A comparison of methods to assess site index in young Norway spruce stands

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Swedish University of Agricultural Sciences

Master Thesis no. 227

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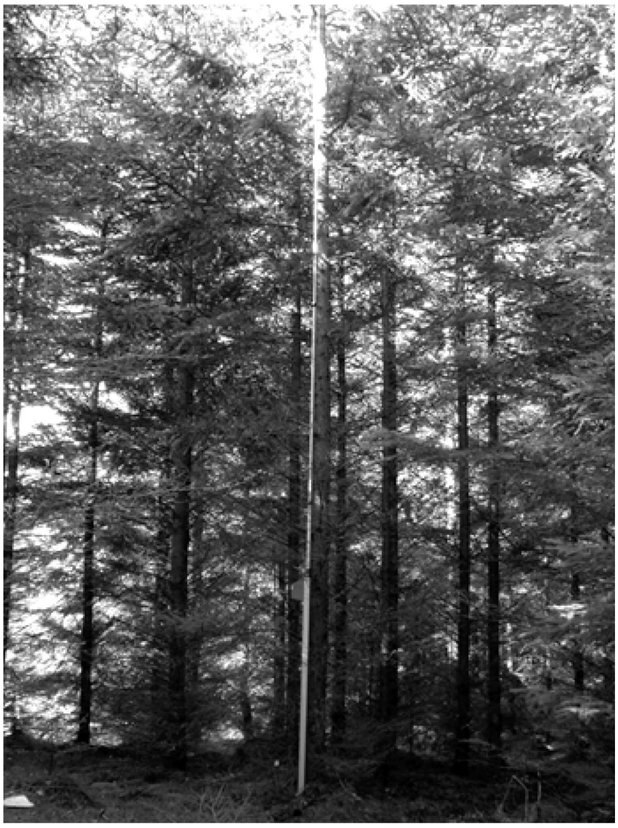

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Abstract

This study investigates whether the site index curve method (SICM) and the growth intercept method (GIM) can be used for site index predictions in younger Norway spruce (*Picea abies* (L.) Karst.) stands than recommended by current guidelines. For SICM it was thus investigated whether the method could be used for stands younger than ten years, and for GIM it was tested whether a starting point for the intercept measurements could be used below the recommended 2.5 meter. This was tested based on measurements taken from experimental stands in Tönnersjöheden Research Forest.

For GIM it was found that the method can only be used when the TH-trees of a stand have five complete intercepts above 2.5 meters. For the method to be applicable beyond this, it will be necessary to adapt the underlying equations, perhaps following the Canadian example where a 1.3 meter intercept start is used. In conclusion it is not currently possible to apply the approach beyond the current recommendations.

For SICM, SI predictions are accurate for the study area already form year three. This indicates that SICM may be applicable to stands that are significantly younger than ten years. These results are very promising, but due to the geographical limitations of the study, no general conclusions can be drawn. For SICM to be used confidently on younger stands on a regular basis it is necessary to conduct a larger field study that covers a whole range of Swedish latitudes across the entire spectrum of spruce site types.

Key words: site index, growth intercept, site index curves, height development, site class, Norway spruce, *Picea abies*

Sammanfattning

Detta examenarbete undersöker, om höjdutvecklingskurvor och interceptmetoden kan användas till bestämning av ståndortsindex i yngre granbestånd (*Picea abies* (L.) Karst.) tidigare än vad som rekommenderas idag. För höjdutvecklingskurvor undersöktes möjligheten att använda metoden i bestånd yngre än tio år, och för interceptmetoden undersöktes möjligheten att använda en utgångshöjd för interceptet lägre än 2,5 meter. Undersökningarna genomfördes på Tönnersjöheden försökspark.

Resultaten av undersökningen av interceptmetoden visade att den endast kan användas om övre-höjds träden i beståndet har fem årsväxter över 2,5 meter. Om metoden skall kunna användas vid lägre höjd kommer det bli nödvändigt att anpassa funktionen bakom metoden. Detta skulle kunna vara möjligt om man antog det kanadensiska tillvägagångssättet för interceptmetoden, där man använder en utgångshöjd på 1,3 meter. Slutsatsen är, att det för närvarande inte är möjligt att använda interceptmetoden för att bestämma ståndsortsindex av yngre granbestånd och med lägre intercepthöjd än det som rekommenderas idag.

För undersökningen med hjälp av höjdutvecklingskurvor visar resultaten, att det beräknande ståndortsindexet för försöksbeståndet är rättvisande redan från år tre. Detta indikerar, att höjdutvecklingskurvor kan vara användbara i bestånd som är betydligt yngre än tio år. Trots lovande resultat är det inte möjligt att dra några generella slutsatser om användningen av höjdutvecklingskurvor i yngre granbestånd på grund av försökets geografiska begränsning. En större fältstudie som täcker hela Sverige och inkluderar alla granens beståndstyper, skulle dock kunna avgöra den generella användbarheten av höjdutvecklingskurvor för att bestämma ståndsortsindex för yngre granbestånd.

Key words: Såndortsindex, intercept, höjdutvecklingkurvor, höjdutveckling, bonitet gran, *Picea abies*

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Introduction

Site index (SI) is a central parameter in forestry practice, and is defined as the dominant height that an ideal stand will reach at a predetermined reference age. An ideal stand is understood to be a stand that is more or less dominated by the same species, even-aged and undamaged. In Sweden, SI is probably the most common predictive indicator of stand growth and yield (Johansson *et al*., 2014), and can thus be used in forest inventory, silviculture and timber supply analysis (B. C. Ministry of Forests, 1999). Some of the first scientific research in this area was carried out by Tor Jonson as early as 1914 (Jonson, 1914). The work of Jonson was built upon by several researchers up to the 1970s where the SI system of Hägglund and Lundmark was developed. The SI system consists of three recognized methods for determining site index in Sweden (Hägglund and Lundmark 1982a, 1982b, 1982c), namely the biogeoclimactic ecosystem classification, the growth intercept method and the site index curve method.

The Biogeoclimatic Ecosystem Classification (BEC) is often also referred to as the "site index by means of site properties" –method. It uses site specific properties such as local climate, soil type, soil moisture content, water table and composition of field vegetation to determine site index. SI is determined by using the collected information in conjunction with an SI table (Hägglund & Lundmark, 1982b). Though this method adequately predicts SI, it is generally considered less accurate than the growth intercept- and site index curve methods (Hägglund & Lundmark, 1977).

The Growth Intercept Method (GIM) was originally developed in the 1930s, with the idea that for young stands, a periodic growth measure may be more descriptive than total height, especially for stands of an unknown age. This method is also applicable to stands where growth has been hampered by frost or browsing. (Skovsgaard & Vanclay, 2008) The growth intercept method is used in younger stands not exceeding 30 years of age. This method is based on intercept measurements, where intercept length is given as the length between the first six branch whorls above 2.5 meters on the stem. The intercept is used to determine SI from published tables and curves based on mathematical algorithms developed from larger Swedish datasets (Hägglund, 1976).

The Site Index Curve Method (SICM) uses tree height and age to determine the site index. The age and height information is used as input for predictive curves to determine SI. The method is applicable for stands down to 25 years according to the Hägglund and Lundmark curves (Hägglund and Lundmark, 1982a), but new curves have recently been developed that are applicable down to ten years of age (Johansson *et al*., 2014).

Because the SICM is now applicable to stands down to ten years of age, it is possible for the first time to compare SICM to GIM in young stands. This thesis therefore aims to determine the accuracy and applicability of these two methods in young stands of Norway spruce (*Picea abies* (L.) Karst.), while at the same time investigating whether it is possible to stretch the applicability of each approach beyond the recommended minimum stand age. The stand in focus was carefully selected because it is part of a greater experiment where trees were planted in randomized plots in annual intervals over a five year period. This unique study design minimizes the potential for uncertainties caused by annual climate fluctuations.

Problem formulation

- Determine the earliest time when the methods can be used
  - Determine whether GIM can be used for intercepts below 2.5 m
  - Determine whether SICM can be used before year ten
- Compare and discuss strengths and weaknesses of each approach
  - Determine whether there are any annual or geospatial effects on site index calculations
  - Analyse necessary sample size of GIM and SICM

Theory

Applicability domains for GIM, SICM, and BEC

There are many factors that determine which method is optimal for predicting site index for a given area. If the area of interest already has forest cover, stand age is probably the most important factor when choosing method. Figure 1 gives a general overview of the suggested application range for each method in terms of stand age.

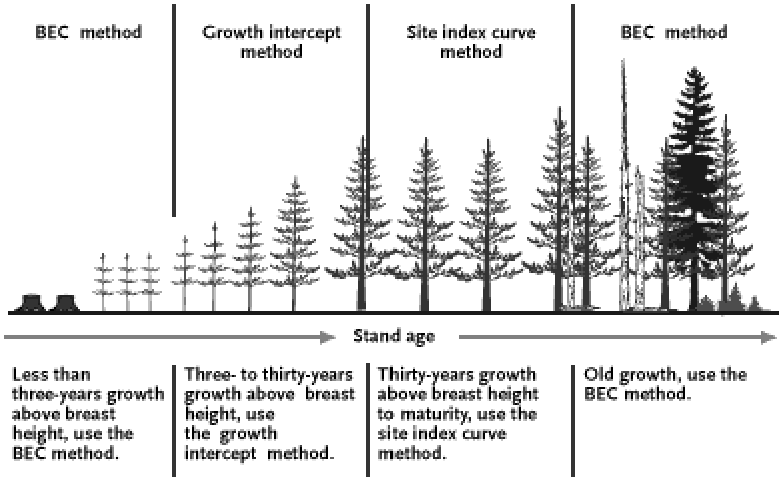


Figure 1: Applicability domains for SICM, GIM, and BEC (B. C. Ministry of Forests, 1999).

Hägglund and Lundmark (1982a) developed a decision tree to help Swedish forest owners to make quick decisions on which method to use for a given stand, assuming that the user is always interested in achieving the greatest degree of accuracy (Figure 2). In supplement to the decision tree, Table 1 summarizes some of the more detailed criterion for GIM and SICM. BEC is not included in Table 1, but generally BEC will be applicable where GIM and SICM are not. There are a number of exceptions to this including very heterogeneous sites and peatlands for which a specific method has been developed (Hånell, 2008).

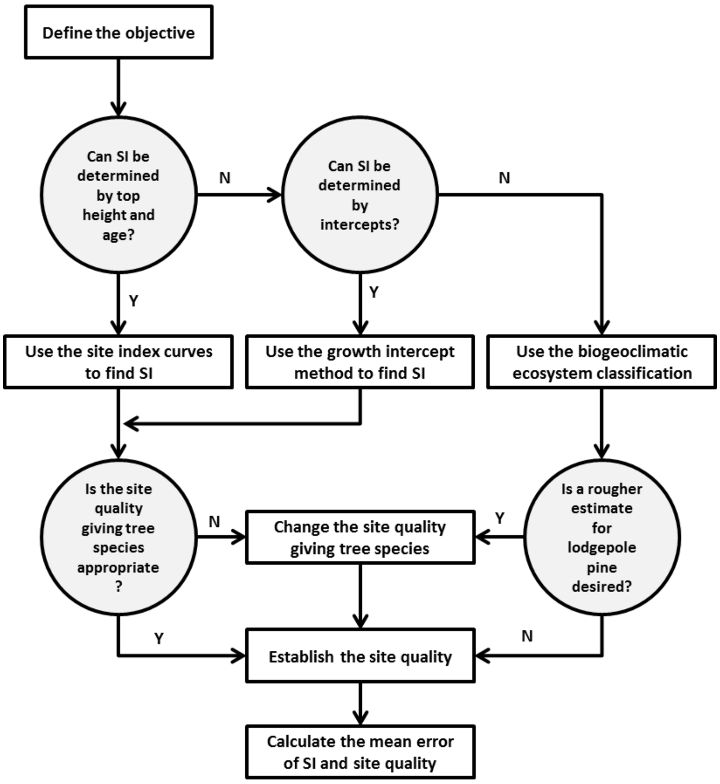


Figure 2: Decision tree for site index method. Adapted from Hägglund and Lundmark (1982a).

Table 1: Specific criteria for each of the two methods (Hägglund & Lundmark, 1982a).

