenz area (Stöcker, 2002) - calculated as the area beneath the $45^{\circ}$ line ( 0.5 ) minus the area beneath the Lorenz curve - in percent of the area below the $45^{\circ}$ line (triangle area), which is 0.5 (Dixon et al, 1987; Neumann and Starlinger, 2001; Stöcker, 2002; Lexerød and Eid, 2006; Sterba and Zingg, 2006).
A high Gini-coefficient indicates that the distribution of the basal areas (volumes) in a stand is very heterogeneous, because the more the tree sizes differ, the smaller the area below the Lorenz curve is. In contrast, a small Gini-index indicates that the stand is homogenous. The smallest value the Gini-index can reach is 0 , then the Lorenz curve is identical with the $45^{\circ}$ line and thus the Lorenz area is 0 ; that means that all trees are of the same size.
This index allows comparing the structures of different stands. Furthermore, this index can be used to analyse structural changes within a stand. However, stand structures can be manipulated by human impacts such as thinning or tree harvesting (Kramer, 1988; Linares, 2011).


Figure 2.2: The Lorenz curve from the example below. The Lorenz curve results from plotting $\Sigma b a / B A$ over $\Sigma n / N$. The red arrows show the marks for sample tree \#12, where, up to a dbh of $16.2 \mathrm{~cm}, 80 \%$ of the trees have only $8.74 \%$ share of the basal area of the stand.

Table 2.1: Simple example for the calculation of the Gini-index; The area under the Lorenz curve is calculated as the sum of trapezoids, each of which is calculated as $a_{i}=\left(\Sigma b a_{i} / B A+\Sigma b a_{i}-1 / B A\right) / 2 *$ $\left(\Sigma n_{i} / N-\Sigma n_{i}-1 / N\right)$. For example, the area for sample tree \#12: $a_{4}=(0.0874+0.0364) / 2 \cdot(0.8-$ $0.6)=0.0124$. The Gini-coefficient is then (0.5-0.1299)/0.5=0.7401 or $74.01 \%$ indicating a high variability of tree sizes in the stand.

| Sample tree <br> $\#$ | $\mathrm{dbh}[\mathrm{cm}]$ | Basal <br> area (ba) <br> $\left[\mathrm{cm}^{2}\right]$ |  |  |  |  |  | $\Sigma$ ba | $\Sigma \mathrm{ba} / \mathrm{BA}$ | Area under <br> the Lorenz <br> curve |
| :---: | ---: | ---: | ---: | ---: | ---: | ---: | :---: | :---: | :---: | :---: |
| 1 | 5.5 | 0.20 | 23.76 | 23.7583 | 0.0059 | 0.0006 |  |  |  |  |
| 3 | 8.5 | 0.40 | 56.75 | 80.5033 | 0.0199 | 0.0026 |  |  |  |  |
| 9 | 9.2 | 0.60 | 66.48 | 146.9794 | 0.0364 | 0.0056 |  |  |  |  |
| 12 | 16.2 | 0.80 | 206.12 | 353.0993 | 0.0874 | 0.0124 |  |  |  |  |
| 14 | 68.5 | 1.00 | 3685.28 | 4038.3838 | 1.0000 | 0.1087 |  |  |  |  |
|  | $\Sigma$ | 4038.38 |  |  |  |  |  |  | 0.1299 |  |

### 2.2 Deviation from equilibrium

Sterba and Zingg (2006) showed that the Gini-index is significantly correlated with the variance of deviation from equilibrium. The variance of deviation from equilibrium of uneven-aged stands is a measure to evaluate, whether such a stand is in a state of equilibrium or not. For the interpretation of this variance, Zingg and Duc (1998) suggest the following guidelines: A variance under 0.5 indicates that a stand is in a state of equilibrium. Values between 0.5 and 1 are "critical" and thus it is likely that such a stand will get into a state of imbalance; stands with variances of deviation from equilibrium that exceed 1 are not in a state of equilibrium, but in a state of imbalance. The variance of deviation from equilibrium is calculated by subtracting the predicted logarithmic number of trees within a dbh-class of the equilibrium stage from the measured logarithmic number of trees within this class and squaring these values. Then all values are summed up and divided by the number of dbhclasses.
There mainly exist two different approaches for calculating the target or equilibrium distribution of uneven-aged stands (Sterba, 2004), namely the dbh-distribution according to De Liocourt (1898) and the equilibrium model of Schütz (1975), which recently seems to be used more frequently in studies (Sterba and Zingg, 2006; Bachofen, 1999).

### 2.3 Growth dominance

Although the growth dominance, developed by Binkley (2004) and Binkley et al. (2006) is similarly calculated as the Gini-index, it is not a diversity index and it has a different meaning for stand analysis: An individual tree is - independent of its size or social class - classified as growth dominant, if its growth has a greater share of stand grow than its biomass has of stand biomass (Bradford et al., 2010). Regarding the stand level, here as well the relationship between growth and biomass is expressed by the growth dominance.

As mentioned above, the calculation of the growth dominance according to Binkley (2004) and Binkley et al. (2006) is similar to the calculation of the Gini-index. Again, the trees within a stand have to be sorted by their diameters in ascending order. The growth dominance curve (Binkley et al., 2003a) can be plotted by using the cumulated mass of trees on the x -axis and the corresponding cumulated relative growth on the $y$-axis. If each tree in the stand represented the same share of growth as of stand biomass, then the Lorenz curve would be identical with the $45^{\circ}$ line. The growth dominance-coefficient is the area below the $45^{\circ}$ line minus the area below the growth dominance curve in percent of the area below the $45^{\circ}$ line.
In contrast to the Gini-coefficient, the growth dominance can also take on values which are below 0 . This negative growth dominance, also called "reverse growth dominance", is the case when the growth dominance curve rises above the $45^{\circ}$ line.
Negative growth dominance-coefficients indicate that smaller trees have a greater proportion of stand growth than they have of stand biomass. Positive growth dominance occurs if the
growth dominance curve is below the $45^{\circ}$ line, then the larger trees account for even more of the stand growth than of the stand biomass.


Figure 2.3: Exemplary growth dominance curves.

Binkley (2004) concluded that the examined pattern of stand growth in most even-aged forests - acceleration, peak, and decline (Binkley et al., 2002) - might result from shifts in dominance among trees and from different efficiencies of resource use between the different dominance classes. When there is no dominance, efficiency use is high for all trees and stand growth is increasing, this is the case prior to canopy closure. Near canopy closure, tree sizes become more differentiated and the dominance increases, the dominant trees suppress the resource use of non-dominant trees, as a result overall stand growth is decreasing. Later on, the level of dominance decreases again, because also the efficiency of resource use of dominant trees is reduced.

In addition, Binkley (2004) and Binkley et al. (2006) stated the hypothesis that the stand development in stands with no intervention between establishment and end of observation corresponds to specific growth dominance curves and therefore also to a specific growth dominance pattern, which may also be connected to the often noticed decline in stand growth in older forests. Four phases of stand development can be distinguished.

An early phase, where there is little competition between the individuals and where the growth dominance curve follows the $45^{\circ}$ line, which means that the trees account for the same proportion of stand growth as of stand biomass.

A second phase is marked by increasing growth dominance, where larger trees suppress the growth of smaller trees and where larger trees consequently display proportionally greater growth than smaller trees. The diameter distribution becomes wider in this phase and the growth dominance curve is below the $45^{\circ}$ line.

The third phase of stand development is characterized by a decline in growth dominance, the growth dominance curve approximates to the $45^{\circ}$ line again.

In the fourth and last phase, finally reverse growth dominance appears. The larger trees account for a smaller proportion of stand growth than of stand biomass and the growth dominance curve rises above the $45^{\circ}$ line.


Figure 2.4: Exemplary growth dominance curves for the four phases of stand development after a figure in Binkley et al. (2006).

Reverse growth dominance may be caused by an acceleration in growth of the smaller trees, by a decline in growth of the dominant trees, or it may be the result of both phenomena (Binkley et al., 2006). Binkley et al. (2006) hypothesized, that reverse growth dominance
mainly resulted from declining growth of the dominant trees. Despite intensive research on that topic (cf. Ryan et al., 1997; Binkley et al. 2002; Rudnicki et al., 2003) the exact triggering causes of this decline have not been found yet, even though some possible factors have recently been identified.

Binkley's study from 2004 in two mixed species stands, the studies of Binkley et al. (2002) and (2003b) in Eucalyptus spp. plantations as well as the study by Bradford et al. (2010) supported the theory of the growth dominance pattern and its four phases in unmanaged plantations.
Binkley et al. (2006) also tested the hypothesis by examining growth dominance-coefficients in different kinds of stands, which differed in age as well as in tree species. In this study, the proposed growth dominance pattern was not consistent with the results from all stands. Also other studies (Martin and Jokela, 2004; Fernández and Gyenge, 2009) did not find the suggested pattern in various stands of Pinus species.

