# Demographic equilibrium modelling of single tree selection stands in Siljansfors

## Sustainability of single tree selection systems

Ludwig Olofsson

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# Demographic equilibrium modelling of single tree selection stands in Siljansfors. Judging the sustainability of single tree selection systems in Sweden

Ludwig Olofsson

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| **Supervisor:** | **Prof. Arne Pommerening, Swedish University of Agricultural Sciences, Department of Forest Ecology and Management** |
| **Examiner:** | Dr. Torgny Lind, Swedish University of Agricultural Sciences, Department of Forest Resource Management |

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**Swedish University of Agricultural Sciences**
Faculty of Forest Science
Department of Forest Ecology and Management

# Abstract

Lately debates have occurred questioning the rotation system, which is the most used silvicultural system in Sweden. Continuous cover forestry (CCF) has therefore been suggested as an alternative management method, due to its environmental benefits such as increased biodiversity and higher resilience against extreme weather which is important with the current climate change. One CCF method in particular is the single tree selection system, which depends on a complex forest structure in order to sustainably yield economic and ecological values over time. Experience and knowledge of the dynamics of forest stands managed with the single tree selection system in Sweden are insufficient. One way to increase the understanding of stand dynamics in single tree selection systems is by using demographic models. This thesis aimed to examine the sustainability of single tree selection systems in Sweden, using a dynamic demographic equilibrium model called the Schütz model. Additionally, this dynamic model was translated to the simpler de Liocourt (q-factor) model to facilitate practical use. Based on the models, adapted management suggestions and a judgement of sustainability were made. The results shows that the Swedish selection forest grows slower compared to other selection forest in Europe and have a relative high mortality. Thus, a high rate of regeneration is needed, and the target diameter was limited to smaller diameters than seen in more southern latitudes. However, when comparing the observed diameter distribution of the stands with the model outcome it was seen that well adapted management is crucial for stand development. Furthermore, this comparison suggests that the selection stands can reach their equilibrium. In conclusion, it is possible to sustainably manage forests in Sweden using the single tree selection system. This thesis also suggests that both dynamic and static models can be relied on when making stand evaluations in Swedish forests.

*Keywords:* CCF, continuous cover forestry, single tree selection, equilibrium models, forestry,

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# Abbreviations

| | |
|---|---|
| AGR | Absolute growth rate |
| BAL | Basal area of larger trees |
| CCF | Continuous cover forestry |
| dbh | Diameter at breast hight |
| RGR | Relative growth rate |

# 1. Introduction

Approximately 58% of the total land area of Sweden are covered by productive forests and are therefore suitable for forest management (Nilsson et al. 2022). Lately in Sweden debates in the media have occurred questioning the traditional Swedish forestry model involving the rotation system as the main management method. The rotation system has been criticized for various reasons including loss of biodiversity and the visual impact of a forest stand after a final felling (Lindhagen 1996; Naumov et al. 2018; Hertog et al. 2022). Studies have showed that people living close to forest lands prefer mixed-species forests with a diverse range of tree sizes (Lindhagen & Hörnsten 2000). Climate change is another reason for the debates, since other forest management systems have shown higher resilience against natural disturbances (Dvorak & Bachmann 2001; Hanewinkel et al. 2014; Nevalainen 2017). On top of this, according to Skogsstyrelsen (2023) does Sweden not reach her environmental goal of living forests. Alternative methods of forest management have therefore been discussed such as continuous cover forestry (CCF), which leads to forest stands with more complex structure (O'hara et al. 2007).

This thesis focus on a CCF system called the single tree selection system. For management with this systems, a heterogeneous and complex structure is crucial for having a sustainable forest outtake over time where a complex forest structure can be defined as a forest with more than two storeys (Mason & Kerr 2001). Forests with complex structures are sustainable in more ways than in just a production perspective (Fries et al. 1997). Several studies carried out in Europe have measured the forest structures and development in complex forests in order to examine demographic dynamics and equilibrium conditions (Schütz & Pommerening 2013; Brzeziecki et al. 2016). The same experience of CCF is not found in Sweden. However, CCF experience in the form of research plots used to be found in Sweden around 1920 to 1940, but have unfortunately been lost over time due to misconception of the system, regulations preventing CCF methods in forestry and a significantly higher popularity of the rotation system (Lundqvist 2017). Fortunately, a small number of plots still remains and are being managed with CCF.

CCF forestry is based on the ecological and biological principles of natural stand dynamics and can be compared to small and very local natural disturbance where only one or a few trees are affected. Definitions of CCF can be ambiguous, since different countries and organizations tend to have their own definition and agenda (Pommerening & Murphy 2004). However, most definitions seem to acknowledge the abandonment of large-scale clearcutting and favour natural regeneration.

There are different types of CCF managed forest (*Hyggesfritt skogsbruk - Skogsstyrelsens definition* u.å.). However the CCF method used in this thesis occurs mostly in central Europe and is the single tree selection system. This method has its origin in upland small-scale forestry where farmers, mainly in Austria, France, Germany, Slovenia, and Switzerland, have used this method all the way back to the 15th century (Hasel & Schwartz 2006). These forests where usually just a small part of the farmers work compared to the agricultural part. However, by using this system the farmers could sustain themselves with timber and it was also common that big parts of the forests were left without human impact for many years (Schütz 2001).

The single tree selection system is based on the dynamic that smaller trees are constantly growing into bigger size classes. Eventually they will take the place of previously dominant trees after their death or removal from the stand. For this to work, it is crucial to have uninterrupted natural regeneration since no planting occurs. However, when comparing single tree selection to other forest management systems, this is not primarily a method focusing on regeneration. The focus is to maintain a forest stand structure over time that ensures a constant supply of harvestable timber in the largest size class (Schütz 2001). Well-managed single tree selection systems provide selective harvests of the predominantly large trees without the execution of costly replanting or precommercial thinnings. Compared to most other CCF methods the selection system does not have a clear regeneration phase and the typical forest has a tendency of tree crowns filling the whole growing space (Schütz 2001).

Not all species are suitable for single tree selection forests. Since regeneration occurs under already established stands, intermediate to shade tolerant species are often preferred. Classic species used in Central Europe include *Picea abies*, *Abies alba*, and *Fagus sylvatica* (Matthews 1991) and they are commonly grown in mixture. In northern Europe mono-species stands are more common, in particular stands based on *Picea abies* or *Fagus sylvatica* (Schütz 2001, 2006; Petersen & Guericke 2004; Schütz & Pommerening 2013; Pommerening 2023). For Sweden and the study area of this thesis *Pice*a *abies* is nearly the only species used in single tree selection systems (Lundqvist 2017; Olofsson et al. 2023), since *Fagus sylvatica* has the northern natural distribution limit only in the most southern parts of Sweden and other species suitable for single tree selection systems are not native to the country.

In Europe, the selection system is rarely used with proportions differing between 1 to 13 percent depending on country (Mayer 1984; Schütz 2001). In Fennoscandia the proportions of selection systems are even lower and in Sweden is the proportion is markedly less than one percent of the country’s forest area. According to Lundqvist (2017), in the 1950s conclusions were made that single tree selection systems were not considered a system suitable to Sweden due to the harsh climate and to regeneration problems.