	Criteria description	SICM	GIM
K1	Target species minimum proportion	50%	75%
K2	Max volume outside age range 20 years	20%	20%
K2	Max DBH-age difference	15yrs	15yrs
K3	Thinning from above	No	No
K4	Mass density*	>0.5	>0.5
K5	Valid DBH-age range	25-100	<30
K6	Growth suppression in pre-commercial phase	No	No
K7	Application of fertilizer**	No	No
K7	Drainage after trees have reached BH	No	No
K8	TH-trees damage affecting height growth	No	No***
K9	TH-trees must be relevant species ****	Yes	Yes
K10	Topsoil depth >70cm	Yes	Yes

* more detail in Hägglund and Lundmark (1982a)
** one-time application allowed for older stands
*** damage above the intercept section is allowable
**** exceptions to this are listed in Hägglund and Lundmark (1982a)

TH-trees and sample plots

Site index is often calculated based on information on top height (TH) trees. TH-trees are the two trees with the greatest diameter at breast height (dbh, 130 cm) within a circular plot with a radius of 10 meters. The top height is calculated as the arithmetic mean of the height of the TH-trees (Figure 3).

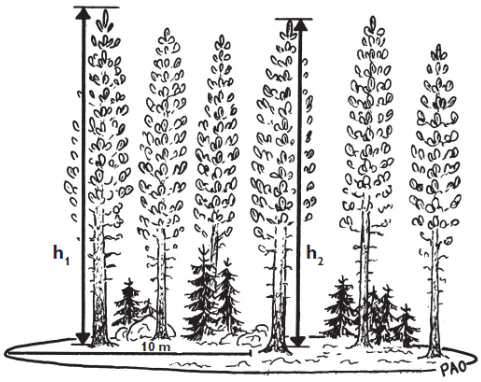


Figure 3: Ten meters radius plot for the selection of TH-trees. Figure from Hägglund and Lundmark (1982a).

TH-trees have traditionally been defined as the 100 trees per hectare with the largest dbh (B. C. Ministry of Forests, 1999). However, this allows for the theoretical situation where all the TH-trees are clustered in one corner of the hectare. The definition of TH-trees has been changed to the ten largest trees in a 0.1 ha to match the size of the plots where the height development has been studied. (Johansson *et al*., 2014)

In Sweden the reference age for site index predictions is typically 100 years, with the notation H100 and less frequently 50 years (e.g. birch). (Hägglund & Lundmark, 1982a)

Accuracy and sample size

Although GIM, SICM and BEC are all recognized as valid approaches for determining SI, the necessary sample size depends on the degree of spatial SI variation, and the willingness of the user to accept uncertainty. Sample sizes are suggested based on these considerations in Hägglund and Lundmark (1982a). The BEC method is seen as the method with the lowest accuracy, but it is often the fastest and therefore also the cheapest. However, due to the lower accuracy it is only suggested for sites that have been newly clearcut or for mixed species stands, and stands with an uneven age distribution. The reliability of GIM is higher than BEC, but this method has more costly input requirements, and can only be used for spruce (*Picea abies*) and pine (*Pinus sylvestris*) stands in Sweden. SICM is generally considered to be the most accurate method for determining SI for commercial species in Sweden.

Hägglund and Lundmark (1982a) provide a table with guidelines for selecting an appropriate number of sample plots based on variability in site quality, and the user's willingness to accept error in SI (Table 2).

Table 2: Guidelines for selecting number of sample plots for SICM (younger than 50 years), SICM (older than 50 years), GIM and BEC.

Guidelines for estimating appropriate no. of sample plots for a hectare				
SI-method	accepted	variation		
	std. error	low	intermediate	large
	(m)	*(no. of sample plots pr. ha)*		
SICM	1.5	11	20	35
dbh-age < 50 years	1.75	3	5	9
	2	3	3	5
SICM	1	9	16	28
dbh-age > 50 years	1.25	4	6	11
	1.5	3	4	6
GIM	1.75	6	11	20
	2	3	4	7
	2.25	3	3	4
BEC	2.75	3	3	4
	3	3	3	3
	3.25	3	3	3

To validate whether the number of sample plots suggested by Table 2 is in fact within the users willingness to accept error, the following formula can be used:

$$E = \sqrt{S^2 + V/n}$$

Where:
E = the total error in SI (meter)
S = Standard deviation (Figure 4)
V = variance in SI between sample plots for an area: $V = \frac{1}{n-1} \cdot [\sum(SI^2) - (\sum SI)^2/n]$
n = number of sample plots

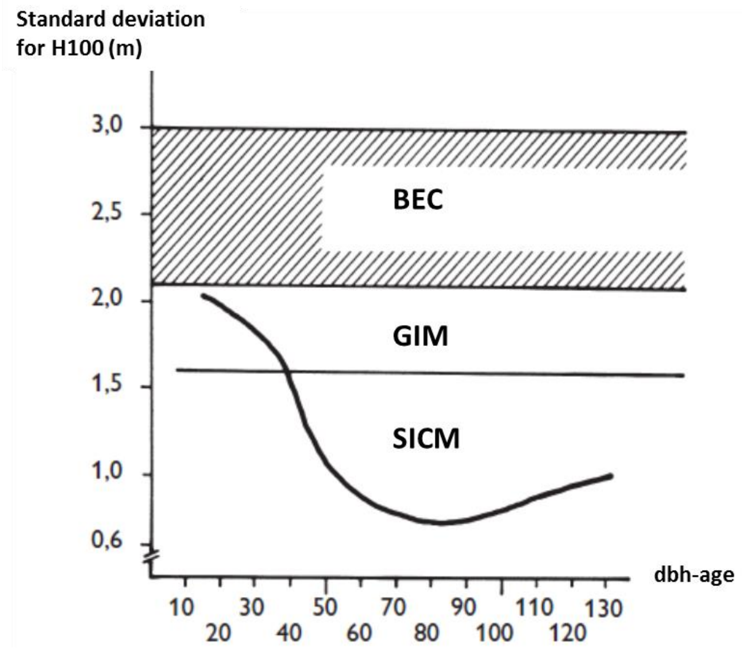


Figure 4: Standard deviation in SI, H100 (m) for BEC, GIM and SICM as a function of age. Adapted from Hägglund and Lundmark (1982a).

Method

Area description

The stand selected for this study is part of a larger Norway spruce seedling experiment that was established between 1989 and 1993 (experiment number 8175), with the overall purpose of investigating how annual weather conditions and time since clear cutting affects stand establishment (Nilsson & Örlander, 1995) (Nilsson & Örlander, 1999) (Karlsson *et al.*, 2002). The original experiment spanned across four sites on two locations, one near Växjö and one at Tönnersjöheden (15 km east of Halmstad). The study area of this thesis is part of one of the sites close to Halmstad (Figure 5) and is under the administration of the SLU Tönnersjöheden Experimental Forest (Bergquist & Örlander, 1998a & 1998b).

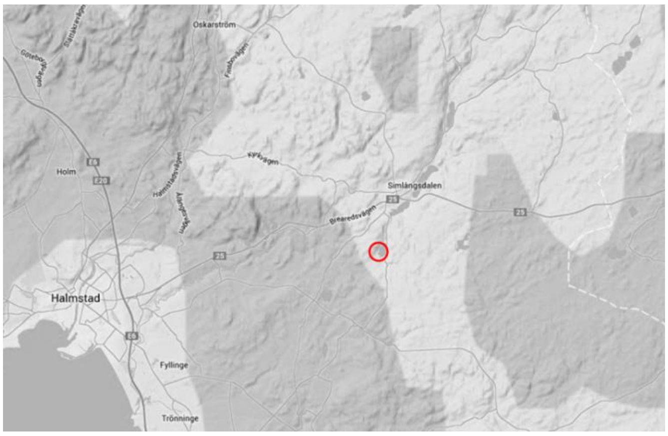


Figure 5: Tönnersjöheden (adapted from Google Earth, 2013).

The plots in question are located at 56°41’39.52”N 13°06’39.16”E, approximately 100 meters above sea level. The areas shown in the aerial photo in Figure 6 are a segment of the experimental plots from experiment 8175. These plots are the focus of this study. Experiment 8175 is described in (Nilsson & Örlander, 1995) (Örlander *et al.*, 1997) (Bergquist & Örlander, 1998a & 1998b) (Bergquist *et al.*, 1999) (Nilsson & Örlander, 1999) (Örlander & Nilsson, 1999) (Högbom *et al.*, 2002) (Karlsson *et al.*, 2002) (Bergquist *et al.*, 2003) (Johansson *et al.*, 2006). In brief, the experiment 8175 was designed as follows. Five future clearcuts were selected for each site (in 1988). These sites were segmented and randomized and selected areas (1-4 ha) were clearcut each year between 1989 and 1993. Each of these clearcuts was divided into to two equal parts. On one part the slash was removed while on the other the slash was retained. Planting was carried out at various intervals after clearcut (i.e. on fresh clearcuts or clearcuts aged 1-5 years).

Since this forest area has been monitored and measured regularly all the way through the pre-commercial phase, it is very well suited for my investigation of methods to assess site index.

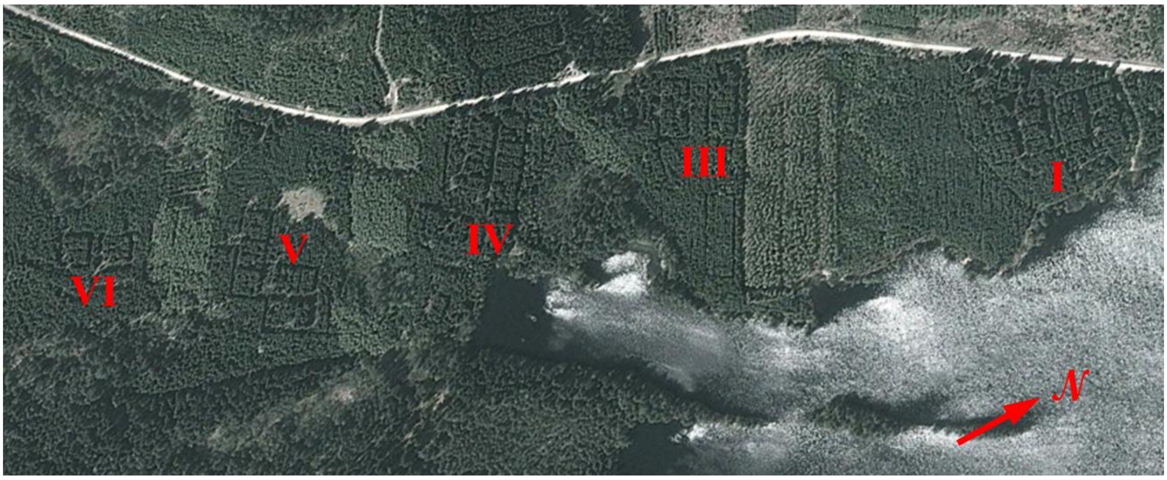


Figure 6: Aerial photo of the study site. Each area is marked with a red number (adapted from Google Earth, 2013). Area II is a control plot and is therefore not included in the present study.

The experiment is made up of blocks divided into plots. Each plot consists of eight sub-plots, which contain 16 trees each (Figure 7). Appendix 1 gives the individual plot numbers.

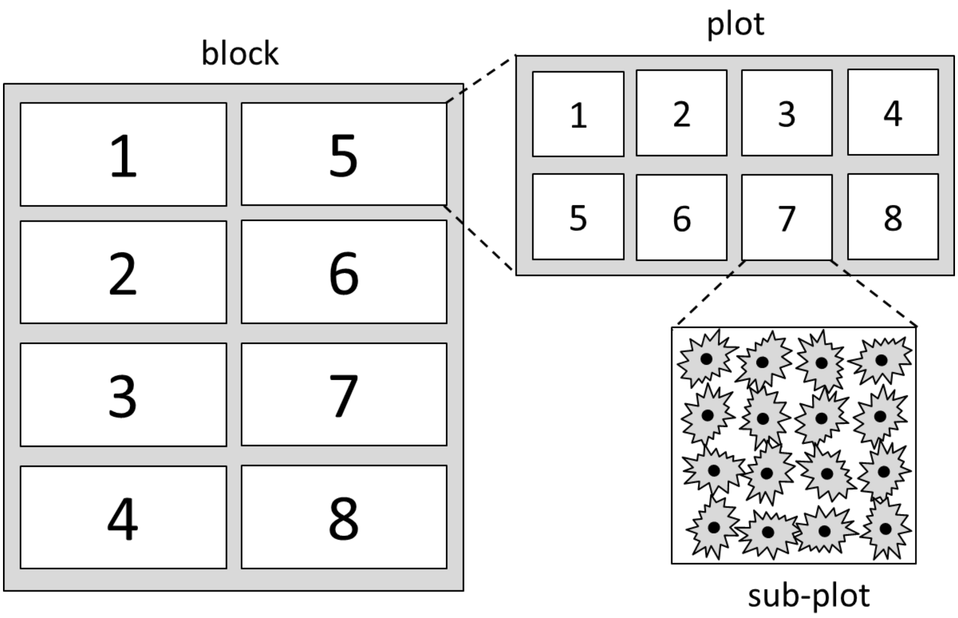


Figure 7: Experimental layout, adapted from Nilsson & Örlander (1999). Example for illustrative purposes.