Theories trying to account for differences in the growth dominance patterns of different unmanaged stands either focus on species composition or environmental factors.
Binkley et al. (2006) identified for example the wind exposure of a lodgepole pine stand as a possible factor for the divergence of this stand from the expected growth dominance pattern: If trees in this stand become dominant, they also have to face a higher wind stress, that might have a limiting effect on the growth of these trees and be the reason why the growth dominance pattern in this stand is not as marked as it should be according to the theory. Another attempt to explain the growth dominance pattern of the lodgepole pine stand is, that there could be a grafted root system or a mycorrhizal network among trees in the stand, through which non dominant trees could have access to the carbohydrates of dominant trees and which as a consequence would reduce the dominance (Binkley et al., 2006). However, as such an effect would require a large net flow between the trees, which is improbable, even Binkley et al. (2006) considered this theory to be unlikely. As a possible explanation for the more or less similar growth dominance coefficients of an aspen stand in different stages, which was always close to 0 , Binkley et al. (2006) mentioned root connections among the trees and the involved interactions. These may have an influence on the growth dominance of the stand.
It might also be the case that site quality or site properties as for example elevation, inclination, precipitation and so on influence the development of the growth dominance.

A species based approach tries to explain the different growth dominance patterns by putting growth dominance in dependence on tree species and the differences in resource use of the species (Doi et al., 2010). This could for example explain, why in Eucalyptus stands high levels of growth dominance were found, but no reverse growth dominance in old stands (Doi et al. 2010), and on the other hand, Pinus stands showed a strongly developed reverse growth dominance in older stands, but never a phase two with high growth dominance (Binkley et al., 2006).

Fernández et al. (2011) explain the different growth dominance patterns of Eucalyptus sp. and Pinus sp. by their different physiological plasticity.

In a few studies also the correlation between dominance and resource use efficiency as well as between dominance and growth efficiency (= stem growth per foliar area or biomass; Waring et al., 1980), proposed by Binkley (2004) and Binkley et al. (2006), was tested. Binkley et al. (2002) found evidence according to this hypothesis in a Eucalyptus sp. stand, where no differences in resource use efficiency and growth efficiency between the trees within the stand could be observed when also the dominance was 0 , which was the case prior to canopy closure. And a high gradient in resource use efficiency and growth efficiency from large to small trees went hand in hand with a high growth dominance, which occurred after canopy closure.
In contrast to that are the results of the study by Fernández and Gyenge (2009), which did not find the postulated connection between growth dominance and water use efficiency on the one hand, and growth dominance and growth efficiency on the other hand, in stands of Pinus ponderosa. Nevertheless, Fernández and Gyenge (2009) suggested an own hypothesis, that is, that the resource use efficiency resulted from the resource availability for the individual trees themselves. Based on this hypothesis and according to the results of their study, differences in resource use efficiency can also occur before canopy closure and dominance. These differences at a very early stage of stand development might determine whether individual trees are going to be the dominant ones or the non-dominant (Fernández and Gyenge, 2009). Another possible explanation for these results is that Binkley's theory only holds for the asymmetric competition for light, while the competition for water is usually assumed to be symmetric.

Naturally, the growth dominance in an unmanaged stand will have a different course than in stands, where human intervenes deliberately in resource availability and stand structure. Because thinning treatments usually remove weaker competitors, differences in tree sizes and resource use will be less developed than in unmanaged stands. Bradford et al. (2010) examined the growth dominance in managed stands of Pinus resinosa and compared them to those in unmanaged stands. They found that the growth dominance-coefficients in unmanaged stands were all higher than those in managed stands. The growth dominance in stands, which were thinned from above, decreased with increasing age. At low stocking levels, the growth dominance tended to be negative in stands, which were thinned from above. This indicates that here the free space is better used by smaller trees. At high stocking levels the growth dominance was positive; apparently, the larger trees contribute proportionally more to stand growth than the smaller trees. In stands that were thinned from below or both from above and below, growth dominance remained close to 0 for the whole stand development. In unthinned stands of this study the growth dominance increased with increasing age between age 50 and age 91 .
Martin and Jokela (2004) discovered that in the first 18 years increasing growth dominance of a Pinus elliotti stand was even more raised by the addition of fertilizer.

## 3 Hypotheses and Objectives

In this study the following hypotheses are postulated and tested:

The Gini-index of the previous period is correlated with the growth dominance-coefficient of the following period, because stand structure influences growth and stand structure of the following period.

The more inhomogeneous a stand is (the higher Gini-index it has), the more probable it is, that its growth dominance becomes negative. This hypothesis will be especially tested by the comparison of even- and uneven-aged stands. Uneven-aged stands are usually very heterogeneous; in these stands the diameter of the trees is not a function of social class but of age. In this study, it is postulated that in uneven-aged stands, the younger smaller trees account for a greater proportion of stand growth than of stand biomass. However, the hypothesis will not only be tested by the differentiation in even and uneven-aged stands, but by another criterion of heterogeneity, which is the mixture of species within a stand. In this study, it is postulated that in a mixed stand, the stand structure is less homogeneous than in a pure stand and the growth dominance is lower because different species often occupy different optima and so the competition within a stand tends to be less. The different species can better use the resources according to their demands; niches can develop where smaller trees can grow.

Another hypothesis, which is connected with uneven-aged stands, is that the growth dominance of a stand is determined by its Gini-index and its variance of deviation from equilibrium. If this hypothesis can be corroborated that uneven-aged stands usually have a negative growth dominance, then in all probability a high variance of deviation from equilibrium results in a positive or at least a less negative growth dominance.

An objective of this study is also to find out whether there is a correlation between stand increment and growth dominance on one side, and stand increment and Gini-index on the other side. While on the one hand it is often pointed out that homogeneous even-aged stands have higher increment than heterogeneous even-aged stands (e.g. Binkley, 2009; Ryan et al., 2010; Stape et al., 2010), on the other hand uneven-aged stands showed no influence (Bachofen, 1999) or a reverse relationship (De Camino, 1976). A relationship between growth dominance and stand increment is indicated by Binkley et al. (2002), Binkley (2004) and Doi et al. (2010).

Another objective is to examine the course of the growth dominance coefficients in even- and uneven-aged stands. An important question is to explore whether there can be a uniform pattern made out for even-aged stands, and if so, will it be following the phases of Binkley (2004) and Binkley et al. (2006) in a reduced form as the stands of this study are managed; or will the development follow Bradford et al.'s (2010) conclusions for managed stands.

If no uniform pattern can be found, the different developments of growth dominance of the individual stands will be examined and maybe specific species-wise or elevation-wise patterns can be identified.

## 4 Materials and Methods

### 4.1 Plots

Originally, data material from 83 plots was available. However, some plots had to be sorted out for different reasons: on one plot no heights have been measured at all, with others, reasonable height curves could not be fitted.
Finally, a total of 65 plots were analysed in this study. The plots are situated in different parts of Switzerland. The area of the plots ranges from $1001 \mathrm{~m}^{2}$ to $20024 \mathrm{~m}^{2}$ and the elevation from 385 m to 1640 m . The plots are parts of different testing plots from thinning tests to tests on uneven-aged stands. Consequently, all stands of this study were managed and not without intervention since establishment as was the case in most of the above mentioned studies. The plots were measured several times, but the measuring periods differed from one plot to another and also within one and the same plot. Also the number of records was dissimilar. Period length was between 1 year and 13 years, number of observations varied between 3 and 18.

For the purpose of this study, the plots were classified as even- or uneven-aged and mixed or pure stands; stands were characterized as mixed from $10 \%$ share of the stand volume of other tree species onwards. The stands were sorted in even- and uneven-aged stands according to their diameter distributions and according to the testing group they belonged to. However, in some cases the problem occurred that a stand, which had been recorded for several times, would in some phases be classified as mixed and in others as pure. Due to the fact, that sometimes even-aged stands had been turned into uneven-aged stands, characterizing the stands in even- and uneven-aged could imply similar difficulties. In these cases, the predominant stand characteristics were chosen. All in all, there were 29 pure even-aged stands, 2 pure uneven-aged stands, 22 mixed even-aged stands and 12 mixed uneven-aged stands (compare Table 4.1).