As mentioned earlier, there is an ongoing debate in Sweden about how the forest should be managed. This debate has shed new light on the single tree selection system which has been proven to produce good recreational values (Arnberger 2006) and is also used to prevent rock falls , landslides, avalanches and degradation of human settlements (Dorren et al. 2005; Brang et al. 2006; Rammer et al. 2015). The single tree selection system is also known for a better tolerance of natural disturbances (Dvorak & Bachmann 2001; Hanewinkel et al. 2014) which is particularly important in times of climate change. According to Pommerening (2023), many benefits of the single tree selection systems can be relevant or observed in other forms of CCF. The Finnish nature panel (Suomen Luonto Paneeli) released three reports stating that CCF forestry in Finland could be both ecologically and economically sustainable (Kotiaho et al. 2022; Peura et al. 2022; Tahvonen 2022). Since the climate in Finland is very similar to Sweden’s, sustainable CCF forests should be applicable here as well. However, it has also been stated in the report by the Finish nature panel that more research needs to be done. Therefore, research on all CCF systems is of interest. One way of gaining more knowledge about the dynamics in CCF systems is to use models. In this thesis demographic equilibrium models was used in order to determine the sustainability of two single tree selection stands in central Sweden.

## 1.1 Objectives

Demographic equilibrium models have only been applied very scarcely in Sweden to date and it is hard to find published material about it. Therefore, this study can bring more knowledge about stand dynamics in Swedish selection forests and contribute to increased management confidence. The objectives of this thesis was to;

1) analyse the dynamics of observed diameter-distributions of two stands managed with single tree selection principles from central Sweden,

2) fit dynamic demographic models as a silvicultural reference structure,

3) translate these dynamic models to the simpler de Liocourt (q-factor) models to facilitate practical use,

4) thereafter, the observed dbh-distributions for the two stands were analysed based on the outcomes of the dynamic demographic model in order to arrive at adapted future management suggestions for each stand.

The hypothesis for this thesis is that the observed dbh-distributions are far from demographic equilibrium since single tree selection methods have only loosely been applied for the two studied stands in the past.

# 2. Material and method

## 2.1 Site information and data collection

The data used in this study was collected from two different stands, 9022 and 9082, located in Siljansfors Experimental Forest (60° 52’ – 60° 55’ N, 14° 19’ – 14° 25’ E) southwest of Mora in central Sweden. Stand 9022 is situated at an altitude of 400 meters above sea level and has a total area of one hectare. For measurement purposes, the stand is divided into four plots of 0.25 hectares each. The four plots are referred to as 31, 32, 33, and 34 in the remainder of this document. Stand 9082 is located at an altitude of 260 meters above sea level and has a total area of 0.52 hectares. Stand 9082 was not subdivided into plots. A target diameter of 50 cm was selected for both stands.

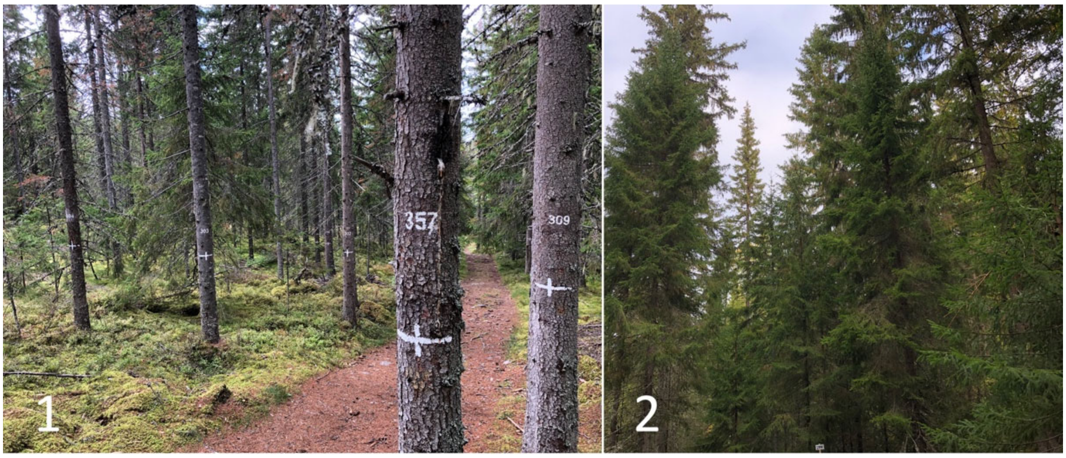

*Figure 1. (1) Tree numbers and marks for diameter measurements at 130 cm above ground level in stand 9022. (2) Tendency of the tree crowns filling the whole vertical growing space.*

The stands have been managed according to the principles of a single-tree selection system. Stand 9022 has a site index[1] (SI) of 22 (Lundqvist 1993), was established in 1923 and has been subjected to selection cuttings since then. Individual tree diameter measurements began in 2006, where every tree higher than breast height (130 cm above the point of germination) was measured. The breast hight was also permanently marked on the tree to reduce measurement errors. However, the trees were only marked and given individual numbers by the time of the second survey in 2017. Therefore, only the data from survey year 2017 and 2022 will be used in this thesis.

Stand 9082 with a SI of 24 (Lundqvist 1993) was established in 1959, and continuous single-tree measurements have been carried out approximately every 10 years since then. Every tree has been numbered and the location of diameter measurement has been marked at breast height. The latest remeasurement was conducted in 2021. Prior to 2012, trees that had surpassed breast height and thus had to be included in the survey were measured and counted without being assigned a specific number. Therefore, data collected prior to 2012 cannot be used in the growth and mortality models because it is not possible to determine individual-tree growth or deaths. In stand 9082 trees with a diameter at breast hight (dbh) smaller than 4 cm have not been assigned individual numbers. Therefore, a minimum dbh-limit of trees used in the model was set to 4 cm for this stand.

The method for collecting data was the same in both stands. On all trees in the plot that surpassed 1.3 m height, the dbh was measured. The trees were cross-calipered to calculate a consolidated diameter measurement. Tree species was recorded and also whether the tree was still alive or had died since the last survey. The data of stand 9022 and 9082 were summarised in Table 1 and 2, respectively.

*Table 1. Inventory data from year 2017 and 2022 for stand 9022. N – number of stems per hectare > 130 cm height, G – basal area at dbh, dg – quadratic mean diameter at brh, GD – growth domination index (Binkley et al., 2006), G% P. abies percentage of total basal area*

| | $N$ [ha$^{-1}$] | | $G$ [m$^2$ha$^{-1}$] | | $d_g$ [cm] | | $G_D$ | *G% P. abies* | |
|---|---|---|---|---|---|---|---|---|---|
| Plot | 2017 | 2022 | 2017 | 2022 | 2017 | 2022 | 2017-22 | 2017 | 2022 |
| 31 | 1800 | 1464 | 31,0 | 24.4 | 14.8 | 14.6 | -0.09 | 79 | 80 |
| 32 | 1416 | 1216 | 24.6 | 22.6 | 14.9 | 15.4 | -0.11 | 73 | 71 |
| 33 | 2160 | 1932 | 28.2 | 23.5 | 12.9 | 12.4 | -0.15 | 89 | 90 |
| 34 | 1508 | 1360 | 25.9 | 23.7 | 14.8 | 14.9 | -0.23 | 88 | 85 |
| Stand | 1721 | 1493 | 27.4 | 23.5 | 14.2 | 14.2 | -0.15 | 82 | 82 |

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[1] Site index (SI) is a way of measuring the site qualities. This thesis refers to the site index used in Sweden which is the height of the highest trees in the stand at age 100 for the dominant species (Albrektson et al. 2012).

*Table 2. Inventory data from stand 9082. N – stems above brh per hectare, G – basal area at brh, dg – quadratic mean diameter at brh, GD – growth domination index (Binkley et al., 2006), G% P. abies percentage of total basal area*

| Survey year | $N$ [ha$^{-1}$] | $G$ [m$^2$ha$^{-1}$] | $d_g$ [cm] | $G_D$ | *G% P. abies* |
|---|---|---|---|---|---|
| 1969 | 521 | 18.0 | 21.0 | -0.30 | 99 |
| 1979 | 721 | 17.7 | 17.7 | -0.14 | 99 |
| 1990 | 1054 | 22.0 | 16.3 | -0.34 | 97 |
| 2000 | 1210 | 26.7 | 16.8 | -0.21 | 97 |
| 2012 | 1167 | 30.8 | 18.3 | -0.21 | 96 |
| 2021 | 1173 | 28.2 | 17.5 | - | 95 |

As part of this thesis, an additional survey of stand 9022 was carried out in 2022, i.e. five years after the last survey in 2017 to obtain sufficient data for the analyses. For stand 9082, another survey was not necessary, since the data from previous surveys were available and the last survey was conducted in 2021.