A summary of the general stand characteristics is given in Table 3.

Table 3: Average details for each forest area.

	total area ha	plots	stems no./ha	average height m	basal area m^2/ha	standing volume m^3/ha
I	0.19	16	4883	10.0	35.8	193.6
III	0.10	8	4163	11.5	36.3	222.4
IV	0.24	20	4747	9.9	34.0	180.2
V	0.14	12	5026	9.5	32.6	167.3
VI	0.05	4	5323	10.3	38.2	212.2

Calculation methods

SI was estimated using SICM and GIM. The following briefly describes the details of each approach.

Site Index Curve Method (SICM)

The curves used in this study to estimate SI with SICM are updated versions (Elfving & Kiviste, 1997) of the Hägglund and Lundmark curves developed in the 1970's. The data behind the new curves consists of repeated measurements on permanent sample plots in spruce stands with an even distribution over all of Sweden. Most of the stands are planted stands, though a minority were naturally regenerated. A rough overview of the data can be found in Elfving (2003). The mathematical model behind the new curves is based on a review of methods for constructing SI curves (Elfving & Kiviste, 1997), and uses dynamic growth rates, with rapid growth rates in younger stands, relative to older stands. This approach to modelling SI allows for a flexible reference age. The new site index curves give the most reliable predictions where tree spacing is normal (~2500 trees/ha), and where the stand is even-aged within an age range of 10-80 years. Figure 8 gives the SICM H100 curves for spruce, which are used in this study (Johansson *et al.*, 2014).

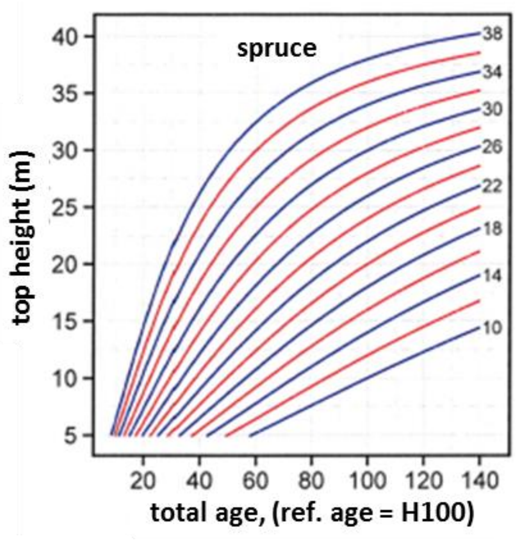


Figure 8: SICM curves for spruce in Southern Sweden (Elfving, 2003). Figure adapted from Johansson *et al.* (2014).

Growth Intercept Method (GIM)

The intercept method requires knowledge of certain variables for the target area including latitude (only relevant for spruce), height above sea level, field vegetation and frequency of surface/subsurface water flow.

Figure 9 gives the GIM curve adapted to conditions for the stands used in this thesis (located in the Halland area). Specific input parameters for Figure 9 are latitude = 56.5, altitude = 100m above sea level and field layer vegetation class = broad leaved grasses.

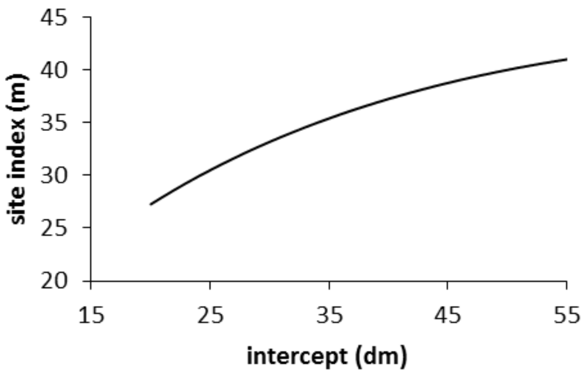


Figure 9: GIM curve for Spruce for site conditions relevant to the study area.

Data

The data used in this thesis is a combination of historical data collected as part of experiment 8175, and of measured data collected specifically for this study. Both measured and historical data is based on TH-trees as defined by experiment 8175.

TH-trees

TH-trees were selected as part of experiment 8175. On average there were approximately five TH-trees per plot (Table 4).

Table 4: Average number of TH-trees (± standard deviation), and number of trees that could not be measured due to low visibility.

area	TH-trees	not measured
I	4.6 ± 0.8	0
III	4.9 ± 0.4	1
IV	4.6 ± 0.8	1
V	4.6 ± 1.2	5
VI	4.8 ± 0.5	1

As an example of the distribution of TH-trees, the relative placement is roughly sketched out for area IV (Figure 10). Similar sketches for the remaining areas are given in Appendix 2.

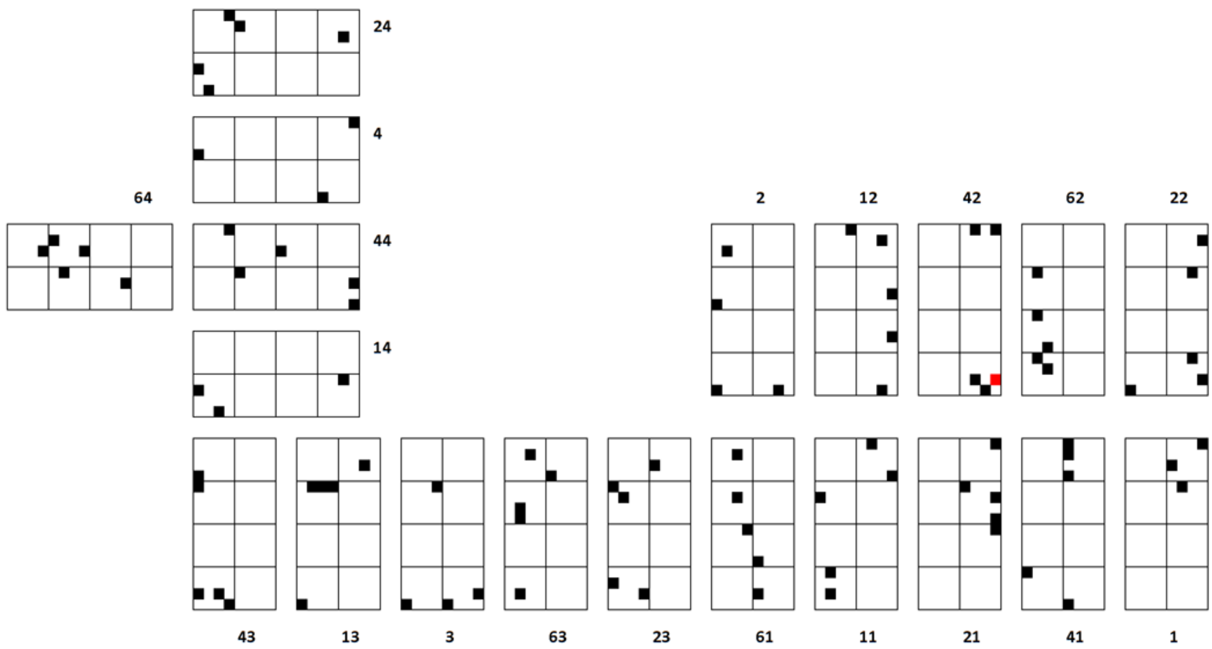


Figure 10: Distribution of TH-trees for area IV. Red dot represent TH-trees that could not be measured.

For area IV the TH-trees are approximately 379 trees/ha. This should be seen relative to the 100 trees/ha specified in Hägglund and Lundmark's guidelines.

In some cases measurements were difficult due to the condition of the plots. For instance some plots were damage in the 1992 summer drought that affected Southern Scandinavia (Nilsson & Örlander, 1995). Specifically, a number of the seedlings that were planted in '92 died the same or the following year. This means that some of these plots are not intact. Upon inspection these plots appeared to have comparatively larger living crowns that extend lower on the stem, and the growth intercept measurements were therefor difficult to carry out, and in a few cases measurements could not be made, because it was not possible to see the endpoint of the intercept length.

Most of the data in this thesis is based on the TH-trees (year 20) in the 8175 experiment. However, the TH-trees are not necessarily the trees with the greatest diameters in previous inventories. For this reason the effect of selecting TH-trees manually from the historical data is also investigated later in this thesis.

Measured data

Intercepts were measured the first week of September 2013 using a telescope measuring pole (see front page picture). This measuring technique makes it possible for a single person to take the readings (down to the nearest decimetre) without assistance. Specifically, the procedure was as follows:

1. Location of the 2.5m point above ground on the stem.
2. Location of the first whorl of branches above this point.

3. Measurement of the distance between this whorl and the consecutive 6th whorl (using measuring pole).

If a whorl of branches is located exactly at 2.5m it is not counted as starting point for the intercept. This is because the intercept is defined as starting at the first whorl *above* 2.5m (Hägglund & Lundmark, 1982a). The procedure is schematized in Figure 11.

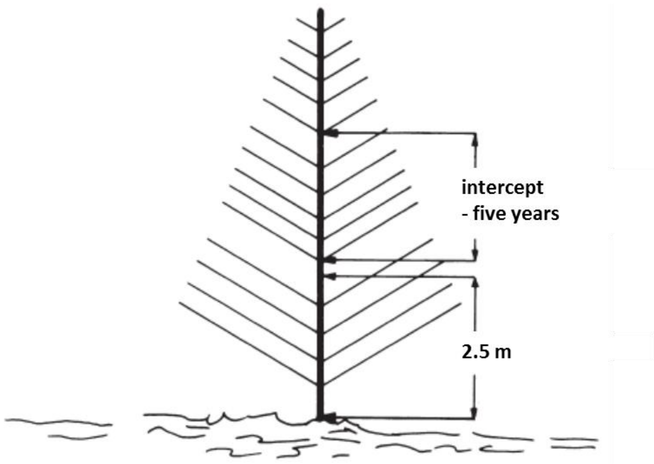


Figure 11: Standard procedure for determination of the intercept length. Adapted from Hägglund and Lundmark (1982a).

The number of TH-trees for which the intercept was measured was 275.

Historical Data

The 8175 dataset consists of measured total height, annual height increment and diameter data. The data collection has not been constant over the years. Figure 12 gives an overview of the dataset, where it is apparent that data is sparse for trees aged 8 and 9.

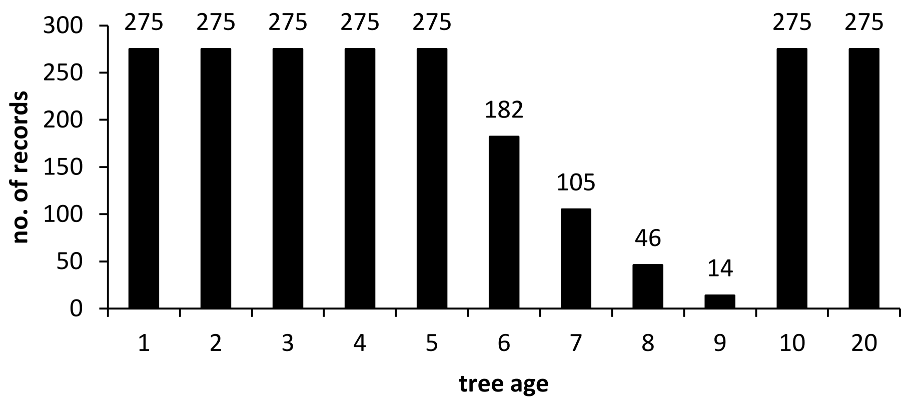


Figure 12: Number of measured trees for each tree age.

Statistics and calculations

The overall approach to analysing data in this thesis is summarized in the following three points:

- Grouping trees by tree age
- Visualizing data by box plots to evaluate the distribution of data including median and outliers.
    - Consider trends in historical data (height, increment, diameter, etc.)
    - Analyse results of GIM and SICM calculations (grouped by age and by area)
- Using linear regressions to identify trends and significant differences between data sets.
    - Investigate the correlation between SI found by GIM and SICM
    - Investigate correlation between SICM calculations for different years.
- Evaluation of sample size based on standard deviation, analysis of variance, and 95% confidence intervals.

All calculations and statistics were carried out in Excel and R (R Core Team, 2013).

Normalization by tree age

Because the trees were planted in annual intervals over a five year period, the age distribution of the plots is not even. To allow statistical comparison of the trees, they were grouped by age, rather than by planting year. This means that trees in the same age class have not necessarily had the same conditions at various growth stages.