Table 4.1: Plots of the study (Plot 1021000 is classified as even-aged (*e) although it belongs to a testing group "uneven-aged stands", because the diameter distribution of this stand corresponds for most of the records to that of even-aged stands)

| $\begin{aligned} & \ddot{0} \\ & \text { en } \\ & \vdots \\ & \frac{0}{2} \end{aligned}$ |  |  |  |  | ت 0 0 0 0 0 0 0 0 0 |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1002000 | 3955 | 1475 | 1898 | 1995 | e | m | Hospental |
| 1012000 | 4984 | 1630 | 1905 | 1992 | e | m | Morissen |
| 1013000 | 4949 | 1640 | 1905 | 1992 | e | m | Morissen |
| 1015001 | 17824 | 947 | 1906 | 1993 | u | m | Niederhünigen |
| 1015002 | 12373 | 931 | 1906 | 1993 | u | m | Niederhünigen |
| 1019000 | 19880 | 575 | 1908 | 1991 | u | m | Oppligen |
| 1021000 | 4000 | 1050 | 1912 | 1993 | * e | m | Oberhünigen |
| 1027000 | 19852 | 861 | 1912 | 1996 | u | m | Bowil |

Table 4.1: (continued)

| $\begin{aligned} & \# \\ & \frac{\#}{a} \end{aligned}$ |  |  |  |  |  |  | 它 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1028000 | 11826 | 920 | 1912 | 1996 | u | m | Bowil |
| 1030003 | 5946 | 883 | 1914 | 1997 | u | m | Lauperswil |
| 1031000 | 13081 | 920 | 1919 | 1997 | u | m | Landiswil |
| 1041000 | 14998 | 1294 | 1928 | 1995 | u | m | Rougemont |
| 1042000 | 20024 | 1185 | 1928 | 1995 | u | m | Rougemont |
| 1046000 | 19966 | 930 | 1932 | 1996 | u | m | Oberlangenegg |
| 2016000 | 3332 | 520 | 1907 | 1990 | e | m | Murten |
| 2017000 | 3333 | 530 | 1907 | 1990 | e | m | Murten |
| 2018000 | 5011 | 530 | 1907 | 1990 | e | m | Murten |
| 2035000 | 19797 | 983 | 1913 | 1998 | u | m | Buttes |
| 2042000 | 5000 | 670 | 1921 | 1992 | e | m | Biel-Bienne |
| 2043000 | 5002 | 670 | 1921 | 1992 | e | m | Biel-Bienne |
| 13007005 | 2000 | 480 | 1943 | 1996 | e | p (larch) | Schaffhausen |
| 13007006 | 2022 | 480 | 1943 | 1996 | e | p (larch) | Schaffhausen |
| 13007007 | 2011 | 480 | 1943 | 1996 | e | p (larch) | Schaffhausen |
| 13007023 | 1001 | 480 | 1940 | 1996 | e | m | Schaffhausen |
| 21012000 | 2471 | 460 | 1889 | 1963 | e | p (fir) | Olten |
| 21221000 | 1991 | 1515 | 1898 | 1985 | e | p (fir) | Hospental |
| 21290000 | 5000 | 960 | 1919 | 1997 | e | m | Landiswil |
| 21293001 | 15261 | 1370 | 1926 | 1997 | u | p (fir) | Sigriswil |
| 21293002 | 4898 | 1405 | 1926 | 1997 | u | p (fir) | Sigriswil |
| 21294000 | 19960 | 1340 | 1926 | 1994 | u | m | Chenit |
| 22034000 | 2000 | 385 | 1986 | 1996 | e | m | Künten |
| 22035000 | 2000 | 385 | 1986 | 1996 | e | m | Künten |
| 24019000 | 4967 | 570 | 1927 | 1990 | e | m | Maienfeld |
| 24020000 | 3289 | 660 | 1927 | 1992 | e | p (larch) | Untervaz |
| 24031010 | 1998 | 535 | 1944 | 1996 | e | m | Lenzburg |
| 24031011 | 1995 | 535 | 1944 | 1996 | e | m | Lenzburg |
| 24031020 | 1998 | 535 | 1944 | 1996 | e | m | Lenzburg |
| 24031021 | 1995 | 535 | 1944 | 1996 | e | m | Lenzburg |
| 25015000 | 3800 | 495 | 1928 | 1990 | e | m | Wettingen |
| 36001001 | 1580 | 455 | 1963 | 1997 | e | p (Jap. larch) | Oensingen |
| 36001002 | 1580 | 455 | 1963 | 1997 | e | p (Jap. larch) | Oensingen |
| 36001003 | 1580 | 455 | 1963 | 1997 | e | p (Jap. larch) | Oensingen |
| 36001004 | 1580 | 455 | 1963 | 1997 | e | p (Jap. larch) | Oensingen |
| 36001005 | 1580 | 455 | 1963 | 1997 | e | p (Jap. larch) | Oensingen |
| 36002001 | 1580 | 455 | 1964 | 1997 | e | p (Jap. larch) | Oensingen |
| 36002002 | 1580 | 455 | 1964 | 1997 | e | p (Jap. larch) | Oensingen |
| 36002003 | 1580 | 455 | 1964 | 1997 | e | p (Jap. larch) | Oensingen |
| 36002004 | 1580 | 455 | 1964 | 1997 | e | p (Jap. larch) | Oensingen |
| 36002005 | 1580 | 455 | 1964 | 1997 | e | p (Jap. larch) | Oensingen |
| 41014000 | 2502 | 510 | 1889 | 1997 | e | p (beech) | Zofingen |
| 41017000 | 2502 | 560 | 1889 | 2001 | e | p (beech) | Zofingen |
| 41018000 | 2499 | 560 | 1889 | 2001 | e | p (beech) | Zofingen |
| 41022000 | 2501 | 475 | 1889 | 1994 | e | p (beech) | Aarburg |
| 41023000 | 2500 | 485 | 1889 | 1978 | e | p (beech) | Aarburg |
| 41024000 | 2500 | 485 | 1889 | 1994 | e | p (beech) | Aarburg |
| 41036000 | 2500 | 530 | 1890 | 1950 | e | m | Concise |
| 41118000 | 2000 | 490 | 1893 | 1997 | e | p (beech) | Zofingen |
| 41193000 | 1673 | 585 | 1905 | 1991 | e | p (beech) | Embrach |
| 41194000 | 2499 | 585 | 1905 | 1991 | e | p (beech) | Embrach |
| 42005000 | 5000 | 505 | 1922 | 1991 | e | m | Winterthur |
| 42018000 | 3003 | 445 | 1926 | 1991 | e | m | Galmiz |
| 61018104 | 2525 | 475 | 1922 | 1991 | e | p (oak) | Payerne |
| 61018203 | 1955 | 475 | 1922 | 1991 | e | p (oak) | Payerne |
| 61018206 | 2359 | 475 | 1921 | 1991 | e | p (oak) | Payerne |
| 61029107 | 3056 | 420 | 1926 | 1995 | e | p (oak) | Dietikon |

### 4.2 Analysis

### 4.2.1 Dataset

At each measurement, the dbh of every tree within a plot was recorded as well as the heights of some of the trees. The dbh-classes started with 10 cm , all smaller dbh were sorted out.

### 4.2.2 Height curves

With this data, for each stand, record and species two height curves were calculated according to the general height curve types in equation 4.1 and equation 4.2. Subsequently, the equation with higher $\mathrm{R}^{2}$ was chosen and with this equation, predicted heights were calculated for all trees of the stand.

$$
\begin{gather*}
\ln (h-1.3)=a+b * \frac{1}{d} \\
\frac{1}{\sqrt{h-1.3}}=a+b * \frac{1}{d}
\end{gather*}
$$

However, for some records no heights had been measured at all and at other times, measured heights were not available for all species. For these cases, overall height curves with the data of all plots were calculated for each species according to equation 4.3 (modified version of Pollanschütz's (1974a) general height curve). In this formula, tree height is determined by the quadratic mean diameter of the stand as a measure for the age of the stand, the basal area per hectare, which is a measure for the density of the stand, and naturally the diameter at breast height of the tree. This equation allowed estimating heights for trees, even if no height for this species had been measured at the record or no heights were available for this species in the stand at all.

$$
\frac{1}{\sqrt{(h-1.3)}}=a 0+a 1 * \ln (\mathrm{dg})+\mathrm{a} 2 * \ln (\mathrm{G})+\mathrm{b} 0 * \frac{1}{\mathrm{~d}}+\mathrm{b} 1 * \ln (\mathrm{dg}) * \frac{1}{\mathrm{~d}}+\mathrm{b} 2 * \ln (\mathrm{G}) * \frac{1}{\mathrm{~d}}
$$

The coefficients for equation 4.3 according to the different species are shown in Table 4.2.