## 2.2 Demographic modelling

The first model that described the diameter distribution of a single tree selection forest was proposed by François de Liocourt in 1898 (de Liocourt 1898). This model would later be known as the law of de Liocourt and can be described as in Eq. 1:

$$n = n_0 \times e^{-\lambda \times d} \tag{1}$$

where

$n$, is the number of trees,
$d$ is the stem diameter
$\lambda$ is a constant model parameter
$n_0$ is the initial number of trees for $d$ when $d$ is infinitesimally small and where the ordinate is crossed,
$e$ stands for the base of the natural logarithm and

This simple model has in the past become a tool for foresters to determine thinning cycles and intensities to achieve self-sustainability of timber resources in selection forests (Pommerening 2023). It was later discovered that the reduction of successive stem diameter classes in the de Liocourt model can be quantified by one constant parameter $q$ (Meyer 1933). This parameter $q$ can be derived as in Eq. 2:

$$q = \frac{n_i}{n_{i+1}} = \frac{n_0 \times e^{-\lambda \times d_i}}{e^{-\lambda \times d_i} \times e^{-\lambda \times d_i \times w}} = \frac{1}{e^{-\lambda \times w}} = e^{\lambda \times w} \quad (2)$$

In Eq. (2), $n_i$ and $n_{i+1}$ are the number of trees in successive diameter classes where $d$ is increasing from $d_i$ to $d_{i+1}$. $w$ is the constant width of the diameter classes. $\lambda$ represents the relative growth rate (RGR) relating to the change of tree numbers with increasing size and $q$ is equivalent of tree-number growth multiplier (Wenk 1994; Cancino & von Gadow 2002). However, $q$ is usually not constant throughout all diameter classes for observed stem-diameter distributions (Olofsson et al. 2023; Pommerening 2023).

The de Liocourt and the associated $q$-factor model gained popularity due to their simplicity where largely only one parameter, $q$, was needed to describe the whole diameter distribution of a stand (Hansen & Nyland 1987). This implies that the $q$-factor model summarises complex dynamics such as growth, mortality, and tree migration through classes. The dynamic information needed for these models is hard to obtain in forest practice and determination of the parameters for Eq. (1) is difficult, as they should reflect the corresponding stand dynamics and with that information predict a future stem-diameter distribution in equilibrium. Earlier studies have tried to optimise parameter $n_0$ and $\lambda$ using nonlinear regression (e.g. Meyer 1952) but then the model parameters only reflect currently observed forest structure. Due to shortcomings of the $q$-factor model the use of dynamic demographic equilibrium models have been proposed in multiple papers (Prodan 1949; Schütz 2001; Brzeziecki et al. 2016; Kärenlampi 2019). Dynamic models are more accurate in explaining the demographic processes in stem-diameter distributions.

The demographic equilibrium model selected for this thesis is the Schütz model. In this kind of model, migration of trees through diameter classes is a function of growth and mortality. To achieve demographic sustainability according to Schütz (2006), ingrowth, mortality and outgrowth in diameter classes are the main processes. To attain demographic equilibrium, it is essential that the number of trees growing into a dbh class (ingrowth) equals the number of trees growing into the next larger dbh class minus the number of dead trees (mortality). This can be described by Eq. (3) (Schütz, 2001, 2006):

$$\underbrace{n_{i-1} \times p_{i-1}}_{\text{Ingrowth from class } i-1} = \underbrace{n_i \times m_i}_{\text{Mortality in class } i} + \underbrace{n_1 \times p_i}_{\text{Outgrowth towards class } i+1} \quad (3)$$

In Eq. (3), $n_i$ is the number of trees in diameter class $i$, $p_i$ are the outgrowth and $m_i$ the mortality rates of class $i$. The growth and mortality rates are determined by model functions (Schütz 2001, 2006). Both the outgrowth rate $p_i$, and the mortality rate $m_i$, come from model functions that for each diameter class defines the growth and mortality. The outgrowth rate is therefore calculated using the following equation:

$$p_i = \frac{(\delta d)_i}{w} \tag{4}$$

In Eq. (4) $(\delta d)_i$ is the mean annual absolute growth rate (AGR) which is divided by $w$, the width of the stem diameter distribution. Here is it important that AGR and $w$ use the same unit, i.e. centimetre in our case. The number of trees in each diameter class is based on the number of trees in the largest diameter class ($n_{\max}$). Therefore, all other $n_i$ except for $n_{\max}$ can be calculated based on Eq. (5) as follows:

$$n_{i-1} = \frac{n_i \times (p_i + m_i)}{p_{i-1}} \tag{5}$$

In Eq. (5), $n_{i-1}$ is the number of trees in diameter class $i-1$. The demographic processes involved in this model are illustrated in Fig. 1 which follows the illustration in a previous paper by Schütz & Pommerening (2013).

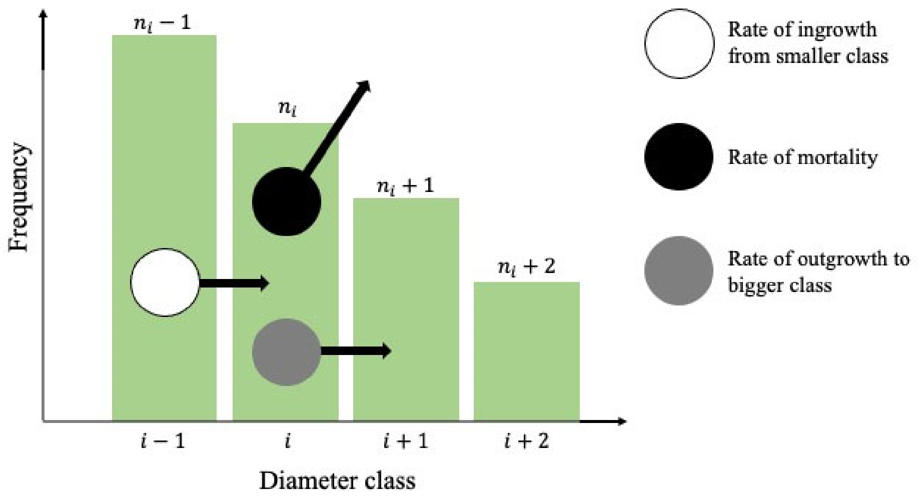

*Figure 2. Visualization of fundamental dynamics of demographic models based on diameter classes $n_i$ is the number of trees in diameter class i.*

The various parameters shown in Fig. 1 form the basis of the Schütz model. However, competition is also an important factor that is considered as a part of the growth modelling.

### 2.2.1 Modelling growth

The modelling of absolute annual stem diameter growth was carried out using the competition concept of basal area of larger trees (BAL), according to Wykoff (1990) and (Schütz 2006) based on Eq. (6).

$$\delta d = a_1 + b_1 \times BAL^{c_1} \tag{6}$$

where
$\delta d$ is annual absolute growth (AGR) of stem diameter,
$a_1$, $b_1$ and $c_1$ are model parameters,
BAL is basal area of larger trees.

Since both stands were dominated by *P. abies* (as shown in Tables 1 and 2), AGR included all trees regardless of species. Since the data used for modelling were aggregated in empirical diameter distributions, BAL was defined as the sum of cross-sectional areas of all diameter classes in each class that are larger than the considered diameter class multiplied by the corresponding number of trees per hectare. This means that BAL is a cumulative measure of the basal area and therefore works as an expression of resource availability including light, water, and nutrients (Wykoff 1990; Olofsson et al. 2023). The growth model was fitted based on Eq. (6) using nonlinear regression.