Exploring data by box plots

The majority of the data is illustrated in the form of box plots (produced in R). A box plot is built up around a box that consists of three quartiles (Figure 13). The two endpoints of the box represent quartile 1 and quartile 3 (Q1 and Q3), and the line that divides the box in two gives the second quartile (Q2). This line is also the median. This means that the area of the graph above this line represents 50% of the data, while the part of the graph below the line represents the other 50%. It is important to remember that the median is not an expression for the mean value but visualizes the distribution of the data. The box represents the 25% of the data that lies respectively above and below the median, and the whiskers and outliers represent the remaining 50% of the data relative to the median. Modified box plots, which are used in this thesis, take outliers into account such that Q1 and Q3 only extend to maximum and minimum values if these fall within 1.5 units of the interquartile ranges (Figure 13).

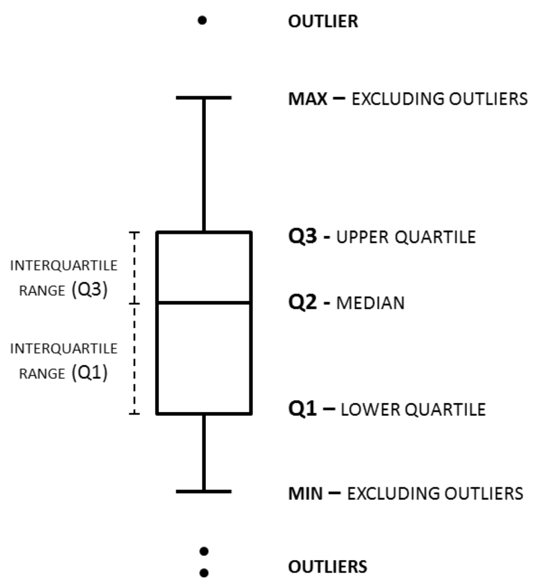


Figure 13: Schematization of a box plot with labels. Adapted from Johnson *et al*. (2011).

Results and discussion

This section gives an overview of both historical and measured data in the thesis. This is followed by the presentation of calculated SI based on both GIM and SICM illustrated graphically as box plots. Next it is investigated whether there is evidence of any area dependent differences in calculated SI, and whether annual seasonal factors contribute significantly to the variation in site index predictions. The correlation between GIM and SICM is calculated, and the necessary number of data points to confidently determine SI is investigated.

Data overview

General site data

Figure 14 gives a general overview of the historical data for all trees in the study area. Although the remainder of this thesis considers only the TH-trees (year 20), the overview in Figure 14 gives an impression of the overall state of the stands in the study area. Figure 14 includes historical data of total height (14a), average height increment (14b) and diameter (14c).

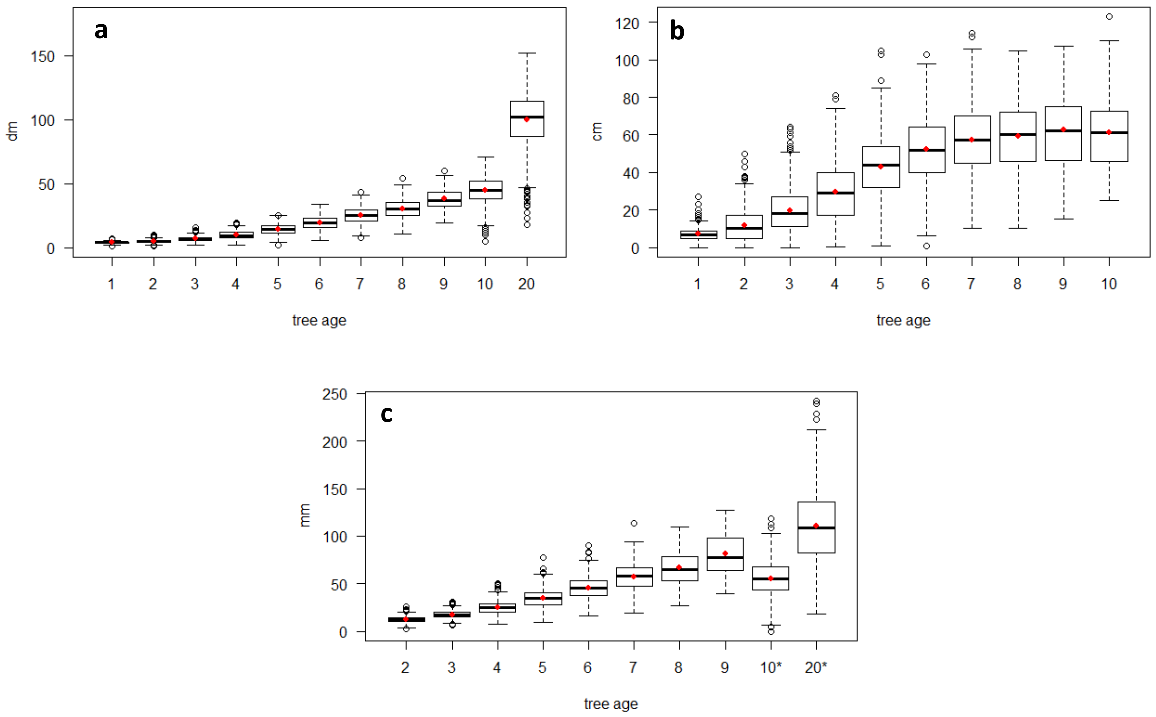


Figure 14: The average total height (**a**), annual height increment (**b**) and diameter (**c**) of all trees in the study area. The measurements in year 10 and 20 (*) are based on diameter at breast height, while the remaining measurements are based on diameter at ground level. The red points indicate the mean values.

The data in Figure 14 has been collected as part of the 8175 experiment, and it has therefore not been specifically designed to suit the objectives of this thesis. Therefore there are certain discrepancies in the data that must be accepted. For instance, average diameter decreases for year 10 (Figure 14c), because measurements in years 2-9 were taken at stump height, while measurements in years 10 and 20 were taken as dbh (1.3m).

Site index predictions

The following presents the input data and the results of calculations of site index using both GIM and SICM.

Growth intercept method

The intercept measurements used for GIM are summarized in Figure 15. Intercepts for trees at age 5-10 are calculated from historical height data, while intercepts for trees at age 20-24 are measured.

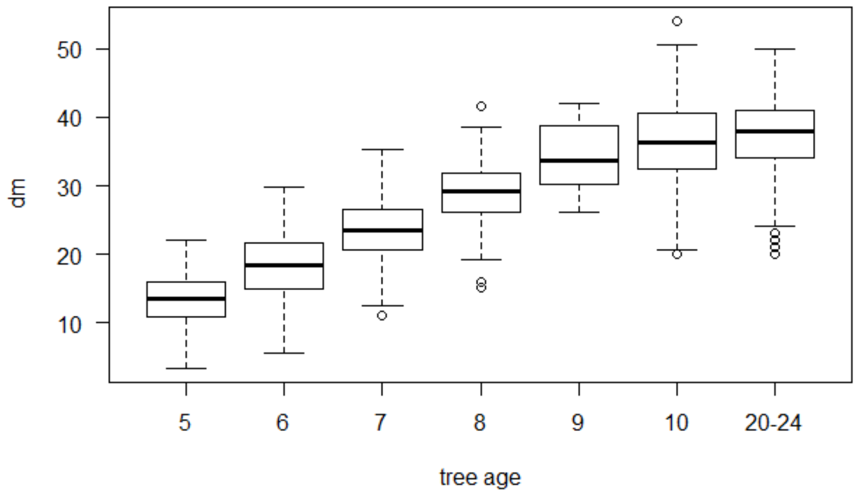


Figure 15: Intercept data for trees at age 5-24. Intercept data for 5-10 is calculated from historical height data while intercepts for years 20-24 are measured.

The measured intercept data for trees in the age range of 20-24 are grouped together because the intercept of the trees in this age range is not expected to be different (i.e. intercept length does not change as the tree grows). The validity of this statement is tested in Figure 16a where the intercept lengths are plotted for trees at age 20-24.

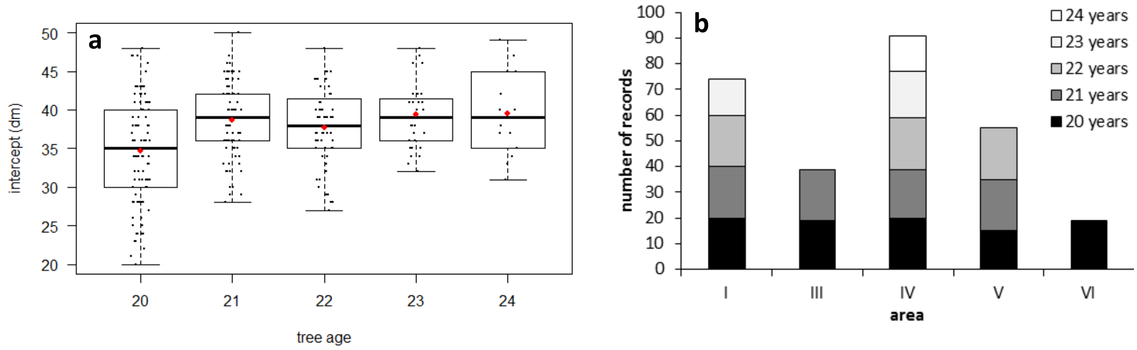


Figure 16: The age distribution of measured intercept lengths (16a) and the age distribution across the five study areas (16b). The red points indicate the mean values.

The intercept measurements appear to have similar mean, median and quartile ranges for trees aged 21 to 24. There is a slight tendency for lower intercepts in year 20. The age distribution across the five areas is given in Figure 16b, where it is seen that trees of 20 years are represented in all five study areas.

Young trees (< 10 years) have not reached a height where it is possible to follow this 2.5m starting point for intercept. The height of the first whorl of the intercept is given in Figure 17 for trees aged 5-10.

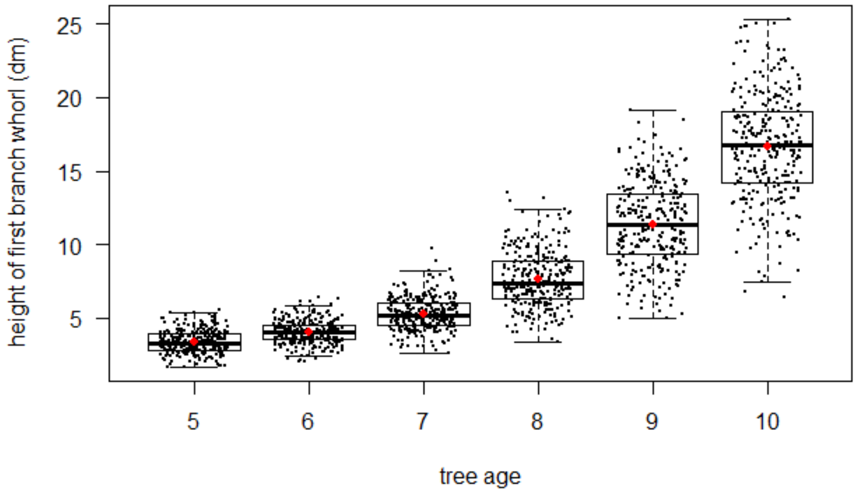
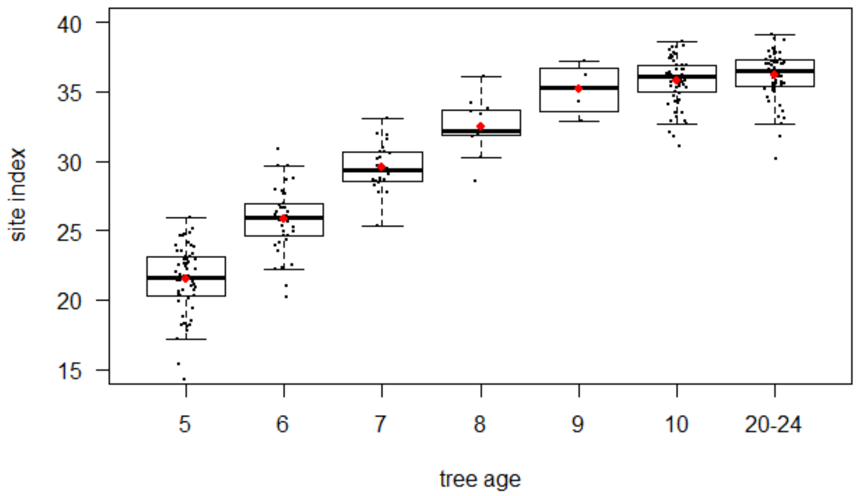


Figure 17: Height of the first whorl for trees aged 5-10. The red points indicate the mean values.