Table 4.2: Coefficients for equation 4.3 for different species.

| Species | a 0 | a 1 | a 2 | b 0 | b 1 | b 2 | Sample <br> size | $\mathrm{R}^{2}$ |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Picea abies | 0.23334 | -0.03676 | 0.00713 | 1.09428 | 0.56355 | -0.20126 | 8925 | 0.866 |
| Abies alba | 0.25503 | -0.05024 | 0.01583 | 1.80786 | 1.12575 | -0.96769 | 6715 | 0.883 |
| Pinus silvestris | 0.16792 | -0.06023 | 0.05355 | 4.25916 | 0.90035 | -1.57275 | 120 | 0.849 |
| Larix decidua | 0.24825 | -0.04012 | 0.01658 | 2.76120 | -0.32598 | -0.21453 | 2762 | 0.855 |
| Pinus strobus | 0.35010 | -0.05550 | 0 | 1.63070 | 0.69300 | -0.66770 | 202 | 0.968 |
| Pinus cembra | -0.01098 | -0.04009 | 0.08465 | 13.59440 | -0.80265 | -2.35584 | 835 | 0.888 |
| Larix kaempferi | 0.61110 | -0.03388 | -0.08831 | 0.62817 | -0.73848 | 0.65893 | 2941 | 0.936 |
| Fagus sylvatica | 0.23102 | -0.04113 | 0.01510 | 0 | 1.05792 | -0.58448 | 8226 | 0.727 |
| Quercus sp. | 0.38357 | -0.02825 | -0.03873 | 0.46415 | 0 | 0.19225 | 2068 | 0.912 |
| Other deciduous trees | 0.60658 | -0.10138 | -0.03311 | -4.57745 | 1.41841 | 0.42203 | 317 | 0.728 |

### 4.2.3 Volume estimation

Subsequently, the volume of each tree was calculated using the volume equation 4.4 and the form factor function according to Pollanschütz (1974b).

$$
\begin{gather*}
V=f * h e i g h t[m] * \frac{d b h[m]^{2} * \pi}{4} \\
f=b 1+b 2 * \ln ^{2(\mathrm{dbh}[\mathrm{dm}])}+b 3 * \frac{1}{h[d m]}+b 4 * \frac{1}{d b h[d m]}+b 5 * \frac{1}{d b h[d m]^{2}} \\
+b 6 * \frac{1}{d b h[d m] * h[d m]}+b 7 * \frac{1}{d b h[d m]^{2} * h[d m]}
\end{gather*}
$$

The coefficients for equation 4.5 were taken from Pollanschütz (1974b). As for these species no own coefficients were available, for Pinus strobus the coefficients of Pinus silvestris were used, the volume for Larix kaempferi was calculated with the coefficients of Larix decidua and the coefficients of Fagus sylvatica were additionally used for Juglans regia, Tilia sp., Prunus avium, Sorbus sp. and "other deciduous trees".

### 4.2.4 Increment estimation

In a next step, the increment of each individual tree was calculated by subtracting the volume of the previous measurement from that of the following measurement and dividing this value by the length of the interval between the two measurements.
Stand annual increment was calculated by summing the annual increments of the individual trees up and adding the annual ingrowths (ingrowth of record divided by interval length) and converting these plot-values to ha-values.

### 4.2.5 Gini-index

The Gini-index was calculated from cumulative stem numbers and volumes as described in 2.1.

### 4.2.6 Growth dominance

The growth dominance was calculated not with biomass and biomass growth as proposed by Binkley (2004) and Binkley et al. (2006), but with stem volume and volume increment instead.

### 4.2.7 Variance of deviation from equilibrium

The variance of deviation from equilibrium was calculated for all uneven-aged stands of the study according to the equation proposed by Zingg and Duc (1998).
In a state of equilibrium, when plotting the dbh-classes of a stand on the x -axis and the corresponding logarithmic number of trees in each class on the $y$-axis, the result is a straight line from top left to bottom right (compare right side in Figure 4.1). The more the actual curve (Figure 4.4, left side) differs from this equilibrium line, the more the uneven-aged stand is in a state of imbalance.
The equation for calculating the variance of deviation from equilibrium is shown below (equation 4.6), where $n$ is the number of dbh-classes, Nmeas is the measured number of trees in a dbh-class and Npred is the predicted number of trees in the dbh-class in a state of equilibrium. The dbh-classes started with 10 cm and were 5 cm wide.
The predicted number of trees in the different dbh-classes was obtained by calculating a hypothetical balanced diameter distribution, for which a regression between $\ln$ Nmeas and bhd-class was calculated resulting in, as explained above, a straight line. This approach is slightly different from that proposed by Zingg and Duc (1998) and Sterba and Zingg (2006), where the equilibrium-diameter distributions were constructed with diameter increments and percentages of removal according to Schütz (1975).

$$
\text { Var }=\frac{1}{n} * \sum_{i=0}^{n}(\ln \text { Nmeas }-\ln \text { Npred })^{2}
$$



Figure 4.1: Example of the diameter distribution of an uneven-aged stand on the left side and the corresponding distribution of the stand in a state of equilibrium on the right side. Dbh-class 1 means here the class from $10-15 \mathrm{~cm}$, class 2 is from $15.1-20 \mathrm{~cm}$ and so forth. In this example, the variance of deviation from equilibrium was 0.3908 .

### 4.2.8 Statistical methods

All calculations and statistical analyses were conducted with the statistical software package R ( R Core Team, 2012). Mean values and standard deviations were used to describe the data; analyses of variance and Tukey's test were run to test for differences between the different classes of stands.
Furthermore, various simple and multiple linear regressions as well as analyses of variance to analyse these regressions were applied to the dataset.

## 5 Results

### 5.1 Mean values

The mean values for the Gini-index given in Table 5.1 as well as Figure 5.1 show that on average, the uneven-aged stands were more heterogeneous than the even-aged stands. A mixture of species heightened the heterogeneity both in even- and uneven-aged stands.
In the uneven-aged stands the average growth dominance was negative, whereas in the evenaged stands it was slightly positive. A mixture of species in uneven-aged as well as in evenaged stands resulted in lower growth dominance-coefficients compared to the values in pure uneven-aged and even-aged stands respectively (compare Table 5.2 and Figure 5.2).
Pure even-aged stands had the highest mean value for the growth dominance; in these stands the average Gini-index was the smallest. In contrast, the highest mean for the Gini-index found in mixed uneven-aged stands went hand in hand with the lowest average growth dominance.

Table 5.1: Mean values and standard deviations of the Gini-index for the different categories of stands.

| GINI |  | pure | mixed | all |
| :--- | :--- | ---: | ---: | ---: |
| even | mean | 0.2849 | 0.3607 | $\mathbf{0 . 3 1 8 6}$ |
|  | stand. dev. | 0.1063 | 0.1091 | $\mathbf{0 . 1 1 3 9}$ |
|  | sample size | 263 | 211 | $\mathbf{4 7 4}$ |
| uneven | mean | 0.5086 | 0.6375 | $\mathbf{0 . 6 2 5 6}$ |
|  | stand. dev. | 0.0480 | 0.0824 | $\mathbf{0 . 0 8 8 1}$ |
|  | sample size | 16 | 157 | $\mathbf{1 7 3}$ |
| all | mean | $\mathbf{0 . 2 9 7 7}$ | $\mathbf{0 . 4 7 8 8}$ | $\mathbf{0 . 4 0 0 7}$ |
|  | stand. dev. | $\mathbf{0 . 1 1 6 2}$ | $\mathbf{0 . 1 6 8 8}$ | $\mathbf{0 . 1 7 3 3}$ |
|  | sample size | $\mathbf{2 7 9}$ | $\mathbf{3 6 8}$ | $\mathbf{6 4 7}$ |

Table 5.2: Mean values and standard deviations of the growth dominance-coefficients for the different categories of stands.

| GrowthDom |  | pure | mixed | all |
| :--- | :--- | ---: | ---: | ---: |
| even | mean | 0.0495 | 0.0104 | $\mathbf{0 . 0 3 2 1}$ |
|  | stand. dev. | 0.0576 | 0.0615 | $\mathbf{0 . 0 6 2 4}$ |
|  | sample size | 234 | 189 | $\mathbf{4 2 3}$ |
| uneven | mean | -0.0715 | -0.1586 | $\mathbf{- 0 . 1 5 0 9}$ |
|  | stand. dev. | 0.0807 | 0.1073 | $\mathbf{0 . 1 0 7 9}$ |
|  | sample size | 14 | 145 | $\mathbf{1 5 9}$ |
| all | mean | $\mathbf{0 . 0 4 2 7}$ | $\mathbf{- 0 . 0 6 3 0}$ | $\mathbf{- 0 . 0 1 7 9}$ |
|  | stand. dev. | $\mathbf{0 . 0 6 5 3}$ | $\mathbf{0 . 1 1 8 9}$ | $\mathbf{0 . 1 1 2 5}$ |
|  | sample size | $\mathbf{2 4 8}$ | $\mathbf{3 3 4}$ | $\mathbf{5 8 2}$ |



Figure 5.1: Box-and-whisker plot of the distribution of the Gini-indices within the four stand classes "mixed/even-aged", "mixed/uneven-aged", "pureleven-aged" and "pure/uneven-aged". The solid black lines show the median ( $2^{\text {nd }} q u a r t i l e, 50^{\text {th }}$ percentile); the two lines that form the box are the $1^{\text {st }}$ quartiles ( $25^{\text {th }}$ percentile) and the $3^{\text {rd }}$ quartiles ( $75^{\text {th }}$ percentile); the whiskers are the minima and maxima within $1.5 *$ interquartile range from the $1^{s t}$ and $3^{\text {rd }}$ quartile; points beyond the whiskers are outliers, which are smaller or larger than the whiskers.