### 2.2.2 Modelling mortality

Mortality was modelled according to Eq. (7);

$$m = c_2 \times (d - a_2)^2 + b_2 \tag{7}$$

where
$m$ is the annual mortality rate,
$d$ stands for diameter class and works as an independent variable,
$a_2$, $b_2$ and $c_2$ are model parameters.

As for the growth model, aggregated data were used here as well. In the mortality model, both natural deaths as well as tree fellings were included. Observed mortality of selection forests does not always reflect the mortality that they would have at demographic equilibrium (Schütz & Pommerening 2013). Therefore, after the model has been fitted based on Eq. (7) using nonlinear regression, fine-tuning of model parameter $a_2$, $b_2$ and $c_2$ is needed in order to achieve an exponential distribution that increases with diameter class. To attain realistic parameter values, information about demographic equilibrium models was collected from previous studies where mortality models have been used (Schütz 2006; Schütz & Pommerening 2013).

### 2.2.3 Modelling number of tress in smallest dimameter class

To accurately determining the number of trees in each diameter class when the forest is at equilibrium, it is crucial to have a correct estimation of the number of trees in the smallest diameter class ($n_{\min}$). To obtain a good estimation of $n_{\min}$ according to Schütz (2006), it is essential to use a number that reflects reality and is preferably based on observations. An important input of the Schütz model is the number of trees in the largest diameter class ($n_{\max}$), which is one of the parameters needed to determine $n_{\min}$ using Eq. (3). In this thesis, the final stem diameter was set to $d_{\max}$ = 50 cm with target diameter harvest starting at 45 cm. To determine $n_{\min}$ according to Schütz (2006), simulations of different pairs of $n_{\min}$ and BAL based on Eq. (5) were carried out by entering arbitrary $n_{\max}$ values in the Schütz model. This was done after finishing and implementing the growth and mortality models. The values used for $\mathrm{n}_{\max}$ need to within the range for what can be used in the model which varies between stands. After this the simulation results were overlaid by BAL-$n_{\min}$ data which is either based on observations in different plots of the same stand or by using the data of one plot and different survey years. For this thesis the first method was used for stand 9022 and the second for stand 9082. After this, two separate trend lines were drawn through each of the point clouds and the intersection points then indicate $n_{min}$ and the corresponding BAL.

### 2.2.4 Measurement of change over time

Measuring how size structures change and develop over time can be done in various ways. Previously in Tables 1 and 2, the growth dominance characteristic, $G_D$, was used. However, other methods can be used such as the Gini index, $\tilde{G}$, or the related coefficient of variation of stem diameters (Lorenz 1905; Gini 1912; Pommerening 2023). In this thesis, the homogeneity index was applied to measure change over time which is the reciprocal of the Gini index and can be described as $G' = 1/\tilde{G}$. This index was selected due to its suitable properties and can applied to aggregated data using Eq. 8:

$$G' = \frac{\sum_{i=1}^{c-1} \sum_{j=1}^{i} \frac{n_j}{N}}{\sum_{i=1}^{c-1} \sum_{j=1}^{i} \frac{n_j}{N} - \frac{g_j}{G}} \tag{8}$$

Where $n_j$ and $g_j$ are the number of trees and the basal area per hectare for diameter class $j$, respectively. As in Tables 1 and 2, $N$ is the number of trees per hectare above brh and $G$ is the basal area. When $G'$ is calculated for the demographic equilibrium model according to Eq. (3), the result should be close to 1.0 since the homogeneity increases with increasing $G'$. According to de Camino (1976) rigidly planted monoculture forests take on index values of close to 10. The homogeneity index can also be calculated for observed empirical diameter distributions.

### 2.2.5 Modelling efficiency

To be able to evaluate the results of the regressions, efficiency ($E$) was quantified using Eq 9:

$$E = 1 - \frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \tag{9}$$

In Eq. (6), $\hat{y}_i$ is the $i$th prediction of mortality rate or growth rate and $y_i$ the corresponding $i$th observation. The mean observation is symbolized by $\bar{y}$ and $n$ is the number of observations. The more accurate the model is, the closer to one the efficiency value is. If the value of efficiency is zero, this is an indication that the model does not explain more variation than the mean value of the observations. If $E$ is negative, the model is biased.

# 3. Results

## 3.1 Growth analyses

The behaviour of the growth curves for the two stands 9022 and 9082 is a typical outcome of Eq. (6) that has also been seen in previously studies. For both stands the growth rate decreases with increasing BAL according to a concave pattern as shown in Fig. 3. It is expected that small trees have a large BAL and large trees have small BAL values. It can also be seen that the decrease in growth rate with increasing BAL is more rapid in stand 9082 compared to stand 9022 (Fig. 3), which is also indicated by the corresponding values of parameter $b_1$ (Table 3). When comparing the two growth curves, it is clearly noticeable that the curve of stand 9082 is located at a higher level than that of 9022. This is explained by difference in site quality between the stands (Sect. 2.1) and is also quantitatively expressed in Table 3 by the intercept parameter $a_1$. The efficiency ($E$) was lower for stand 9082 which can be explained by the large variance in the data points (Eq. 9, Table 3).

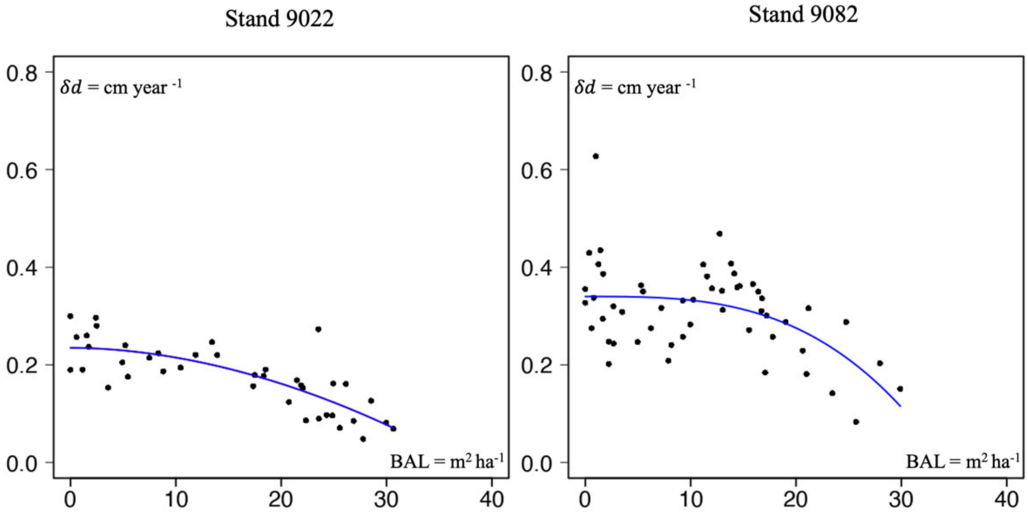

*Figure 3. The relationship between Annual stem-diameter growth, $\delta d$, and basal area of larger trees (BAL) derived from Eq. (6) with additional trend curves for stand 9022 and 9082.*

*Table 3. Parameters of the stem-diameter growth model used for the dynamic demographic models for stand 9022 and stand 9082.*

| Growth model Eq. (6) | | |
|---|---|---|
| Parameter | Stand 9022 | Stand 9082 |
| $a_1$ | 0.23488 | 0.33997 |
| $b_1$ | -0.00026 | -0.00001 |
| $c_1$ | 1.88243 | 3.10286 |
| $E$ | 0.61488 | 0.27475 |

## 3.2 Mortality analyses

The mortality rates ($m$) exhibited high variation across the different diameter classes in both stands, which may be attributed to the fact that the different causes of death were not distinguished in the model. One other reason that might also contribute to the variation in the data might be inconsistency in management during the monitoring period of the stands. However, the expected outcome of Eq. (7) for natural mortality is a U-shaped curve (Sterba and Monserud, 1999) which clearly can be seen for both stands in Fig. (4) and Table (3). The dominant part of mortality, especially in the larger diameter classes, is a result of stand management.