Whether trees that do not yet have six branch whorls above 2.5 meters are suitable for GIM predictions was investigated by applying the GIM formula to younger trees with intercepts starting below 2.5 meters. As given by Figure 17, the trees at age ten have not yet reached a height that allows the 2.5 m criterion from Hägglund and Lundmark to be met. This implies that the GIM method cannot be applied to trees that are younger than 12-15 years old (depending on the SI of the location).

The results of the SI predictions using GIM are given in Figure 18.



	year 5	year 6	year 7	year 8	year 9	year 10
p-value	$3 \cdot 10^{-41}$	$1 \cdot 10^{-26}$	$1 \cdot 10^{-14}$	$2 \cdot 10^{-6}$	$1 \cdot 10^{-2}$	$8 \cdot 10^{-3}$

Figure 18: Site index calculated from the arithmetic mean of intercept measurements for TH-trees distributed on experimental plots using GIM. The red points indicate the mean values. The p-values indicate the probability of a significant difference in mean relative to year 20-24 ($\alpha = 0.05$).

SI calculated using GIM increases as tree age increases (Figure 18). The SI begins to stabilize at around years 9-10, although unfortunately the lack of data in year 8 and 9 make any conclusions for these years difficult.

Site index curve method

SI predicted using SICM relies on total height data. The height data collected for TH-trees is given in Figure 19, for trees aged 1-10 and year 20. All the data is collected as part of experiment 8175, and has thus not been specifically collected for this thesis. Number of observations for each tree age can be seen in Figure 12.

The data in Figure 19 was inserted into the new SICM functions presented in Elfving (2003) and Johansson *et al*. (2014). It is noted that the recommended lower age for these curves is stated to be ten years, for which reason trees aged 1-9 technically fall outside the domain for this method. SI predictions are given in Figure 20.

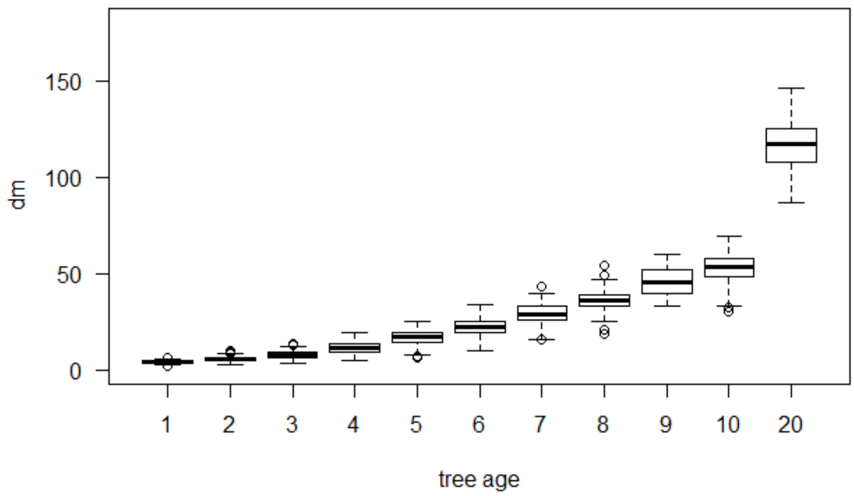
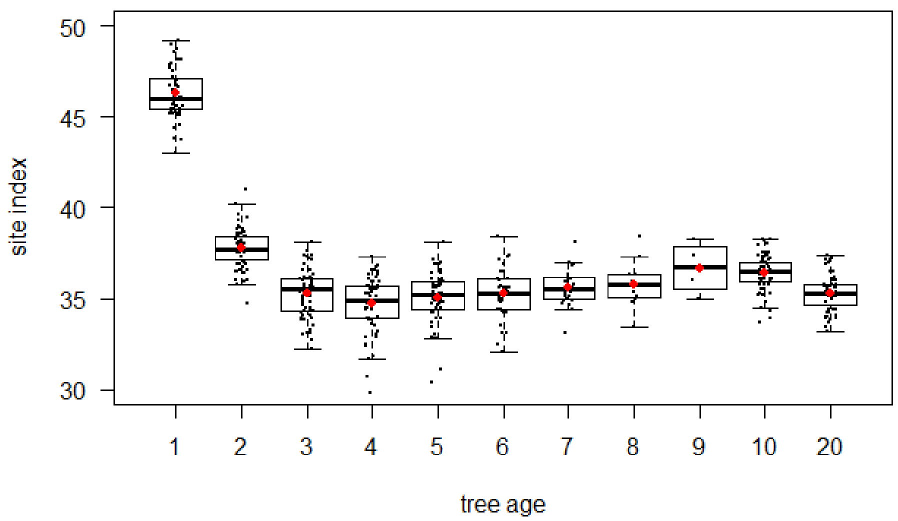


Figure 19: Height data of the TH-trees in the five study areas.



	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10
p-value	$1{\cdot}10^{-50}$	$2{\cdot}10^{-20}$	$8{\cdot}10^{-1}$	$8{\cdot}10^{-3}$	$2{\cdot}10^{-1}$	$3{\cdot}10^{-1}$	$2{\cdot}10^{-2}$	$3{\cdot}10^{-2}$	$6{\cdot}10^{-3}$	$2{\cdot}10^{-18}$

Figure 20: SI calculated from the arithmetic mean of historical height data for TH-trees distributed on experimental plots using SICM. The red points indicate the mean values. The p-values indicate the probability of a significant difference in mean relative to year 20 ($\alpha = 0.05$).

SI calculated using SICM is overestimated for very young trees, but appears to reach a relatively stable level already at age three. The results in Figure 20 seem to indicate that SI predictions reach a level correlating to SI at year 20 at much younger ages than expected based on the recommended age range of the curves.

It is investigated whether the accurate predictions of SICM for young trees could be an artefact of the TH-tree selection process. As previously described, TH-trees were selected as part of experiment 8175 based on diameter at year 20. This means that the TH-trees illustrated in Figure 10 and Appendix 2 were not necessarily the true TH-trees back in time. To investigate whether the use of TH-trees selected in year 20 give a skewed result new SICM predictions are carried out using a TH-tree selection process based on the trees with the biggest diameter for each tree age. Because year 20 is the best available approximation of H100 for this dataset, SI predictions for each tree age are correlated to SI predictions for year 20. Results of this process are given in Figure 21.

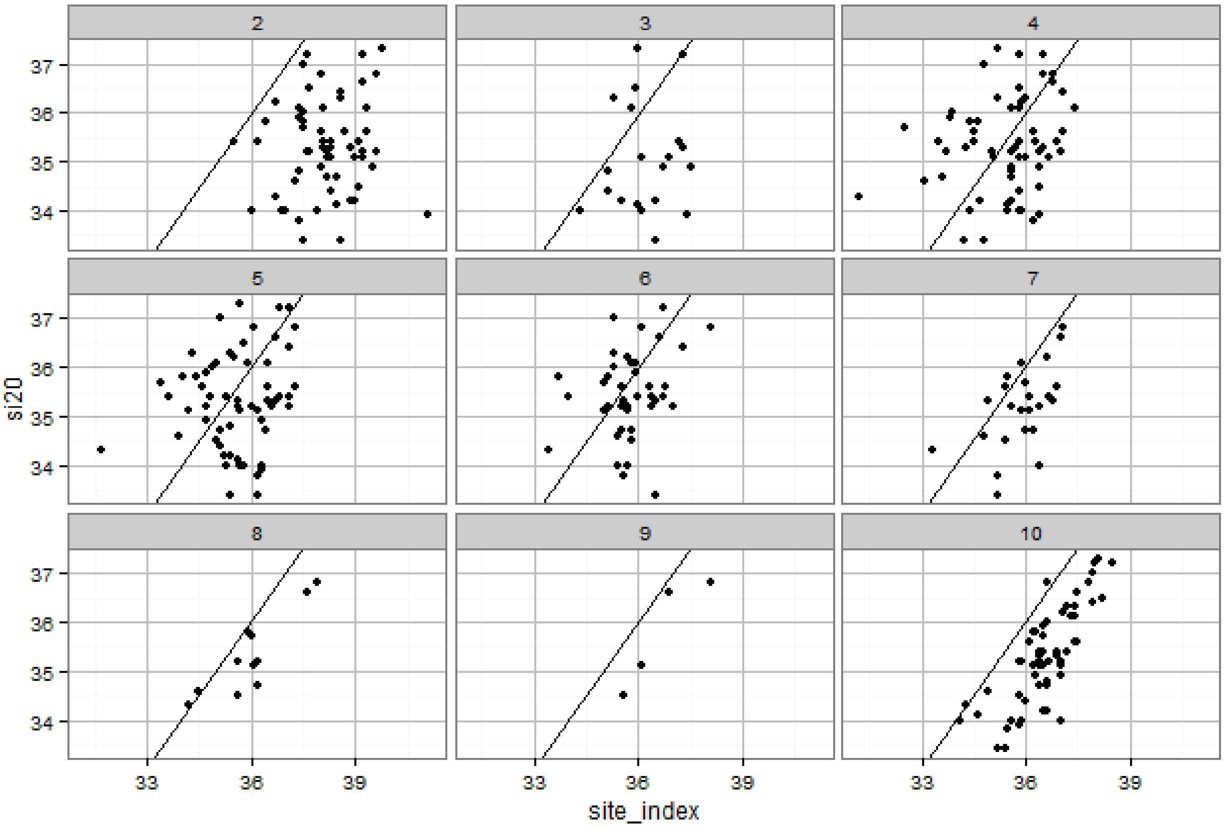


Figure 21: SICM predictions for year 20 correlated to SICM predictions for years 2-10 based on height data for actual TH-trees (rather than 8175-selected) for the given ages. The line indicates a 45 degree angle corresponding to a 1:1 correlation.

Results of the correlation in Figure 21 show the same overall trends as seen in the box plot in Figure 20, namely higher SI predictions for year 2, 3, 9 and 10. The impact of TH-tree selection approaches on site index predictions can be investigated further, perhaps especially for year ten where the prediction seems more biased.

Geospatial effects

The specific location of the plots is not expected to have any significant impact on the SI in this study, because the areas are located in close proximity to one another with similar site conditions (Figure 6). However, to rule out spatial effects, the calculated SI for GIM and SICM are given as box plots sorted by area for year 10 and 20 (Figure 22). There are some minor differences, particularly in the variance of the data, however, median and mean values are in relatively close range, and the overall pattern is the same from year 10 to year 20.

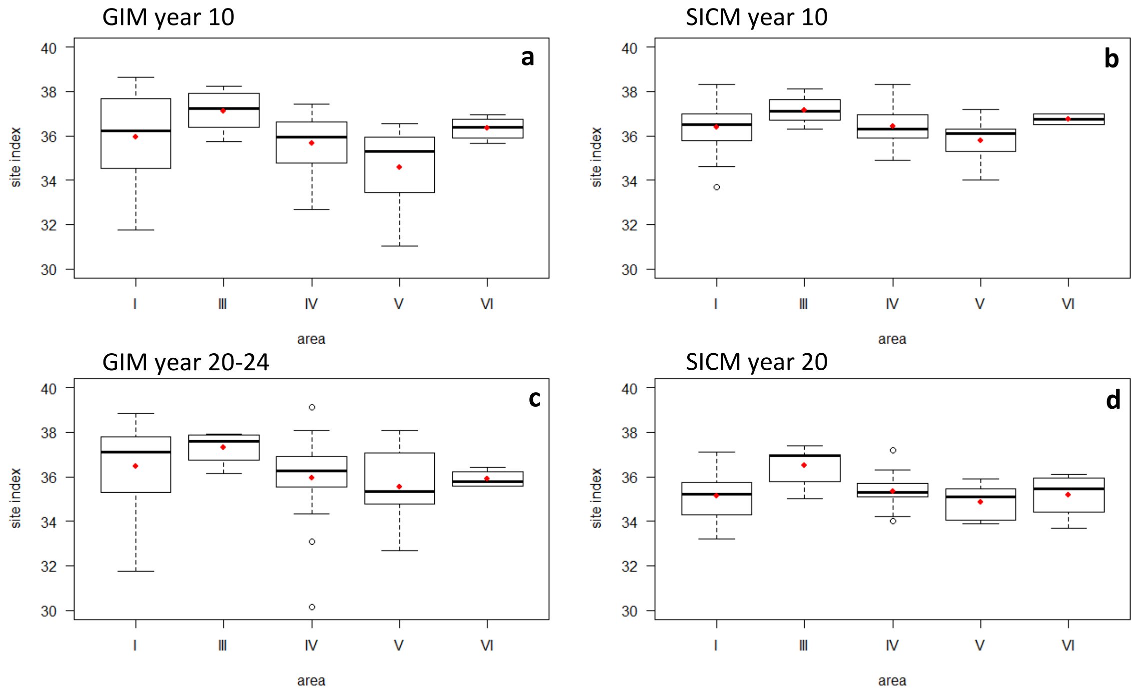


Figure 22: Box plots of SI grouped by stands (1-5 as illustrated in figure 2). Average SI for intercept method year 10 (8a), and year 20 (8c), and average SI for the new SI method year 10 (8b) and year 20 (8d). The red points indicate the mean values.