Figure 5.2: Box-and-whisker plot of the distribution of the growth dominance-coefficients within the four stand classes "mixed/even-aged", "mixed/uneven-aged", "pureleven-aged" and "pure/unevenaged". For interpretation compare Figure 5.1.

The analyses of variance with stand class as fixed and plot number as random factor pointed out that there were significant differences between the mean values of the four classes mixed even-aged, mixed uneven-aged, pure even-aged and pure uneven-aged in regard of the Giniindex as well as in regard of the growth dominance.

Applying Tukey's test to the data, the results in Table 5.3 show that except for the pure uneven-aged and mixed uneven-aged stands the mean Gini-indices of the stand classes were significantly different from each other. Also the mean values of the growth dominance of the four classes all differed significantly from each other (Table 5.4). Nevertheless, the difference between even-aged and uneven-aged seemed to be higher than between mixed and pure.

Table 5.3: Results from Tukey's test for the Gini-index.


Table 5.4: Results from Tukey's test for the growth dominance.

```
Linear Hypotheses:
    Estimate Std. Error z value Pr(>|z|)
mixed/uneven - mixed/even == 0 -0.16480 0.01563 -10.542 < 0.001 ***
pure/even - mixed/even == 0 0.03471 0.01279 2.715 0.02939 *
pure/uneven - mixed/even == 0 - -0.08202 0.03343 -2.453 0.05978 .
pure/even - mixed/uneven == 0 0.19951 0.01493 13.359 < 0.001 ***
pure/uneven - mixed/uneven == lllllll}
pure/uneven - pure/even == 0 -0.11673 0.03311 -3.526 0.00208 **
---
Signif. codes: 0 `***' 0.001 `**' 0.01 `*' 0.05 '.' 0.1 v' 1
```


### 5.2 Gini-index and growth dominance

By plotting the growth dominance-coefficients on the y-axis and the corresponding Giniindices of the previous record on the $x$-axis (Figure 5.3), an impact of the Gini-index on growth dominance is obvious. The pattern of the relationship clearly is a curve with the general trend that the higher the Gini-index is, the more the growth dominance-coefficient tends to get negative (Figure 5.4).
Hence, it is possible to distinguish between the different classes of stands (Figure 5.3). The majority of the values for pure even-aged stands are situated in the upper left corner of the diagram, where highest growth dominance-coefficients combined with lowest Gini-indices are located. The majority of the values for mixed even-aged stands are situated below the
values for the pure stands clearly having lower growth dominance-coefficients than the pure even-aged stands. In contrast, the spectrum of corresponding Gini-indices was not wider than it was in pure even-aged stands; however, whereas most of the pure stands have values that are on the left side of the diagram indicating low Gini-indices, the distribution of Gini-indices for mixed even-aged stands is quite balanced between left (low Gini indices indicating homogeneous stands) and right (high Gini-indices indicating heterogeneous stands). On the lower right-hand corner of the diagram, where the majority of the values for mixed unevenstands are located, highest Gini-indices are combined with lowest growth dominancecoefficients. Most of the values for pure uneven-aged stands are positioned in-between the values for even-aged stands and that of mixed uneven-aged stands.


Figure 5.3: Growth dominance-coefficients and Gini-coefficients of the previous record for all plots and all records.


Figure 5.4: Growth dominance coefficients and Gini-coefficients of the previous record for all plots and all records. The different colours represent the different classes of stands. The fine solid lines between the points show the development of Gini-indices and growth dominance-coefficients within the different stands themselves. The thick black line shows the trend of the relationship expressed by smoothed means.

When the relationship between growth dominance and Gini-index was calculated as a parabola, an $\mathrm{R}^{2}$ of 0.562 was reached, which indicates that $56.2 \%$ of the deviation squares of the growth dominance can be explained by the relationship to the Gini-index of the previous period.

### 5.3 Gini-index and annual increment per ha

A relationship between Gini-index of the previous period and the annual increment per ha was not obvious (Figure 5.5).
However, the highest values of increment were reached when the Gini-index was low indicating homogeneous stands. On the other hand, with nearly the same Gini-indices also the lowest increment values were combined. When looking at the different classes of stands in Figures 5.6 and 5.7 it is remarkable that the highest and lowest values for the annual increment at nearly the same Gini-index of the previous period all occurred within pure evenaged stands.

Within one and the same stand class a distinct relationship between annual increment per ha and Gini-index could not be identified either (Figure 5.7). It is interesting however, that in mixed uneven-aged stands the highest increments went hand in hand with the lowest Giniindices of this class.
Differences between the annual increments of the different classes of stands were also not found, except for the pure uneven-aged stands, which obviously had on average the lowest annual increments, (Figure 5.6). Nevertheless, the small sample size of this class has to be taken into account.


Figure 5.5: Annual volume increments per hectare and Gini-coefficients of the previous record for all plots and all records. The solid line shows the trend of the relationship expressed by smoothed means.


Figure 5.6: Box-and-whisker plot of the distribution of the annual increments per ha within the four stand classes "mixed/even-aged", "mixed/uneven-aged", "pure/even-aged" and "pure/uneven-aged". For interpretation compare Figure 5.1.


Figure 5.7: Annual volume increments per hectare and Gini-coefficients of the previous record for all plots and all records.

However, after adding the elevation as variable, for all uneven-aged stands a significant impact of the Gini-index on annual increment was found. The regression

$$
\text { Increment }=a+b * \text { Gini }+c * \text { Elevation }
$$

with the coefficients of Table 5.5 reached an $\mathrm{R}^{2}$ of 0.427 . This relationship indicates that with decreasing Gini-index and decreasing elevation, the annual volume increment per ha increases.

Table 5.5: Coefficients and significance of variables for equation 5.1.

```
Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) 31.287515 2.603100 12.019 < 2e-16 ***
Gini -12.722689 2.961332 -4.296 3.2e-05 ***
Elev -0.012238 0.001172 -10.446 < 2e-16 ***
Signif. codes: 0 v***' 0.001 v**' 0.01 v*' 0.05 '.' 0.1 v'r 1
```

For the even-aged stands on the other hand, equation 5.1 only reached an $\mathrm{R}^{2}$ of 0.004 . When additionally stand age was used as a variable (equation 5.2), an $\mathrm{R}^{2}$ of 0.085 was reached, but solely stand age was significantly correlated with annual increment per ha (Table 5.6).

$$
\text { Increment }=a+b * \text { Gini }+c * \text { Elevation }+d * \text { Age }
$$

Table 5.6: Coefficients and significance of variables for equation 5.2.

```
Coefficients:
    Estimate Std. Error t value Pr(>|t|)
(Intercept) 17.1612950 1.2252463 14.006 < 2e-16 ***
```



```
Elev -0.0003834 0.0009150 -0.419 0.675
Age -0.0570489 0.0098111 -5.815 1.32e-08 ***
---
Signif. codes: 0 `***' 0.001 `**' 0.01 `*' 0.05 '.' 0.1 v' 1
```


### 5.4 Growth dominance and annual increment per ha

The annual increment per ha had also no obvious relationship to the growth dominance, although highest increments were combined with a growth dominance that was slightly positive (Figure 5.8). Here, a trend could possibly be identified indicating that the increment would be highest if the growth dominance was positive and close to 0 ; however, as there were also other examples, where the increment was very low at approximately the same growth dominance-coefficient, the trend was rather weak. Both extremes were again found within pure even-aged stands (Figure 5.9).


Figure 5.8: Annual volume increments per hectare and growth dominance-coefficients for all plots and all records. The solid line shows the trend of the relationship expressed by smoothed means.


Figure 5.9: Annual volume increments per hectare and growth dominance-coefficients for all plots and all records.

After sorting the stands again according to their structure, for all uneven-aged stands the equation

$$
\text { Increment }=a+b * \text { GrowthDom }+c * \text { Elevation }
$$

with the coefficients of Table 5.7 reached an $\mathrm{R}^{2}$ of 0.428 . The growth dominance was positively correlated with the annual increment meaning that high growth dominancecoefficients indicate high increments; the elevation on the other hand, was again negatively correlated with the increment.