Due to the variation of $m$ and low values of $E$, it is conceivable to assume uncertainties for both stands. Therefore, a realistic mortality function was synthesized using both observed mortality rates and mortality functions from previous studies involving demographic equilibrium models (Schütz 2001, 2006; Schütz & Pommerening 2013). Since the management strategy for selection forests is universal, a theoretical mortality model could be derived. Earlier studies showed that smaller diameter classes typically have lower mortality rates which then exponentially increase with increasing size class. This pattern is easier to distinguish for stand 9082 than for stand 9022. Mortality was perceived as high in stand 9022, particularly since the growth rate was lower than for stand 9082. Due to this, the same mortality function was applied to the demographic equilibrium models for both stands.

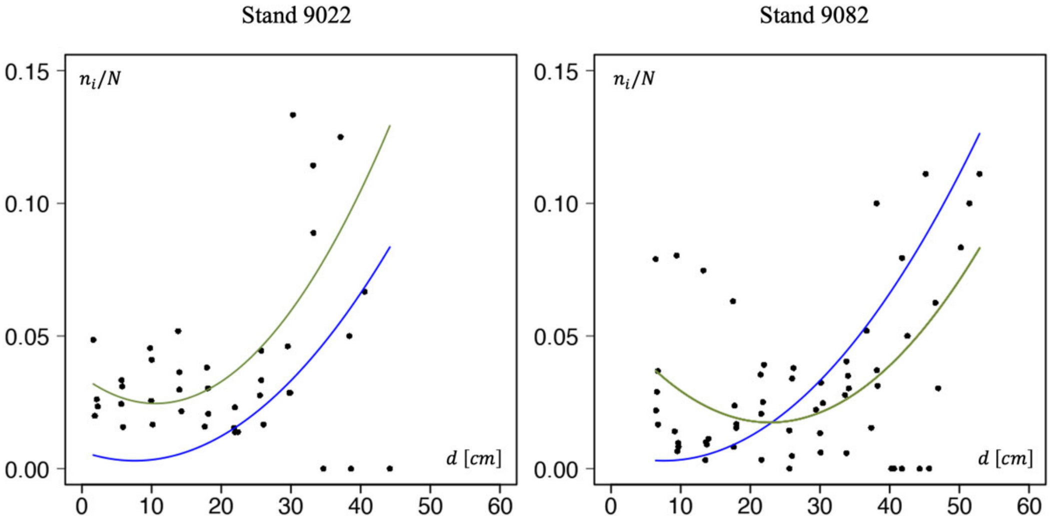

*Figure 4. The relation between annual mortality rates, $n_i/N$ and stem diameter, $d$,derived from Eq. (7) for stand 9022 and 9082. Trend curve for observed mortality rates is showed by the green curve. Synthesised mortality rates are showed by the blue curve.*

*Table 4. Parameters of the mortality model used for the dynamic demographic models for stand 9022 and stand 9082.*

| Mortality model Eq. (7) regression | | |
|---|---|---|
| Parameter | Stand 9022 | Stand 9082 |
| $a_2$ | 10.54993 | 22.80236 |
| $b_2$ | 0.02457 | 0.01741 |
| $c_2$ | 0.00009 | 0.00007 |
| $E$ | 0.30171 | 0.26370 |
| Mortality model Eq. (7) synthesised | | |
| $a_2$ | 0.00006 | |
| $b_2$ | 7.57290 | |
| $c_2$ | 0.00300 | |

## 3.3 N$_{\min}$ determination

The observed pairs of BAL and $n_{\min}$ seen in Fig. 5, is indicated by a linear function (green line) and the results for simulated pairs of $n_{\min}$ and BAL based on Eq. 5, are shown by the power function (blue line). The two functions intersected twice (Fig. 5). Since $d_{\min}$ was set to 2 and 6 centimetres, respectively, for stand 9022 and 9082, the observed data suggested rather large numbers of trees in $d_{\min}$ for each stand. I therefore selected the point of intersection with larger BAL. The selected points of intersection suggests $n_{\min} = 697.34$ for stand 9022 and $n_{\min} = 322.89$ for stand 9082 as can be seen in Fig. 5. An optimization provided $n_{\max}$ values for the two stands of 0.77301 for stand 9022 and 2.24186 for stand 9082. The big differences in $n_{\min}$ values between the two stands is partly due to the differences in $d_{\min}$.

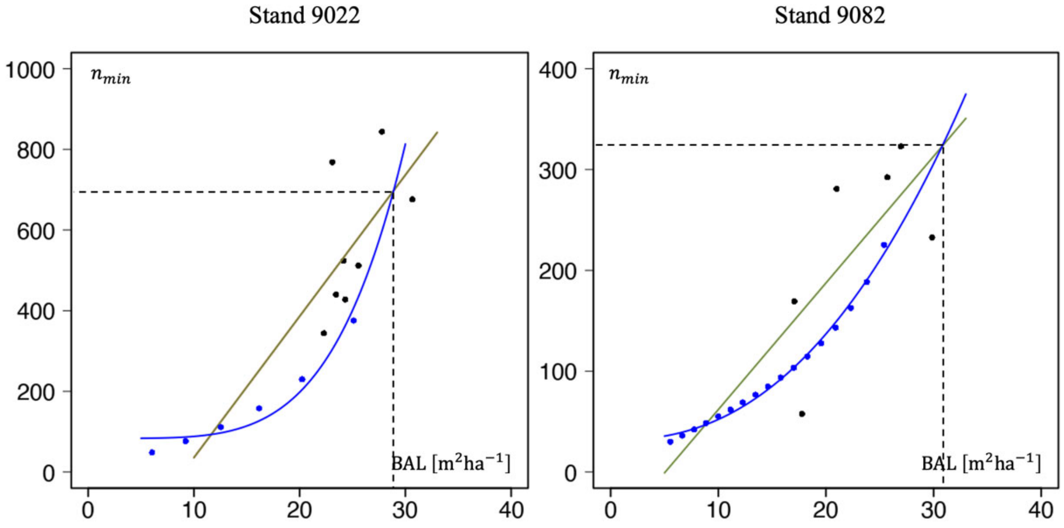

*Figure 5. The black data points shows pairs of basal area of larger trees, BAL, (derived from Eq. 6) and number of trees in the smallest dbh-class,* $n_{min}$*, with trend line in green. The blue data points show simulated pairs of values of BAL and* $n_{min}$ *by using arbitrary* $n_{max}$ *in the demographic model after implementation growth and mortality models. The corresponding blue trend curve follows the function following function:* $n_{min} = a_2 + b_2 \times BAL^{c_2}$.

# Demographic equilibrium models

When comparing the dynamic demographic model fitted for the plots in stand 9022 with the observed dbh distributions a clear difference can be seen in the central dbh classes (Fig 6). This deviation was particular distinct in plots 31, 32, and 34 for classes between 6-18 cm. The development of the diameter distribution between 2017 and 2022 was relatively small. However, the number of trees in the smallest dbh classes decreased in all the plots during this time, which is a negative development for plot 31, 32, and 34, since the numbers of trees in the smaller classes were already lower than the number of trees suggested by the model. Conversely, this was a positive development for plot 33.