To illustrate any potential geospatial effects in higher resolution than given Figure 22, SI values were calculated for each plot and colour coded to give a visual overview. A schematization is given below for both methods based on data from year 20.

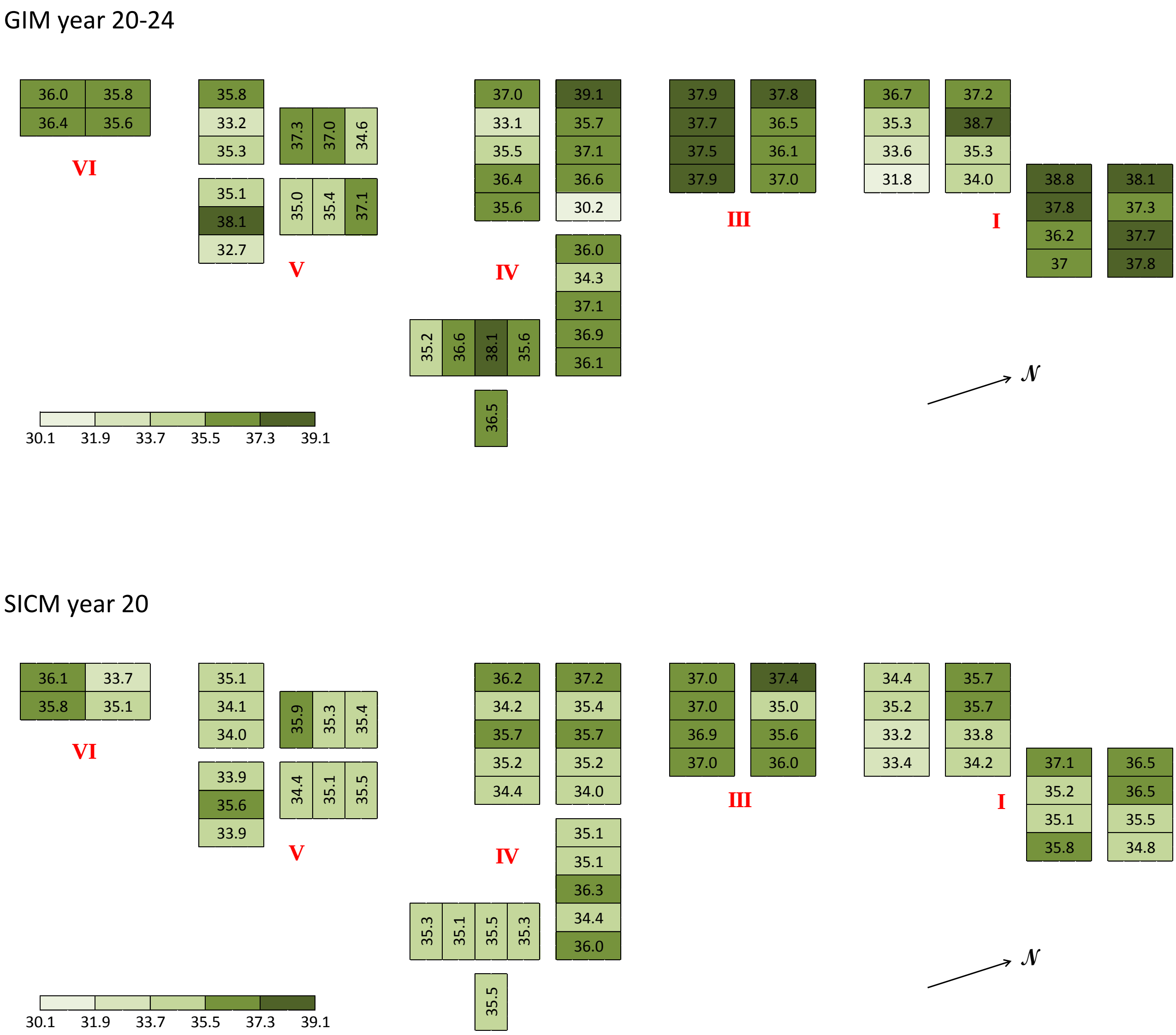


Figure 23: Schematization of the five areas with colour codes indicating the different average SI for the plots. In this case the result for GIM year 20 (upper) and SICM year 20 (lower) is shown.

There appears to be a small trend for increasing SI when moving north (Figure 23). Whether this trend is statistically significant has not been investigated, because the relative difference is quite small. Another thing that can be observed from Figure 23 is the slightly lower SI predictions of SICM relative to GIM, which is also seen in Figure 22c and 22d. This is discussed in further detail below. Similar schematizations with colour coding can be found for GIM and SICM for year ten in Appendix 3.

Annual variation of growth factors

One of the objectives in the problem formulation is to investigate whether there are any temporal effects on SI prediction caused by annual seasonal fluctuation. Trees have been grouped by age regardless of planting year. The trees were planted over a five year period (1989-1993), and were thus not all exposed to the same seasonal conditions at various growth stages. Figure 24 shows the annual height increment over time (1989-1998) for the different tree ages.

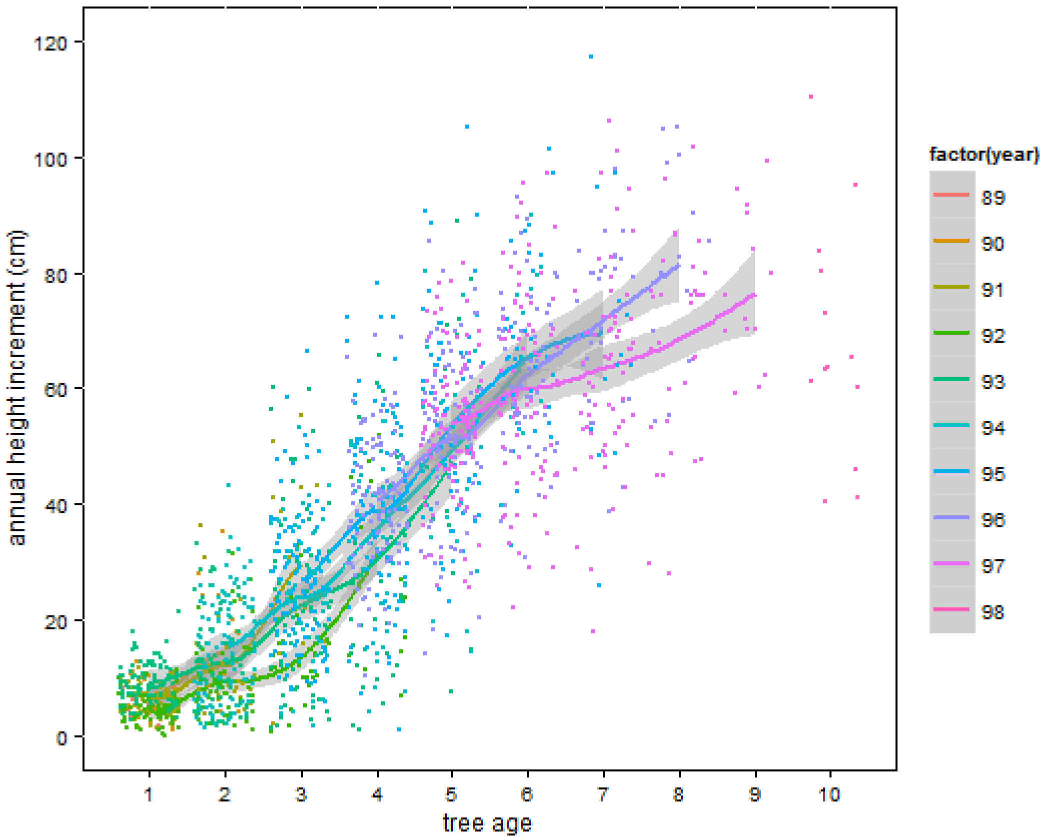


Figure 24: Annual height increment (cm) plotted against tree age. Points are colour coded by measuring year.

From Figure 24 it is apparent that growth was particularly poor in 1992 and in 1997. A possible explanation to this could in the case of 1992 be the earlier mentioned summer drought. The underlying cause for the poor growth in 1997 is unknown but could be attributed to any number of abiotic or biotic factors. The effect of this seasonal variation is not considered further in this thesis, but the variation is acknowledged to contribute to the overall variation seen in both SICM and GIM predictions.

Comparing GIM and SICM

In the following, the predictions of GIM and SICM are compared based on data from year 10 and 20 for all plots. Figure 25 gives the SI predictions for GIM and SICM as box plots.

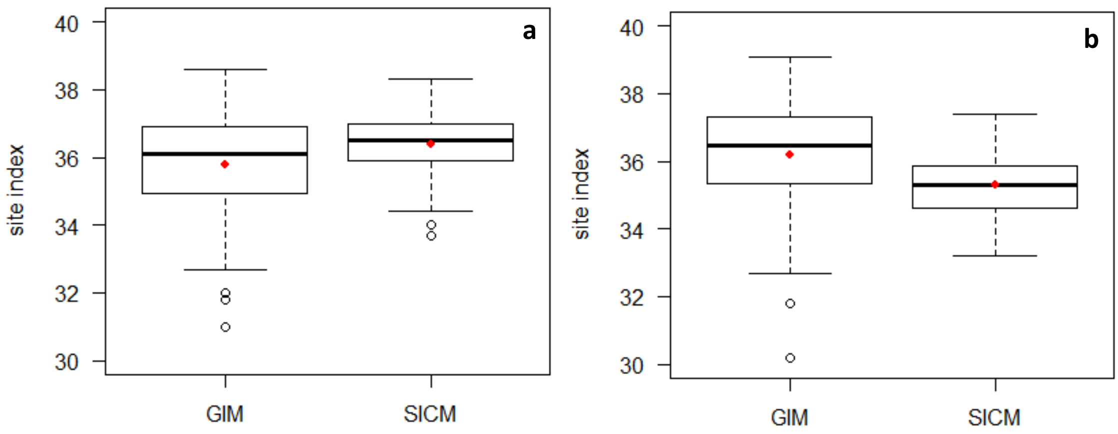


Figure 25: Comparison between the two SI models for year 10 (a) and year 20 (b). The red points indicate the mean values.

GIM predicts a mean SI of 35.8 ±1.7 and 36.2 ±1.7 for year 10 and 20 respectively, while SICM predicts mean SI values of 36.4 ±1 and 35.3 ±1 respectively for years 10 and 20. Thus there is a small difference between the predictions of the two methods, though the variability is higher for GIM as seen by the higher standard deviations, larger whiskers and the occurrence of outliers. This confirms the statement by Hägglund and Lundmark (1982a) that the accuracy of SICM is better than GIM.

For a closer look at relation between the two prediction methods, Figure 26 shows linear correlation analysis of GIM vs SICM.

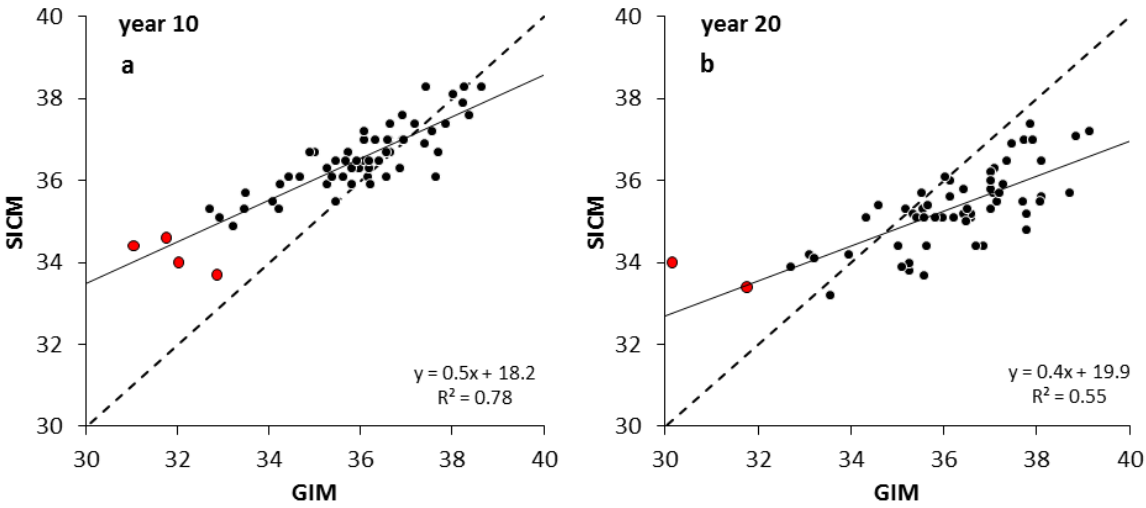


Figure 26: The correlation between GIM and SICM. Outliers from figure 25 are highlighted in red.