Table 5.7: Coefficients and significance of variables for equation 5.3.

```
Coefficients:
    Estimate Std. Error t value Pr(>|t|)
(Intercept) 23.564769 1.150362 20.485 < 2e-16 ***
GrowthDom 9.453092 2.109026 4.482 1.42e-05 ***
Elev -0.011054 0.001029 -10.747 < 2e-16 ***
---
Signif. codes: 0 v***' 0.001 v**' 0.01 v*' 0.05 '.' 0.1 ' ' 1
```

The even-aged stands, in contrast, only reached an $R^{2}$ of 0.035 with equation 5.3. When again, stand age was added as variable (equation 5.4) an $\mathrm{R}^{2}$ of 0.099 was reached with stand age and growth dominance being significant (Table 5.8).

$$
\text { Increment }=a+b * \text { GrowthDom }+c * \text { Elevation }+d * \text { Age }
$$

Table 5.8: Coefficients and significance of variables for equation 5.4.

```
Coefficients:
Estimate Std. Error t value Pr(>|t|)
(Intercept) 1.750e+01 7.335e-01 23.862 < 2e-16 ***
GrowthDom -1.120e+01 3.956e+00 -2.831 0.00486 **
Elev lllll
Age
    -4.649e-02 8.355e-03 -5.565 4.7e-08 ***
---
Signif. codes: 0 v***' 0.001 v**' 0.01 v*' 0.05 '.' 0.1 v' 1
```


### 5.5 Development of growth dominance-coefficients within stands



Figure 5.10: Growth dominance-coefficients and Gini-coefficients of the previous record for all plots and all records. The different colours represent the different plots; the lines between points of the same colour show the development of growth dominance-coefficients and Gini-indices within a plot.

For all stands, the development of the growth dominance showed no general trend (Figure 5.10, compare appendix) and within the even-aged stands, neither could a pattern be identified: in some cases, growth dominance tended to increase with increasing age (Figure 5.11), in other cases it decreased (Figure 5.12) and yet in others, the development of the growth dominance resembled more the pattern of most uneven stands (compare Figures 5.16 and 5.17), which seemed to be unpredictable showing a constant up and down of growth dominance-coefficients.

Even within even-aged stands of the same species and approximately of the same elevation, no specific patterns could be detected. For example, in three pure even-aged larch stands (\#13007005, \#13007006 and \#13007007), all at an elevation of 480 m , growth dominance decreased with increasing age (compare Figure 5.12); growth dominance-coefficients were in all three stands negative at the last record at the age of 56 . However, when the course of plot \#24020000 (Figure 5.13) with a similar elevation of 660 m and starting at the age of 66 was added to the course in Figure 5.12, the two courses did not match, because stand \#24020000 had a positive growth dominance at the beginning (Figure 5.14).

Another example for different growth dominance developments within even-aged stands of the same species is illustrated with Figures 5.15 and 5.16. The growth dominance curves of the two beech stands start at approximately the same stand age (plot \#41018000 and plot \#41118000 were first measured at the age of 31 and at the age of 26 respectively). Also the last records for plots $\# 41018000$ and $\# 41118000$ were taken at a similar stage of stand development at the age of 140 and 125 respectively. Additionally, the two stands had similar elevations of 560 m and 490 m . Despite these facts, the course of the growth dominance in the one stand was very different from the course in the other stand: In plot \# 41018000 (Figure 5.15) the growth dominance increased up to an age of 93 ; then it decreased and finally increased again. On the other hand, the development in plot \#41118000 (Figure 5.16) was characterized by a constant up and down of growth dominance-coefficients.


Figure 5.11: Development of growth dominance-coefficients in plot \#1002000 (even-aged, mixed).


Figure 5.12: Development of growth dominancecoefficients in plot \#13007005 (even-aged, larch).


Figure 5.13: Development of growth dominancecoefficients in plot \#24020000 (even-aged, larch).


Figure 5.14: Combination of the curves in Figure 5.12 and Figure 5.13.


Figure 5.15: Development of growth dominancecoefficients in plot \#41018000 (even-aged, beech).


Figure 5.16: Development of growth dominancecoefficients in plot \#41118000 (even-aged, beech).


Figure 5.17: Development of growth dominance-coefficients in plot \#1015002 (uneven-aged, mixed).

### 5.6 Growth dominance, Gini-index and deviation from equilibrium

The correlation between growth dominance and variance of deviation from equilibrium is illustrated in Figure 5.18. Most of the uneven-aged stands in this study were in a state of equilibrium according to Zingg and Duc (1998) and Sterba and Zingg (2006) meaning that the variance of deviation from equilibrium was below 0.5 .
Growth dominance and variance were positively correlated indicating that the higher the variance of deviation from equilibrium of the previous period is, the more the growth dominance increases. The regression reached an $\mathrm{R}^{2}$ of 0.087 .


Figure 5.18: Correlation of growth dominance and variance of deviation from equilibrium of previous record for all uneven-aged plots. The solid line shows the regression line according to the equation scheme GrowthDom $=a+b *$ Var.

Analysing the development of growth dominance and variance of deviation from equilibrium within two plots, one being balanced (Figure 5.19) and the other being rather unbalanced, (Figure 5.20), the relationship between variance of deviation from equilibrium and growth dominance was indicated: The relationship was not as strong, that the variance could predict differences between growth dominance-coefficients within the stands in all accuracy; however, after comparing the values of the two stands, a clear trend was visible indicating the positive correlation between growth dominance and variance.
In some cases however, the variance of deviation from equilibrium might additionally be valuable to predict trends of the development of growth dominance within a stand: In the balanced stand, where the variances of deviation from equilibrium were constantly below 0.5 , the growth dominance-coefficients were negative. On the other hand, the growth dominance-
coefficients in the unbalanced stand were predominantly positive, especially when the variances of deviation from equilibrium of the previous period were high.
The values for growth dominance-coefficients, Gini-indices and variances of the two stands imply that as long as growth dominance-coefficients in uneven-aged stands remain negative, the Gini-index of the previous period is a sufficient indicator to predict the growth dominance satisfactorily; however, when growth dominance-coefficients get positive, adding the variance of deviation from equilibrium of the previous period as a variable would probably lead to results, that were more precise than those gained by using solely the Gini-index.


Figure 5.19: Plot \#1015001: uneven-aged stand in a state of equilibrium.


Figure 5.20: Plot \#1030003: unbalanced uneven-aged stand.


Figure 5.21: Correlation of Gini-index and variance of deviation from equilibrium for all unevenaged plots. The solid line shows the regression line according to the equation scheme Gini $=a+b *$ Var.

Gini-indices and variances of deviation from equilibrium were negatively correlated (Figure 5.21) with an $\mathrm{R}^{2}$ of 0.288 .

The $\mathrm{R}^{2}$ of the regression between growth dominance and Gini-index for all uneven-aged stands in this study could not be heightened by adding the variance of deviation from equilibrium as a variable to predict the growth dominance.

### 5.7 Gini-index and growth dominance in uneven-aged stands

When analysing only the uneven-aged stands, the best fit for the correlation between growth dominance and Gini-index of the previous record was not a parabola or curve, but a linear regression according to the formula

$$
\text { GrowthDom }=0.27547-0.6601 * \text { Gini }
$$

reaching an $\mathrm{R}^{2}$ of 0.265 (Figure 5.22).


Figure 5.22: Growth dominance-coefficients and Gini-coefficients of the previous record for all uneven-aged plots with the regression line according to the equation scheme GrowthDom $=a+b *$ Gini.

### 5.8 Gini-index and growth dominance in even-aged stands

Examining solely the even-aged stands (Figure 5.23), the relationship between growth dominance and Gini-index was not as marked as in uneven-aged stands (compare figure 5.22). The equation scheme of a parabola reached an $R^{2}$ of 0.036 compared to an $R^{2}$ of 0.018 , which was reached when computing a regression according to the linear regression scheme. Figure 5.23 shows, that the growth dominance-coefficients in the even-aged stands were predominantly close to 0 , even though the corresponding Gini-indices of the previous record sometimes reached very high values of for example 0.6 .


Figure 5.23: Growth dominance-coefficients and Gini-coefficients of the previous record for all evenaged plots with the regression line according to the equation scheme GrowthDom $=a+b * G i n i+$ $c *$ Gini $^{2}$.

### 5.9 Gini-index and growth dominance in mixed and pure stands

Comparing the relationship between Gini-index and growth dominance in mixed and pure stands in Figure 5.24 and in Figure 5.25 respectively, the shape of the two curves calculated according to the parabola-scheme resemble each other (compare also equations 5.7 and 5.8).

In the mixed stands, with equation 5.7, an $\mathrm{R}^{2}$ of 0.541 was reached, whereas the linear regression scheme reached an $\mathrm{R}^{2}$ of 0.461 .

$$
\text { GrowthDom }=-0.10504+0.84631 * \text { Gini }-1.36813 * \text { Gini }^{2}
$$

In the pure stands, equation 5.8 reached an $\mathrm{R}^{2}$ of 0.106 .

$$
\text { GrowthDom }=-0.11880+1.04522 * \text { Gini }-1.50089 * \text { Gini }^{2}
$$



Figure 5.24: Growth dominance-coefficients and Gini-coefficients of the previous record for all mixed plots with regression line according to the equation scheme GrowthDom $=a+b * G i n i+c * G i n i{ }^{2}$.