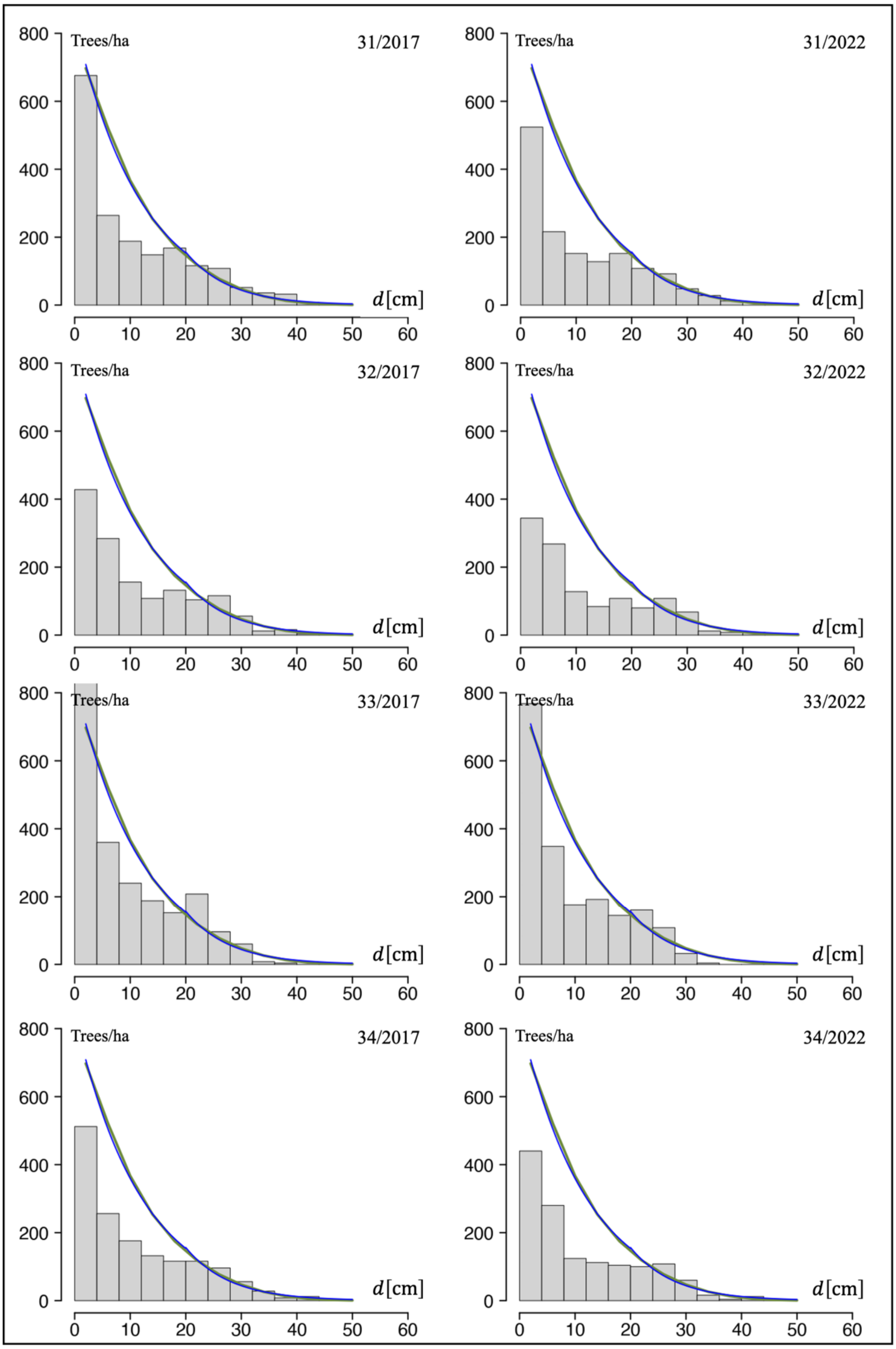

*Figure 6. Dynamic demographic model (green line) and the de Liocourt model (blue line) compared to the observed dbh distribution for plot 31, 32, 33 and 34 in stand 9022 for 2017 and 2022.*

The results from the regression of the simpler de Liocourt model (Eq. 1) can be seen in Table (5) where curve is close to the dynamic demographic model (Eq. 3) according to the values of *E*. To fit the de Liocourt model more accurate, the diameter range was split into two parts with one diameter class overlapping to achieve a smooth transition. Thus, the dynamic demographic model is explained by two *q* factors. These are *q* =1.4 for smaller and *q* =1.7 for larger dbh classes (Table 4) for stand 9022.

*Table 5. Model parameters for the de Liocourt model (Eq. 2) together with corresponding efficiencies, E (Eq. 8) and q-factors (Eq. 2) for stand 9022 and 9082. All values correspond to the dynamic equilibrium model (Eq. 3) for each diameter range (d).*

| De Liocourt model results | | | | |
|---|---|---|---|---|
| Stand | *d* range [cm] | Model parameters | *E* | *q* |
| 9022 | 2-22 | $n_0 = 839.68392, \lambda = 0.08490$ | 0.99736 | 1.40440 |
| | 22-50 | $n_0 = 1981.56793, \lambda = 0.12702$ | 0.99384 | 1.66210 |
| 9082 | 6-30 | $n_0 = 502.18765, \lambda = 0.07260$ | 0.99945 | 1.33696 |
| | 30-50 | $n_0 = 2580.76155, \lambda = 0.12910$ | 0.99320 | 1.67598 |

When comparing the dynamic demographic model fitted for stand 9082 with the observed dbh-distribution (Fig 7), 1990 and onwards shows considerable smaller deviations than seen for stand 9022 (Fig. 6). From 2000 and onwards, this deviation was close to zero even if only central dbh-classes (10-34) is considered. This period also included a small surplus of trees for most of these diameter classes. The difference in dbh distribution between the two stands might be due to a better management of stand 9082 which the growth dominance index also indicated (Tables 1 and 2). When comparing the deviation between the dynamic demographic model and the empirical dbh-distribution for stand 9082 it can be seen that demographic equilibrium is reached during the monitoring period.

Similar to stand 9022, the dynamic equilibrium model for stand 9082 can also be described by the de Liocourt model based on two separate diameter ranges with one common size-class overlap (Table 5). The optimal diameter ranges for stand 9082 were not the same as for stand 9022. However, the *q* factors for stand 9082 were very close to those of stand 9022, with values of *q* = 1.3 for the smaller classes and *q* = 1.7 for the larger classes. 9022.