The first point to note when considering the linear regressions above is that the slope is different from 1 (0.5 and 0.4), and the intercept is different from 0, indicating that the predictions of GIM and SICM do not coincide. This can also be interpreted from the box plots (Figure 25).

The outliers in the box plot that are marked with red in the scatter plot show, that even if they are outliers in the box plot they are still found nicely in range of the regression line in the scatter plots. This means that they are smaller trees and not necessarily that they are outliers due to errors when measured.

Determining the optimal number of measuring points

The effect of sample size on the accuracy of SI predictions for GIM and SICM was calculated using the observed standard deviation. Results are illustrated in Figure 27 below.

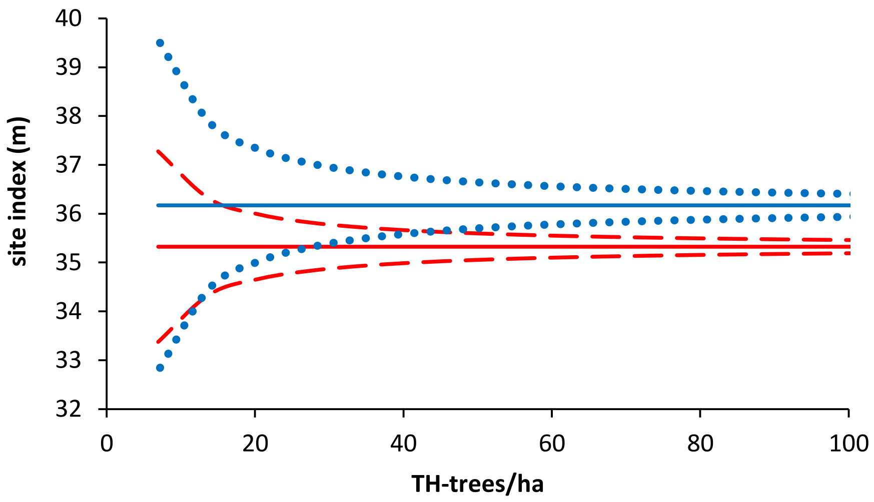


Figure 27: The effect of sample size on accuracy of SI predictions for year 20 by GIM (red) and SICM (blue). Solid lines indicate mean while broken lines indicate the 95% confidence intervals.

It can be seen that the uncertainty increases when the sample size decreases for both GIM and SICM. The minimum possible sample size depends on the level of uncertainty the user is willing to accept, however as mentioned previously the accuracy of SICM is greater than for GIM.

General discussion

Data and study area

The dataset that underpins the work in this thesis is meticulous and consistent, with recordings over a long period of time. The major benefit of this data set is that data are available for several consecutive planting years allowing me to make deviations caused by seasonal fluctuations explicit (Figure 24). In considering trees by age rather than by planting year, a data set of SI predictions is produced that integrates across the seasonal variation of a five year period. This was the main reason for choosing the specific location. However, despite the strength of the dataset, the data is collected from only one location, which could be considered a general limitation of the work. Another limitation of the dataset is the inconsistency in number of measured trees (Figure 12). This uneven data availability is unfortunate as it in particularly affects trees aged nine, and as will be discussed later, this is approximately the age at which GIM predictions seem to stabilize. The dataset covers tree ages 1-10 and 20. It would have been optimal to have data for years 11-19 or at least some measured data for year 15 to reduce the time-gap and to get a more consistent picture of the stand development over the first 20 years.

Another difficulty with the dataset is the different ways diameter was assessed, at stump height and at breast height. The result of this inconsistency is illustrated in Figure 14c. Admittedly it would not have been possible to measure a diameter at dbh until around tree age five where the TH-trees are consistently above 1.3m (Figure 14a). However, it would have been optimal to measure both diameter close to the stem base and dbh diameter from the earliest possible time. This would also have enabled an analysis of the development of basal area over time (something that is not possible with the present data).

The fact that the study area is comprised of experimental plots has several implications which need to be addressed. First, the plots have been subject to various different treatments, all of which could in theory have effects on the predicted SI. The effect of the treatments on SI predictions is unknown, however, there were no apparently visible effects of the treatments, and thus it is assumed that this issue could be ignored. A second possible complication caused by the experimental setup is the fact that the experimental plots are cross sectioned by strip roads. This is likely to have caused artificial edge-effects both between and within the plots (Figure 7). This is not directly considered in the present study, but could be investigated by carefully considering the placement of each tree seen in Figure 10 and Appendix 2. The option of ruling out these edge-trees in the study was briefly considered. However, the remaining trees were predominantly sub-dominating and dominated and therefore not suitable substitutes. In the end, the ideal study area would have been an even-aged monoculture with a conventional plantation layout. Such stands, however, have rarely been monitored in the detail needed for an analysis such as the present study.

Despite the shortcomings of the dataset, it is judged to be suitable to answer the questions posed in this thesis. However, to draw any broader conclusions on a country or regional scale, a dataset of a different calibre is needed. Such a dataset would have to span over a range of altitudes, latitudes, vegetation zones, soil types and climatic differences. Putting together such a dataset is a massive undertaking, which is the likely explanation for the fact that the curves developed in the 1970's by Hägglund and Lundmark have not been refined until just recently. Though this study is far from such a scope, it can be seen as a pilot project, the result of which could work as an argument for investigating how early site index curves can be used across a wider geographical scale.

Intercept measurements

In general, GIM is often difficult to apply in spruce stands due to the growth patterns of the species, and the stand density. The measurement is also complicated by the occurrence of internode branches. Further, the intercept measurements should not be carried out in the middle of a growth season, but rather in autumn or winter (Hägglund & Lundmark, 1982a), as was the case for this work. It is particularly difficult to measure the intercept of younger trees due to the low visibility caused by the living branches. For this reason it is a general problem to measure intercepts in young spruce stands, particularly at stand densities common to Swedish forestry practice (2500 trees/ha). As the tree grows higher the branches die, but it is still possible to measure the intercept based on the remaining impressions from the branches in the bark. An interesting study could be to take time measurements to estimate the cost and effort associated with intercept measurements. This could have been compared to height measurements, and this comparison could have added the additional dimension of time consumption to the scope of this study. For future work it is recommended (as by Hägglund & Lundmark) that a team of two persons is used to measure the intercepts, because it is quite cumbersome and time consuming for a single person. In terms of man-hours it is most likely that this would have been more cost-efficient.

Another thing that should be mentioned is the fact that intercept measurements were only carried out this year as part of this thesis, and thus no historical data is available. Therefore the intercept dataset is much more limited than the height dataset. Instead of measured intercepts, it has therefore been necessary to calculate intercepts from historical height increment data. This data was, as mentioned, only available from years 1-10. In other words the available data does not include the tree ages that are of the greatest relevance for the GIM approach, especially considering that at year ten the trees have not yet reach the minimum height requirements set out for the GIM approach (Figure 17). Again, here it would have been extremely useful with a measurement at year 15.

GIM

One of the main objectives of the study was to investigate the potential for applying GIM to younger stands than specified by the Hägglund and Lundmark guidelines. In principle, the results of this exercise are not expected to show that the method can be applied to younger trees, because the equations are based on intercepts measured above 2.5m. The intercept is a fixed value once the TH-trees have reached the necessary height. This means that from the year where it is first possible to measure the intercept above 2.5m, the intercept will remain the same for any given time later in the rotation of the stand. In contrast to this, intercepts for younger trees will follow the annual increments which are smaller for younger trees (Figure 14b) which results in shorter intercepts (Figure 15). It is therefore expected that the use of intercepts from young TH-trees will lead to an underestimation of SI, also because the model does not take the age factor into account.

As expected, the application of GIM to young trees gave results that were significantly different from results for trees age 20 (Figure 18). This illustrates that the functions behind GIM are not suited to deal with the comparatively small annual height increments of young trees (Figure 14b), and the resulting intercepts (Figure 15). This is not a criticism of GIM, as it is acknowledged that these equations were not designed to deal with very young stands. However, there is a correlation between annual height increments (Figure 14b), intercept length (Figure 15) and predicted SI (Figure 18). This correlation could form the basis for new GIM curves that allow intercept measurements below 2.5m, for instance by incorporating stand age into the existing equations, or perhaps by considering aspects of the model for annual increment for spruce. As a simpler solution it may be possible to establish correction factors when the rule of the 2.5m starting point cannot be met. With such changes, GIM would become very similar to SICM, but would be based on intercept lengths instead of height. The subsequent similarity to SICM could make it difficult to argue for investing research in this area.

An alternative approach to modifying the growth intercept model for use in younger stands would be to lower the intercept starting point. This has been done in Canada, where they have adapted the model to a starting point of 1.3m (B. C. Ministry of Forests, 1995), so that it fits the range of their most important commercial conifer species (Nigh, 1999) (Nigh, 1997). At the same time such an adjustment makes the measuring work easier and necessarily less time consuming. If an update of GIM for Sweden ever becomes relevant, this modification could be considered. The Canadian researcher Professor Gordon Nigh does not see any problem with such an adjustment, arguing that there have not been any problems with the lower measured intercept in Canada (pers. comm, 2013). Furthermore research shows that the current Canadian practise for GIM can be expanded to include trees that do not have visual branch whorls. For this method the intercept is variable as the total height above dbh (Nigh, 1996). However the application of such a method is unlikely to be necessary in Swedish commercial forest practise.

As illustrated in Figure 16, the TH-trees that the intercept measurements were carried out on were between 20-24 years old. As previously explained, the tree age should not have any effect on the intercept lengths when the trees are in this age-range. Therefore the GIM predictions based on these intercepts (age 20-24) can be pooled together for statistical purposes. Having said this, there is still the possibility that there may be slight variations caused by differing growth conditions for different planting years or small variations in site conditions. This is investigated in Figure 16, where it is seen that the intercept lengths are relatively evenly distributed across age 20-24, but with a slight tendency for lower lengths in the age 20 group. A reason for this could be that the age 20 group is present across the entire study area (Figure 16b), and includes the two plots with the lowest predicted SI (plot 61 and plot 66, Appendix 1). In contrast, the other age groups are isolated to fewer areas.

The GIM predictions in Figure 22 are relatively evenly distributed across the five areas, though there is a slightly higher degree of variation in area I, and a lower degree of variation in area VI. This can be explained by the fact that area VI only consists of four plots, and that area I is much larger with 16 plots. Figure 23 gives an overview of the variation in SI that can be found across a relatively limited area for very similar conditions. Considering the various uncertainties associated with GIM measurements, a single sample plot for the study area could easily have given a misleading impression of the true SI.

SICM

The SICM predictions are surprisingly precise already from around year three (Figure 20). This indicates that it may be possible to predict site index sooner than at age ten which is the earliest recommended age. Such predictions, however, may be associated with increased uncertainty, as is seen by the slightly higher variation in predictions found for years 1-6. Whether these levels of uncertainty are acceptable could be the subject of future study, however, the overall impression from this study is that the approach seems applicable. Due to the limitations of this study both in terms of the inconsistencies of the data set, and geographic limitation to one specific site, it is not possible to use the result as an argument for using SICM earlier than recommended. At the same time it cannot be denied that the SICM predictions are very uniform and consistent, which indicates that the method could be used as early as at the age of three. This prospect seems very promising, but the uniform nature of such young stands makes the selection of TH-trees difficult. This is particularly true because the small variation between individuals is caused less by individual growth potential, than by other factors such as interspecific competition with the field vegetation and birch or disturbances such as browsing. In this specific case, also the fact that the trees were planted under different conditions as described in the method distorts the picture. This is also shown when I go back in time to find out which trees were the true TH-trees for a given age (Figure 21). It was found that quite a few trees that were classed as TH-trees at an early stage, no longer were the largest trees at year 20, even though they were often amongst the dominating individuals. Though there was only a very small effect on SI predictions when the TH-trees were substituted with actual TH-trees back in time (as seen when comparing Figure 20 & Figure 21). It could also be argued that since there is very little variation among trees in the first years after planting, almost any tree could be classed as a TH-tree for accurate SI prediction. Another obvious problem when selecting TH-trees is that an alternative selection method has to be implemented, since it is not possible to measure a diameter at dbh until around the age of five years (Figure 14a).