Figure 5.25: Growth dominance-coefficients and Gini-coefficients of the previous period for all pure plots with regression line according to the equation scheme GrowthDom $=a+b * G i n i+c * G i n i{ }^{2}$.

## 6 Discussion

### 6.1 Critical evaluation on the methods used

In this study, heights were not predicted by interpolating or extrapolating height curves of the stand, but for each measurement own height curves were calculated for each species. In cases, where this was not possible, overall height curves for the different species according to equation 4.3 were used. In some of the stands of the originally available data, the height curves for the different records were not compatible at all and many negative volume increments were the consequence; hence, these plots were sorted out. In addition, some of the measuring periods within stands were deleted when no heights had been measured at all and equation 4.3 had led to improbable heights compared to the previous and the following record. As a consequence, relatively long intervals between two measurements could occur at calculating.
Another point, that has to be critically judged, is that the intervals between the measurements were not of the same length. Hence, the comparability of the values might probably be reduced.
For the comparability with other studies, it might also be problematic, that growth dominance was calculated with stand volume instead of stand biomass. Nevertheless, as these two should be positively correlated - also Stape et al. (2010) use for their biomass equations exclusively height and dbh as variables - the difference between the two calculation approaches should only be marginally.
Also the equilibrium state of uneven-aged stands was calculated differently than in other studies (Sterba and Zingg, 2006; Bachofen, 1999), which adopted the approach proposed by Schütz (1975).
The equation for calculating the variance of deviation from equilibrium in this study follows the scheme used by Sterba (2004) and is slightly different from that in Sterba and Zingg (2006), where the sum of squared deviations from the target in the individual dbh-classes is divided by the number of dbh-classes minus 1 . However, this as well should have only marginal effects on the comparability.

### 6.2 General patterns of Gini-indices and growth dominance-coefficients

Concerning stand structures, this study supports the general pattern found in other studies (e.g. Sterba and Zingg, 2006), that even-aged stands are more homogeneous than uneven-aged stands. Highest Gini-indices were found within mixed uneven-aged stands, pure even-aged stands, in contrast, had the lowest Gini-indices. This indicates that generally pure even-aged stands are relatively homogeneous whereas a mixture of species and especially an unevenaged stand structure heightens the heterogeneity of a stand. Nevertheless, in some cases, high values for the Gini-index occurred within even-aged stands of this study; these mainly resulted from a two layer structure of the stands.

Highest growth dominance-coefficients were found in even-aged stands; an uneven-aged mixed stand on the other hand, had the lowest value for the growth dominance with -0.41 . All in all, the growth dominance-coefficients in this study were rather low compared to the values in unthinned stands (Binkley, 2004; Binkley et al., 2006; Doi et al., 2010; Bradford et al. 2010); the highest growth dominance-coefficient was 0.24 .

With these results, one of Bradford et al.'s (2010) conclusions can be confirmed, that is that managed stands have lower growth dominance-coefficients than unmanaged stands. Reflections on the effects of the concrete thinning regimes on growth dominance were not part of this study.

### 6.3 Influence of the Gini-index on growth dominance

A significant correlation was found between growth dominance and Gini-index supporting the above stated theory that the more inhomogeneous a stand is, the more likely it is, that its growth dominance gets negative. This hypothesis appeared to be true in regard of unevenaged structure of a stand as well as in regard of species mixture as both factors led to a higher heterogeneity. However, uneven-aged stand structure appeared to be the triggering factor.
In uneven-aged stands, the younger trees are the smaller trees. Younger trees usually produce proportionally more increment than older ones (Binkley et al., 2002), which can explain the typically negative growth dominance-coefficients in uneven-aged stands. Furthermore, the increment due to increased light in uneven-aged stands, which occurs when bigger neighbours are removed, has an intensifying effect on the growth of smaller trees.
The lower growth dominance-coefficients in stands of mixed species on the other hand, could be explained by the fact that different species often need specific resources in different intensities. Consequently, different species often occupy different optima (Schmider et al., 1993), so that competition in mixed stands of this study did not get as intense as in pure stands.

### 6.4 Impacts on annual increment

Analysing the correlation between Gini-index and annual increment as well as between growth dominance and annual increment, showed that in either case, the relationship was complex.
Using the elevation, as the main site factor, as additional variable, for the uneven-aged stands a significant correlation between Gini-index and annual increment was detected. In even-aged stands on the other hand, it appeared that Gini-index and elevation had no significant impact on the annual increment, which was here first and foremost determined by stand age.
Not finding an influence of stand structure on annual increment in even-aged stands is surprising. It stands in contrast with the results of the studies by Ryan et al. (2010) and Stape et al. (2010), where a higher uniformity within even-aged stands led to a higher stand growth. In this study, instead of finding the postulated relationship within even-aged stands, it was found within uneven-aged stands, where a higher homogeneity resulted in higher increments.

This in turn, stands in contrast with the results of De Camino (1976), who concluded that the homogeneity in uneven-aged stands with high growth-rates was smaller than in other unevenaged stands, which would indicate that there existed a reverse relationship between increment and stand structure compared to the postulated relationship of these two in even-aged stands. Bachofen (1999) on the other hand, did not detect a direct impact of stand structure, which was in his study also measured with the Lorenz curve and a coefficient similar to the Giniindex, on growth when he analyzed the development of two different uneven-aged stands.
A relationship between growth-dominance and stand increment was indicated by Binkley et al. (2002), Binkley (2004) and Doi et al. (2010). In this study, after again adding the elevation as variable, a significant positive correlation between growth dominance and increment was found within uneven-aged stands. In the even-aged stands on the other hand, stand age appeared to be the triggering factor. However, also growth dominance was significantly correlated with stand increment. Furthermore, it was interesting that highest as well as lowest increments occurred in pure even-aged stands when the growth dominance was around 0 indicating that the trees in the stand represent the same proportion of volume as of increment. The different classes of stands only differed marginally in their increments. However, the highest and the majority of the lowest values were found within pure even-aged stands.

### 6.5 Growth dominance pattern

It was obvious from the beginning of this study on, that not all of the stands would show growth dominance patterns according to the phases of stand development proposed by Binkley (2004) and Binkley et al. (2006), as all of the stands in this study were managed and some of them additionally uneven-aged; Binkley's phases, however, were developed for the pattern in even-aged stands where there were no interventions between establishment and end of observation. Furthermore, in all probability neither of the stands in this study reached a stage of stand development, where a phase four would be expected, as the species were predominantly slow-growing.
Nevertheless, it was surprising, that the development of the growth dominance within evenaged stands of this study did not show a uniform course; neither was a reduced form of Binkley's (2004) and Binkley et al.'s (2006) proposed pattern found, nor could another trend be identified.
In the literature, two factors are mentioned, which might account for differences in the growth dominance patterns of different stands; these are species composition and environmental factors. However, for pure stands of the same species, specific trends for the development of the growth dominance as proposed by Doi et al. (2010) or Fernández et al. (2011) could not be identified. A possible influential environmental factor, where data was available, was in this study the elevation; however, a consistent pattern for an elevation class was not found either. This can possibly be explained by the fact, that all stands in this study were managed, probably all stands were managed differently, and consequently, no uniform species-wise or elevation class-wise pattern could develop.
Furthermore, it is possible that more than one factor as for example species composition, environmental conditions or management regime is responsible for the development of


#### Abstract

growth dominance within a stand. It seems to be probable, that all of these different factors some of them being possibly interdependent of others - overlap each other and that this is the reason why in this study no uniform pattern for even-aged stands could be identified at all. This hypothesis is supported by the study of Linares et al. (2011): They concluded that environmental factors as well as land-use influence forest structure and diversity and that the different impacts are difficult to detect. As the Gini-index of the previous period, being a measure of stand structure, correlated significantly with the growth dominance, in all probability, these factors also have an impact on growth dominance and its development.


### 6.6 Impact of the deviation from equilibrium

The prediction of the growth dominance with the Gini-index of the previous period could not be improved by adding the variance of deviation from equilibrium as a variable.
Nevertheless, a relationship between growth dominance and variance of deviation from equilibrium was found: The higher the variance of deviation from equilibrium of the previous period is, the more the growth-dominance tends to get positive. The deviation from equilibrium as a predictor for general trends of the growth dominance might especially be useful, when uneven-aged stands are in a state of imbalance.
The variance of deviation from equilibrium correlated significantly with the Gini-index, which is also pointed out by Sterba and Zingg (2006): A high Gini-index corresponded to a low variance of deviation from equilibrium and vice versa.