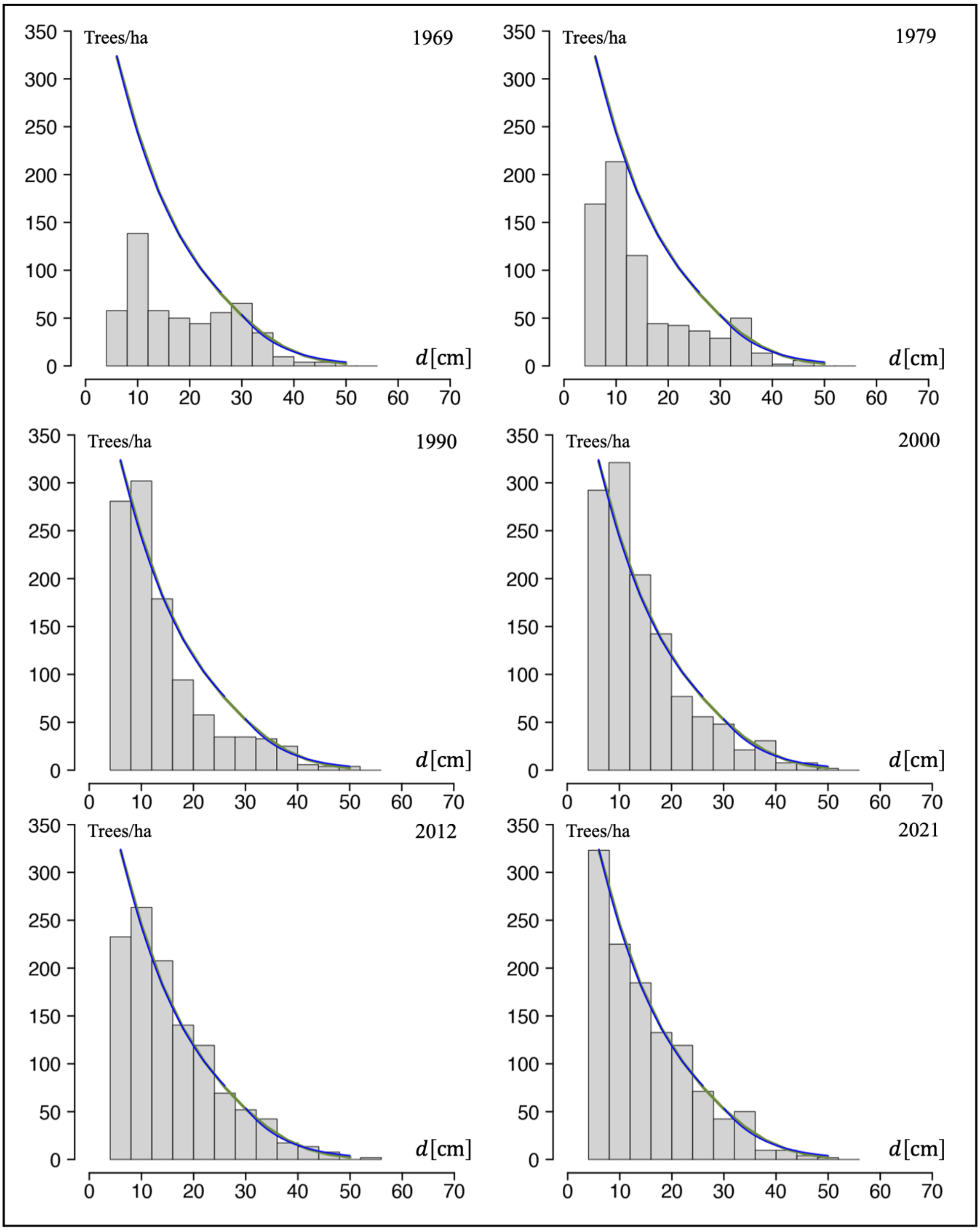

*Figure 7. Dynamic demographic model (green line) and the de Liocourt model (blue line) compared to the observed dbh distribution for stand 9082 from 1969 to 2021.*

The results of the homogeneity index *G*' (Eq. 8) showed values around 1.1 for the dynamic demographic model of both stands (Fig. 8). According to previous research, it is expected to have *G*' close to 1 for equilibrium models (de Camino 1976). Since the results of *G*' showed even lower values for the empirical dbh distribution (except for plot 31 in stand 9022) than the results from the theoretical model, the expectations where well met. The low values of *G*' suggest that the forest structure has a high heterogeneity in both stands which is required for selection forest stands.

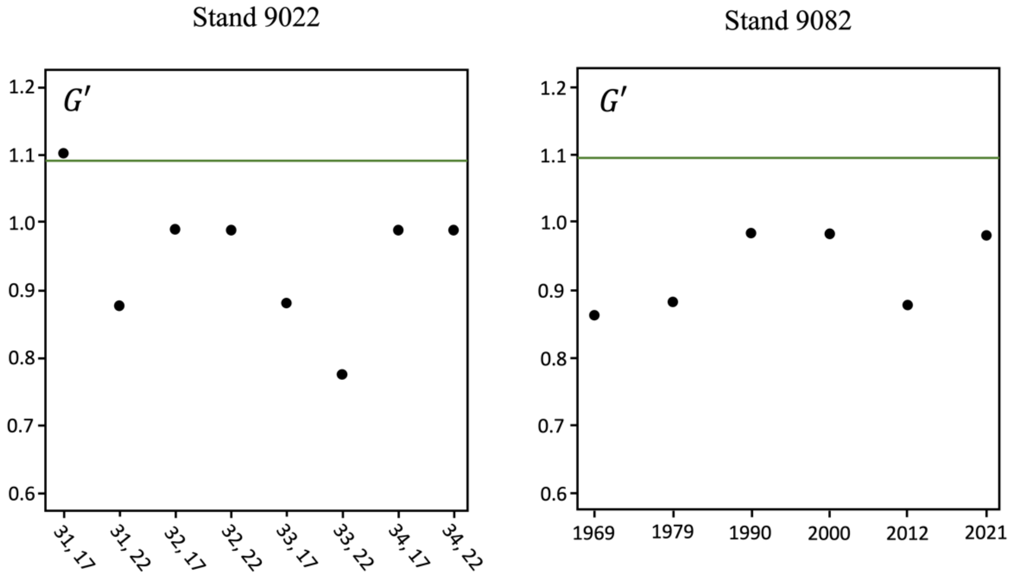

*Figure 8. Illustrates the results from the Homogeneity index,* $G'$*, (Eq. 8) for stand 9022 in different plots and years (plot, year) and in different years for stand 9082. The green line shows the reference value of the dynamic demographic model based on Eq. 3. The reference value for stand 9022 is* $G'=1.08936$ *and* $G'=1.09483$ *for stand 9082.*

The homogeneity index indicates that the empirical dbh distribution is closer to a demographic equilibrium in plots 31, 32 and 34 in stand 9022 (Fig. 8) while looking at the graphs in Fig. 6, the differences seem to be smallest for plot 31 and 33. For stand 9082, the empirical diameter structure moves closer towards the model each of survey (Fig. 7). In year 2012 the diameter distribution deviated slightly from this trend according to the homogeneity index (Fig. 8) although the overall values suggests that the optimal structure for selection forests is close to be reached for both stands.

# 4. Discussion

Assessing the state of a single tree selection forest has always been a challenging task, often relying on the analysis of the dbh distribution of the examined stand. Including information on growth and mortality dynamics of the stands in this analysis is a good way to understand the processes in different dbh classes and helps to better ascertain the sustainability of timber resources (Schütz 2001, 2006; Schütz & Pommerening 2013). The two stands in Siljansfors Experimental Park were interesting for two reasons. Firstly, both stands are monocultures composed only of *Picea abies*, which is not common in areas where the single tree selection system is mostly used. Secondly, when comparing the two stands in Siljansfors to other selection forests in Europe, the final target diameter of 50 cm is markedly smaller than target diameter seen in other studies (Meyer 1952; Schütz 2006; Schütz & Pommerening 2013; Kärenlampi 2019). Felling diameters in Sweden regardless of species are rather small when compared to traditional CCF systems in Central Europe. Lastly, the location of these stands is far beyond the areas where the single tree selection system is commonly practiced, and for many years the system has been considered unsuitable in Sweden.

There are reasons why the target diameter is smaller in Siljansfors and Sweden in generally. Firstly, the site quality at the locations of the two stands is relatively low compared to that of other selection forests in Central Europe. The limitations of available sunlight at these latitudes and the shorter growing season are two main factors for lower growth. This means that an old tree can still have a relatively small diameter. In addition, like in all forests, the mortality rate in these forests increases with the increasing tree age. For that reasons it is difficult to have a target diameter in the stand in Siljansfors and still maintain a consistent harvest of trees. Secondly, the stands in Siljansfors are managed using standard harvesters, which usually have their maximum capacity around the target diameter of 50 cm. Lastly, in order to achieve successful regeneration at these latitudes, it is believed that stand volume needs to be kept low compared to forest areas in central Europe.