The difference in annual height increment over the first ten years (Figure 14b) could explain why the application of the SICM curves is recommend at a minimum age of ten years. This issue however, does not seem to affect the accuracy of the site index predictions. This should be mentioned as another good reason for advocating that the method can be used earlier than at the age of ten.

An interesting observation is that SICM predictions for year 20 seem to be marginally lower than predictions for years 3-10 (Figure 20). The reason for this is unknown, but could be caused by any number of factors, such as the elimination of edge-effect caused by strip roads, or by changes in measuring technique. In theory, the decline could also be caused by either biotic or abiotic factors over the 10-year period without measurements. The latter is probably an unlikely explanation as evidence of e.g. insect attacks, browsing, or drought would have been visible in the stands.

However, analysis with t-tests indicates that the difference is not significant (probably due to the size of the dataset in combination with the variation in predictions). Another interesting observation from Figure 20 is the somewhat higher SI predictions in years 8-10. An initial conclusion on this could be that this is related to the uncertainty caused by the smaller datasets of these years. However, the fact that year 10 has the full 275 measurements seems to contradict this line of thinking.

The spatial distribution of SICM predictions was investigated, first across the five study areas (I, III, IV, V and VI) (Figure 22b and 22d) and next distributed across individual plots (Figure 23 and Appendix 3). The SI predictions are relatively evenly distributed across the four study areas with a slight tendency for higher SI on plot III for both years 10 and 20. On a finer spatial scale it was seen that SICM predictions fall in the range of 33.2-37.4 for year 20 (Figure 23) and 33.7 – 38.3 for year 10 (Appendix 3). There was no very clear pattern in the distribution of SI predictions, though with a little bit of good will, a slight pattern for higher SI predictions towards the North could be imagined. This possible trend can be caused by the changes in altitude, water availability or other factors. However, in general a slight spatial variation must be expected for almost any forest area based on a number of site related characteristics. The results in Figure 23 and Appendix 3 provide a good visual argument for the necessity of measuring more than one sample plot for any given forest area.

Comparison of methods

In general there is a good correlation between the predictions of GIM and SICM for both year 20 and year 10 (Figure 26). For age 10 and 20 the average overall SI of the area was predicted to be approximately 36 by both methods. Further, the spatial trends were also similar for both prediction methods. This was seen in Figure 22 where the SI was depicted across the different areas and in Figure 23 and Appendix 3 where SI of individual plots was given. However, it was also clear that the degree of variation was higher for GIM (Figure 25 and 27). This is in good agreement with the specifications in Hägglund and Lundmark (1982a), where it is stated that GIM should only be used when it is not possible or practical to apply SCIM. The difference is probably also enhanced by the recent work that has been carried out on the SICM equations. This work has improved the equations and is based on a large new dataset. Such work has not been carried out for GIM, which may contribute to the significant difference in accuracy of the two methods. With regards to the necessary sample size the analysis in Figure 27 suggests that a greater sample size is need for GIM than for SICM.

Conclusion

For stands aged 20-24, the average SI predicted using GIM was 36.2±1.7, while it was 35.8±1.7 for stands aged 10. Predictions for years 5-9 significantly underestimated SI with average values in the range of 21.5-35.1. Based on these results it is concluded that it is not possible to apply the approach beyond the recommendations of Hägglund and Lundmark. For the method to be applicable to younger stands, it will be necessary to adapt the underlying equations, perhaps following the Canadian example where a 1.3 meter intercept starting point is used.

For year 20 SI predictions using SICM were 35.3±1.0, and SI predictions for years 3-10 gave very similar predictions. The SICM approach overestimated SI based on data from years 1 and 2. No significant geospatial or annual effects were found. Based on these results it is concluded that SICM has the potential to be applicable to stands that are significantly younger than ten years. However, due to the geographical limitations of the study, no general conclusions can be drawn. For SICM to be used confidently in younger stands it is necessary to conduct a larger field study that covers the whole range of Swedish latitudes across the entire spectrum of spruce site types.

It was found that GIM predictions were subject to higher levels of variation in SI than SICM. This is in agreement with the original assessment by Hägglund and Lundmark. Considering the broader application of SICM in terms of young stands, the justification of using GIM is very limited, in that it is less accurate, and its application in terms of stand age overlaps with SICM. Further, the measurement of intercepts is considered to be more time consuming than height measurements. In conclusion it is not recommended that GIM is used to predict SI unless the stand age is unknown.

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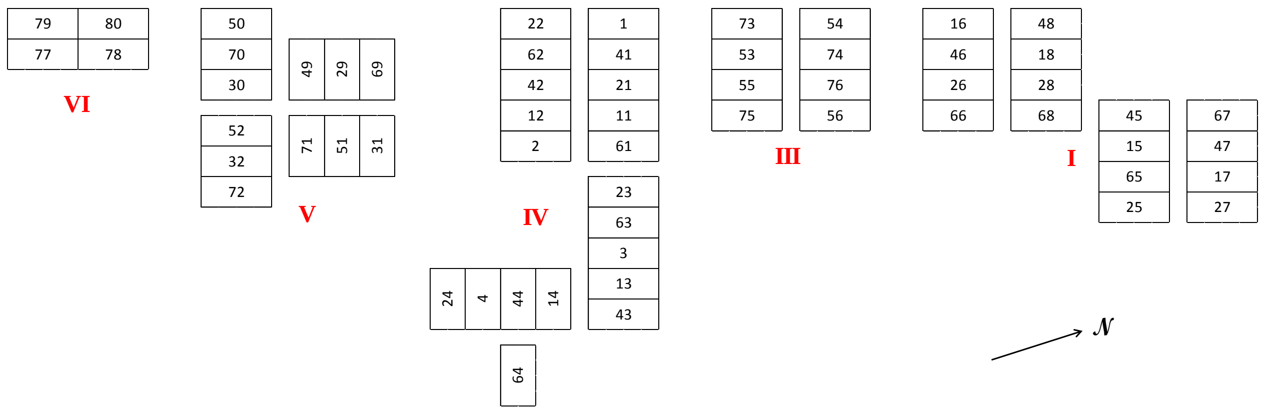
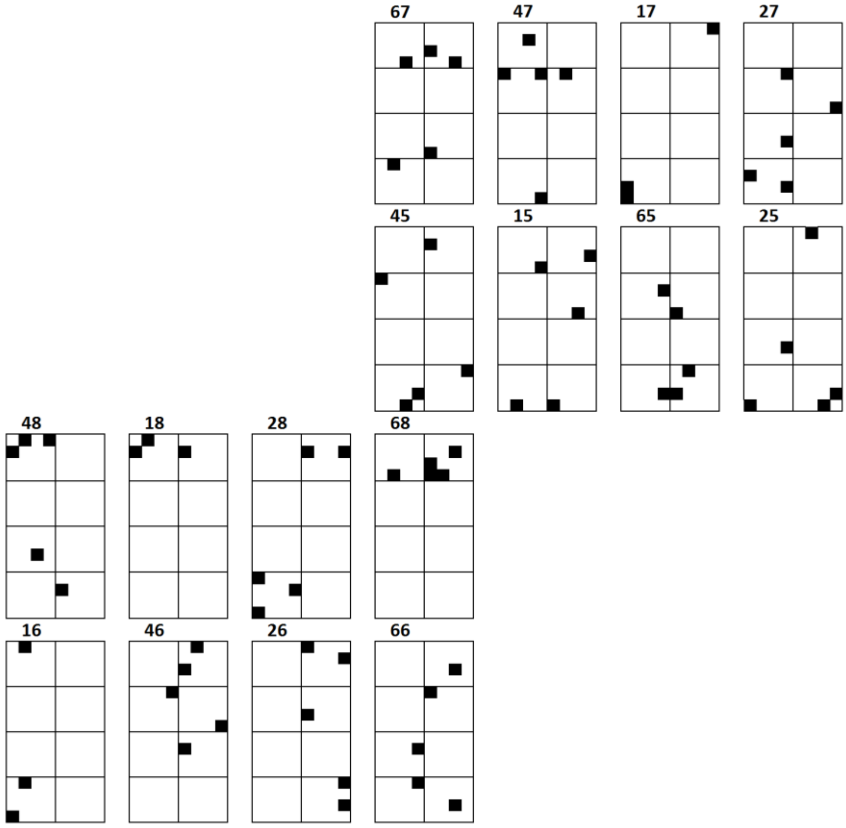
Appendix



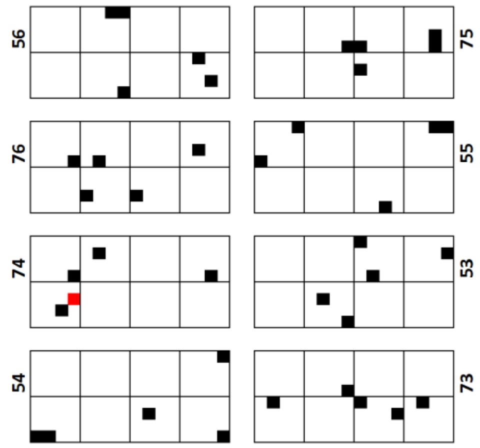
Appendix 1: Schematic diagram of the forest site showing area numbers (red roman numerals) and plot numbers.

Appendix 2: Location of measured TH-trees in area I, III, V, VI. The sketch for area IV is found on page 15.

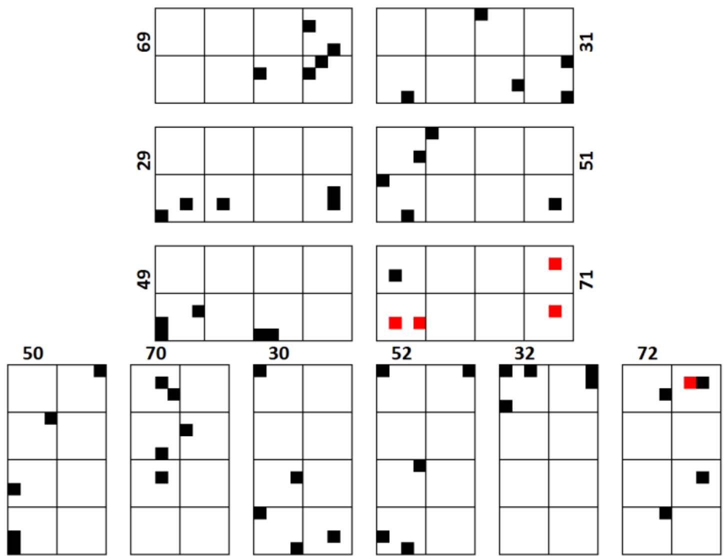
Area I



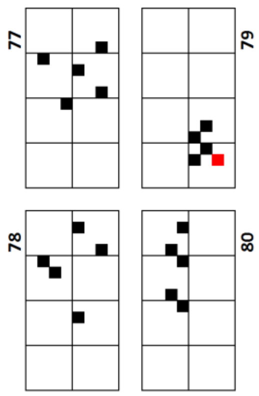
Area III



Area V

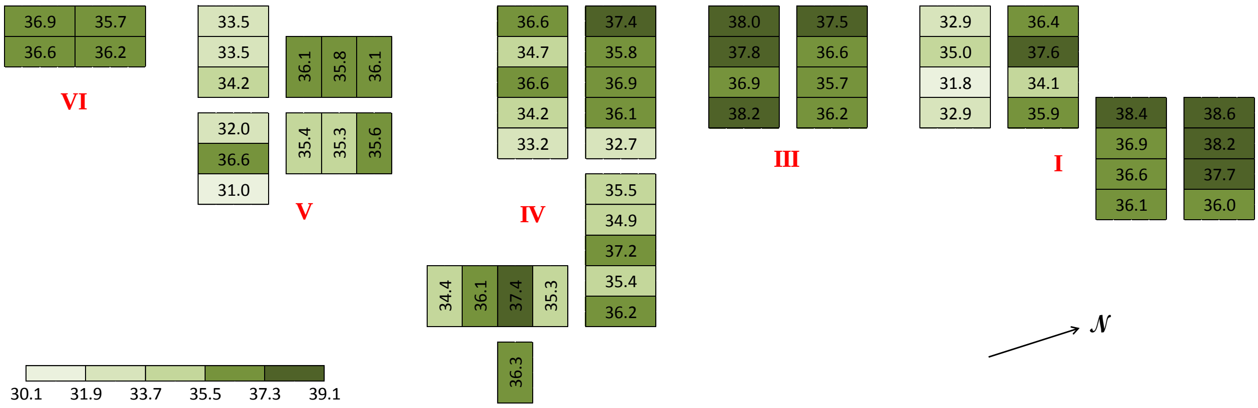


Area VI



Appendix 3: Site indices for all plots at year ten calculated with GIM and SICM.

Map showing the site index value based on growth intercept (year ten)



Map showing the site index value based on site index curves (year ten)