### 6.7 Final conclusion

The different schemes for the regression between Gini-index and growth dominance in evenand uneven-aged stands and their $\mathrm{R}^{2}$ indicate that the shape of the relationship between Giniindex and growth dominance depends on the age-structure of stands. Hence, a differentiated approach analysing even- and uneven-aged stands separately, appears to be more useful than general statements. Also the findings regarding annual increment support a differentiated approach, as only a separated analysis of even- and uneven-aged stands led to significant impacts of stand structure and growth dominance on stand growth, at least in uneven-aged stands.
Nevertheless, further research is necessary, especially in uneven-aged stands, where studies on growth dominance are very scarce.

## 7 List of tables

Table 2.1: Simple example for the calculation of the Gini-index; The area under the Lorenz curve is calculated as the sum of trapezoids, each of which is calculated as $a_{i}=\left(\Sigma \mathrm{ba} a_{i}\right)$

$$
\begin{aligned}
& \left.B A+\sum b a_{i}-1 / B A\right) / 2 *\left(\sum n_{i} / N-\sum n_{i}-1 / N\right) \text {. For example, the area for sample tree } \# 12: a_{4}= \\
& (0.0874+0.0364) / 2 \cdot(0.8-0.6)=0.0124 \text {. The Gini-coefficient is then }(0.5- \\
& 0.1299) / 0.5=0.7401 \text { or } 74.01 \% \text { indicating } a \text { high variability of tree sizes in the stand. ........... } 6
\end{aligned}
$$

Table 4.1: Plots of the study (Plot 1021000 is classified as even-aged (*e) although it belongs to a testing group "uneven-aged stands", because the diameter distribution of this stand corresponds for most of the records to that of even-aged stands) ..... 14
Table 4.1: (continued) ..... 15
Table 4.2: Coefficients for equation 4.3 for different species. ..... 17
Table 5.1: Mean values and standard deviations of the Gini-index for the different categories of stands. ..... 20
Table 5.2: Mean values and standard deviations of the growth dominance-coefficients for the different categories of stands ..... 20
Table 5.3: Results from Tukey's test for the Gini-index. ..... 22
Table 5.4: Results from Tukey's test for the growth dominance. ..... 22
Table 5.5: Coefficients and significance of variables for equation 5.1 ..... 27
Table 5.6: Coefficients and significance of variables for equation 5.2. ..... 27
Table 5.7: Coefficients and significance of variables for equation 5.3. ..... 29
Table 5.8: Coefficients and significance of variables for equation 5.4. ..... 29

## 8 List of figures

Figure 2.1: Two typical diameter distributions from the plots of this study. The numbers of trees in the dbh-classes are total values, not values per hectare. The left diameter distribution is one of the distributions of plot \# 100200, an even-aged stand. On the right side is a diameter distribution of plot \# 1015001, an uneven-aged stand.3

Figure 2.2: The Lorenz curve from the example below. The Lorenz curve results from plotting $\Sigma b a / B A$ over $\Sigma n / N$. The red arrows show the marks for sample tree \#12, where, up to a dbh of $16.2 \mathrm{~cm}, 80 \%$ of the trees have only $8.74 \%$ share of the basal area of the stand....................... 6

Figure 2.3: Exemplary growth dominance curves................................................................... 8
Figure 2.4: Exemplary growth dominance curves for the four phases of stand development after a figure in Binkley et al. (2006).

Figure 4.1: Example of the diameter distribution of an uneven-aged stand on the left side and the corresponding distribution of the stand in a state of equilibrium on the right side. Dbhclass 1 means here the class from 10-15cm, class 2 is from 15.1-20cm and so forth. In this example, the variance of deviation from equilibrium was 0.3908.
Figure 5.1: Box-and-whisker plot of the distribution of the Gini-indices within the four stand classes "mixed/even-aged", "mixed/uneven-aged", "pure/even-aged" and "pure/unevenaged". The solid black lines show the median ( $2^{\text {nd }}$ quartile, $50^{\text {th }}$ percentile); the two lines that form the box are the $1^{\text {st }}$ quartiles ( $25^{\text {th }}$ percentile) and the $3^{\text {rd }}$ quartiles ( $75^{\text {th }}$ percentile); the whiskers are the minima and maxima within $1.5 *$ interquartile range from the $1^{\text {st }}$ and $3^{\text {rd }}$ quartile; points beyond the whiskers are outliers, which are smaller or larger than the whiskers.

Figure 5.2: Box-and-whisker plot of the distribution of the growth dominance-coefficients within the four stand classes "mixed/even-aged", "mixed/uneven-aged", "pure/even-aged" and "pure/uneven-aged". For interpretation compare Figure 5.1.
Figure 5.3: Growth dominance-coefficients and Gini-coefficients of the previous record for
all plots and all records. ................................................................................................... 23
Figure 5.4: Growth dominance coefficients and Gini-coefficients of the previous record for all plots and all records. The different colours represent the different classes of stands. The fine solid lines between the points show the development of Gini-indices and growth dominance-coefficients within the different stands themselves. The thick black line shows the trend of the relationship expressed by smoothed means.
Figure 5.5: Annual volume increments per hectare and Gini-coefficients of the previous record for all plots and all records. The solid line shows the trend of the relationship expressed by smoothed means.
Figure 5.6: Box-and-whisker plot of the distribution of the annual increments per ha within the four stand classes "mixed/even-aged", "mixed/uneven-aged", "pure/even-aged" and "pure/uneven-aged". For interpretation compare Figure 5.1.
Figure 5.7: Annual volume increments per hectare and Gini-coefficients of the previous record for all plots and all records. ..... 26
Figure 5.8: Annual volume increments per hectare and growth dominance-coefficients for all plots and all records. The solid line shows the trend of the relationship expressed by smoothed means. ..... 28
Figure 5.9: Annual volume increments per hectare and growth dominance-coefficients for all plots and all records. ..... 28
Figure 5.10: Growth dominance-coefficients and Gini-coefficients of the previous record for all plots and all records. The different colours represent the different plots; the lines between points of the same colour show the development of growth dominance-coefficients and Gini- indices within a plot. ..... 30
Figure 5.11: Development of growth dominance-coefficients in plot \#1002000 (even-aged, mixed) ..... 31
Figure 5.12: Development of growth dominance-coefficients in plot \#13007005 (even-aged, larch). ..... 31
Figure 5.13: Development of growth dominance-coefficients in plot \#24020000 (even-aged, larch). ..... 31
Figure 5.14: Combination of the curves in Figure 5.12 and Figure 5.13 ..... 32
Figure 5.15: Development of growth dominance-coefficients in plot \#41018000 (even-aged, beech). ..... 32
Figure 5.16: Development of growth dominance-coefficients in plot \#41118000 (even-aged, beech) ..... 32
Figure 5.17: Development of growth dominance-coefficients in plot \#1015002 (uneven-aged, mixed) ..... 32
Figure 5.18: Correlation of growth dominance and variance of deviation from equilibrium ofprevious record for all uneven-aged plots. The solid line shows the regression line accordingto the equation scheme GrowthDom $=a+b *$ Var.33
Figure 5.19: Plot \#1015001: uneven-aged stand in a state of equilibrium. ..... 34
Figure 5.20: Plot \#1030003: unbalanced uneven-aged stand. ..... 34
Figure 5.21: Correlation of Gini-index and variance of deviation from equilibrium for all uneven-aged plots. The solid line shows the regression line according to the equation scheme Gini $=a+b *$ Var. ..... 35
Figure 5.22: Growth dominance-coefficients and Gini-coefficients of the previous record for all uneven-aged plots with the regression line according to the equation scheme GrowthDom $=a+b *$ Gini. ..... 36Figure 5.23: Growth dominance-coefficients and Gini-coefficients of the previous record forall even-aged plots with the regression line according to the equation scheme GrowthDom $=$$a+b * G i n i+c *$ Gini $^{2}$37

Figure 5.24: Growth dominance-coefficients and Gini-coefficients of the previous record for all mixed plots with regression line according to the equation scheme GrowthDom $=a+$ $b * \operatorname{Gini}+c *$ Gini $^{2}$ 38

Figure 5.25: Growth dominance-coefficients and Gini-coefficients of the previous period for all pure plots with regression line according to the equation scheme GrowthDom $=a+b *$ Gini $+c *$ Gini $^{2}$. 38

## 9 References

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## Appendix

Development of Gini-index and growth dominance, Gini-index and annual increment as well as growth dominance and annual increment within the individual stands of this study.
(Further supplements to this study, including diameter distributions of all plots and all records, are available on a CD in the copy of this study at the Institute of Forest Growth and Yield Research)










Plot 24020000


Plot 24031010


Plot 24031011


Plot 24019000


Gini

Plot 24020000


Plot 24031010


Plot 24031011


Plot 24019000


GrowthDom

Plot 24020000


Plot 24031010


Plot 24031011