The analysed results for the diameter growth behaves in a normal way when compared to earlier studies (Schütz 2006; Schütz & Pommerening 2013) and confirms the differences in terms of site index (Sect. 2.1) and site qualities (Fig. 2 and 3). The annual growth is however lower when comparing to other selection systems using *Picea abies* (Schütz & Pommerening 2013). The reason for this might be the same as for the relatively small target diameter, which is differences in growing conditions. As seen in previous studies, BAL worked as a good predictor of growth for the two stands in Siljansfors (Schütz 2006; Schütz & Pommerening 2013). In a similar way the results from modelling mortality turned out as expected (Fig. 4) and when modelling the future equilibrium rates no unexpected challenges were discovered (Schütz & Pommerening 2013). When analysing the mortality results, signs of slightly too big outtake of trees was revealed for stand 9022. This might be one reason why stand 9022 is further away from the demographic equilibrium compared to stand 9082. The past outtakes for stand 9082 seem to have been more appropriate and the benefits of management adapted to the stand clearly shows when comparing Fig. 6 and 7.

The modelling of optimal number of trees in the smallest dbh classes ($n_{min}$) for each plot (Fig. 5) showed relatively high numbers ($n_{min}$=697 for stand 9022 and $n_{min}$=323 for stand 9082) compared to previous research (Schütz 2001, 2006; Schütz & Pommerening 2013; Brzeziecki et al. 2016). The reason for this is mainly due to the small diameter of the first size-class of the stands (0-4 cm for stand 9022 and 4-8 cm for stand 9082). However, the high values of $n_{min}$ are necessary due to the high mortality rates in the medium size-classes. Despite the high numbers required in the smallest classes, regeneration has not been a problem in the past (Fig. 6 and 7).

When examining the observed dbh-distributions in conjunction with the demographic equilibrium model for stand 9022, a deficit of trees in size classes between 6 and 18 cm was apparent, indicating that the desired equilibrium for the stand had not been reached yet. This deficit can be approached in various ways. One way to improve the distribution could be to do thinnings of trees in size class 22 and 26 to reduce the competition in lower size classes and because of this enhance the growth. A similar method has been tested in a former study and worked to some extent although it may be considered a short-term solution (Petersen & Guericke 2004). A more long-term solution would be to continue with target diameter cuttings until the desired dbh-distribution has been reached naturally through ongoing demographic processes. In contrast to stand 9022, only a few deviations were observed for stand 9082, which indicates that hardly any changes from the current management with target diameter cuttings are necessary. The development over time in stand 9082 that can be seen in Fig. 7 indicates that accurate management of the stand have been beneficial to reach the demographic equilibrium. This is further supported by the homogeneity index (Eq. 8, Fig. 8), where values for the observed dbh-distribution over time develop towards the model outcome with exceptions for year 2012. The reason for why the observed diameter observation 2012 deviated from this trend might be due to low numbers in the lowest diameter classes seen in Fig. 7. However, for all plots throughout all years the index takes on very low values, indicating a high level of heterogeneity and which is crucial for in CCF systems.

The results of this thesis demonstrate the benefits of using multiple analytical criteria when evaluating size structures in selection systems to make more confident conclusions. The graphical results (Fig. 6 and 7) together with the homogeneity index (Eq. 8, Fig. 8) resulted in higher quality and more reliable stand analysis. This thesis also suggests that stands with slower growth seems to be more limited to a smaller target diameter. It should be noted that the initial hypothesis that the observed dbh distribution would be far from demographic equilibrium due to the loose application of single tree selection methods in the past was found to be incorrect after the assessment of the results.

The analysis of the results also showed that the dynamic equilibrium model described by Eq. (3) also can be simplified by using de Liocourt model (*q*-factor model) (Eqs. 1 and 2) to facilitate the work of forest practitioners. However, the de Liocourt model has been criticized since the model is static. This means that the model does not take stand dynamics such as growth and mortality into consideration. This model has also been criticized for "*q*" to be constant through all dbh classes (Hanewinkel 1998; Schütz & Pommerening 2013). Previous studies have proposed different methods for the estimation of *q* based on observations (Susmel 1956; Poznanski & Rutkowska 1997; Pretzsch 2009) which have brought more doubt than clarity (Hanewinkel 1998; Pommerening 2023). However, deriving the de Liocourt model using a dynamic demographic model such as Eq. (3) gives more reliable results and was successfully done in this thesis. As learned from previously studies, *q* was not constant through all dbh classes in this thesis either. Therefore, two different dbh ranges had to be formed to describe the dynamic demographic model in a way similar to previous publications (Hett & Loucks 1976; Hansen & Nyland 1987). An interesting difference compared to earlier studies is the fact that the *q* factor was slightly larger for the smaller dbh classes than for the larger dbh classes.

# 5. Conclusions

In conclusion it is possible to establish and maintain single tree selection systems in central Sweden, using *Picea abies* as the sole species. The target diameter for the stands is smaller compared to areas where these selection systems are used in central Europe. Furthermore, it has also been shown that both the static de Liocourt model and dynamic demographic models can be relied on to make evaluations of the structure of forest stands and their long-term resource sustainability. By deriving the de Liocourt model from a dynamic demographic model is it possible to facilitate forest practitioners work. The findings presented in this thesis could be particularly valuable now when the interest for CCF methods is gaining popularity in Fennoscandia and could possibly contribute to achieving the Swedish environmental goal of living forests.

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# Popular science summary

A recent debate has emerged in Sweden regarding the most commonly used silvicultural system, the rotation system with final felling, since research has shown that this system leads to loss of biodiversity. The rotational forest system works with a final felling that clears away all trees, after which the area is usually planted again. Sweden does not reach the environmental goals for the forest, and this has led to the consideration of an alternative way of managing the forest for timber called continuous cover forestry (CCF). Research has shown that CCF forests are better at handling extreme weather and have higher biodiversity compared to the rotation system. One particular CCF approach is the single tree selection system, where harvest of the biggest trees takes place continuously, while all other trees are left untouched. For this management method to function, the forest needs to have a complex structure in which there are enough trees in all sizes to grow into the larger size classes. In Sweden there is a lack of experience with this method, so more research is needed to better understand the dynamics of stands managed using this system. One approach to improve our understanding of single tree selection systems is the use of models that show the steady state of the forest, so called equilibrium.

In this thesis, I used a dynamic demographic equilibrium model, to create a so-called equilibrium-line that shows the ideal numbers of trees in all diameter groups for a sustainable management. This allowed me to compare the real number of trees in all diameter groups to the equilibrium line, and to decide if the single tree selection in these Swedish stands is sustainable. I then translated the complex dynamic model into a simpler static model that could be used in forest management. Based on the real numbers and the equilibrium line from the model, I could also make future management recommendations. I also measured the change of the forest structure over time, using a measurement called the homogeneity index. A high homogeneity means that a lot of trees are the same size, and a low number means that there are many different sizes of trees in the stand, which would be the best for using the single tree selection system.

The results of this thesis show that Swedish selection forests grow slower than forests that are managed in the same way in other parts of Europe, and there are more trees dying in these forests. To balance that out, a lot of new, small trees need to start growing in these stands, and the target diameter for harvesting trees is limited to smaller diameter sizes compared to selection forests in more southern countries. However, when comparing the number of trees in all the different diameter groups of the stands in central Sweden with the modelled equilibrium-line, I showed that it is important to use well adapted management in the selection forests to have a good development over time in the stand. This comparison between reality and the model also suggests that these selection stands can reach a state of equilibrium which means that they can produce timber that can be harvested without affecting the complex structure of the forest.

In conclusion, I found that it is indeed possible to create and sustainably manage forests in Sweden using the single tree selection system. The thesis also highlights that both the more complex dynamic model and more simple static model are good tools to evaluate stands in Swedish forests. It also demonstrates that basing a static model on a dynamic model makes it more reliable as well as with the use of multiple analytical methods. These findings contribute to the ongoing debates and discussions surrounding silvicultural practices in Sweden and can provide valuable insights for forest management and decision-making.

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