APPLICATION OF THE TREE-GROWTH-MODEL MOSES FOR SITKA SPRUCE IN SCOTLAND

Master's thesis

submitted by:

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Declaration

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Abstract

The aim of this Master's thesis is the validation of the application of the MOSES - model for the Sitka spruce *(P. sitchensis)*. Furthermore, the study also aims to give a practical connection to the application of dynamic tree-growth models in forest management.

MOSES (MOdelling Stand rESponse) is a potential growth-dependent tree-growth model developed at the University of Natural Resources and Applied Life Sciences, Vienna. The MOSES modelling approach is structurally based on statistically admitted models. Jonathan Dash (University of Wales) assessed the parameters for *P. sitchensis* in an international study (Tyfian Coed project at the University of Wales) in 2006. Now, the validation of the parameters for real-grown stands has been carried out.

The validation was done by comparing the predicted and observed increment parameters. After validation, different management scenarios were generated to test common and new silvicultural arrangements for *P. sitchensis*. An important outcome was the virtual testing of new forest treatment strategies for the purpose of practical use. The main focus of the simulations was the comparison of various thinning and planting scenarios. Therefore, virtual stands with different basal area and real-grown stands were used for simulation scenarios.

MOSES (MOdelling Stand rESponse) ist ein Einzelbaumwachstumsmodell das ursprünglich für die Anwendung in mitteleuropäischen Wäldern entwickelt wurde. MOSES arbeitet auf Grundlage des potenziellen Wachstumskonzeptes, das eine Adaption für nahezu jede Baumart ermöglicht. Im Rahmen des Tyfiant Coed Projektes der Universität Wales, Bangor und des Forst Research wurde 2006 von Jonathan Dash eine erste Parametrisierung von MOSES für *P.sitchensis* in Wales (Schottland) durchgeführt.

Ziel der vorliegenden Masterarbeit ist es die Validität von MOSES für *P. sitchensis* in Schottland zu untersuchen. Basis der Validierung war der einzelbaumweise Vergleich gemessener Durchmesserzuwächse mit simulierten Zuwächsen. Im Zuge der Validierung wurden auch erste Simulationen verschiedener Management-Konzepte anhand gemessener und virtuell regenerierter Bestände durchgeführt. Die Daten der Simulationen lieferten einerseits Informationen über die Validität des Models bei geänderten Wachstumsbedingungen, sowie anderseits Grundlagendaten über waldbauliche Behandlungskonzepte.

Acknowledgements

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1 Introduction

1.1 Ecology of *P. sitchensis*

The origin of *P. sitchensis* is the wet coastal area of North America. The natural range is from Alaska in the north to Carolina in the south, spanning over 22° of latitude (Savill 1991). The Sitka spruce prefers a maritime climate with cool moist summers (Griffith 1992). Therefore, it is well suited to the north of Great Britain. Because it is highly adaptable, the Sitka spruce grows best on deep, moist and drained soils and shows a high productivity on drained peats and gleys (Griffith 1992). In old-growth forests, trees can reach a height of 80 meters and a diameter at stock of about two meters (Savill et al. 1997). The tree flowers in May and its seeds are ripen by September. Sitka first bears fruit at an age of about 30 to 40 years and produces about 320,000 viable seeds per kilogram (Savill 1991). It has somewhat durable wood with a dry mass of about 350 kg*m^{-3} (Moore 2011).

Figure 1: Distribution of *P. sitchensis* in North America (Bernhardt 2000).

1.2 Silviculture of *P. sitchensis*

1.2.1 *P. sitchensis* in Britain

The Sitka spruce was introduced in Ireland in 1831 (Savill 1991). Because of its high potential rate of growth and wood properties, Sitka spruce was quickly adopted as a commercial forest species in the whole of Great Britain (GB). Today, the total area of stocked woodland is about 3.15 million (mil) hectares in GB. Most of the woodland (about 72 percent) in GB is owned or managed by the private sector. The remaining part is owned or managed by the Forestry Commission, Natural Resources Wales and the Forest Service. More than 41 percent (1.31 mil ha) of woodland is stocked with conifers. Around half of the conifer area (0.665 mil ha) is covered by the Sitka spruce, with an increase from the south (England: 0.080. mil ha) to the north (Scotland: 0.507 mil ha). About 61 percent of the coniferous woodland area is planted with stands younger than 40 years. Only nine percent of the coniferous woodland area is occupied by stands older than 60 years. The future trend shows an increase in woodland area (10,300 ha), especially in broadleaves for new planting areas (7,700 ha). Conifers dominate by restocking an area of about 10,000 hectares (National Statistics 2015).

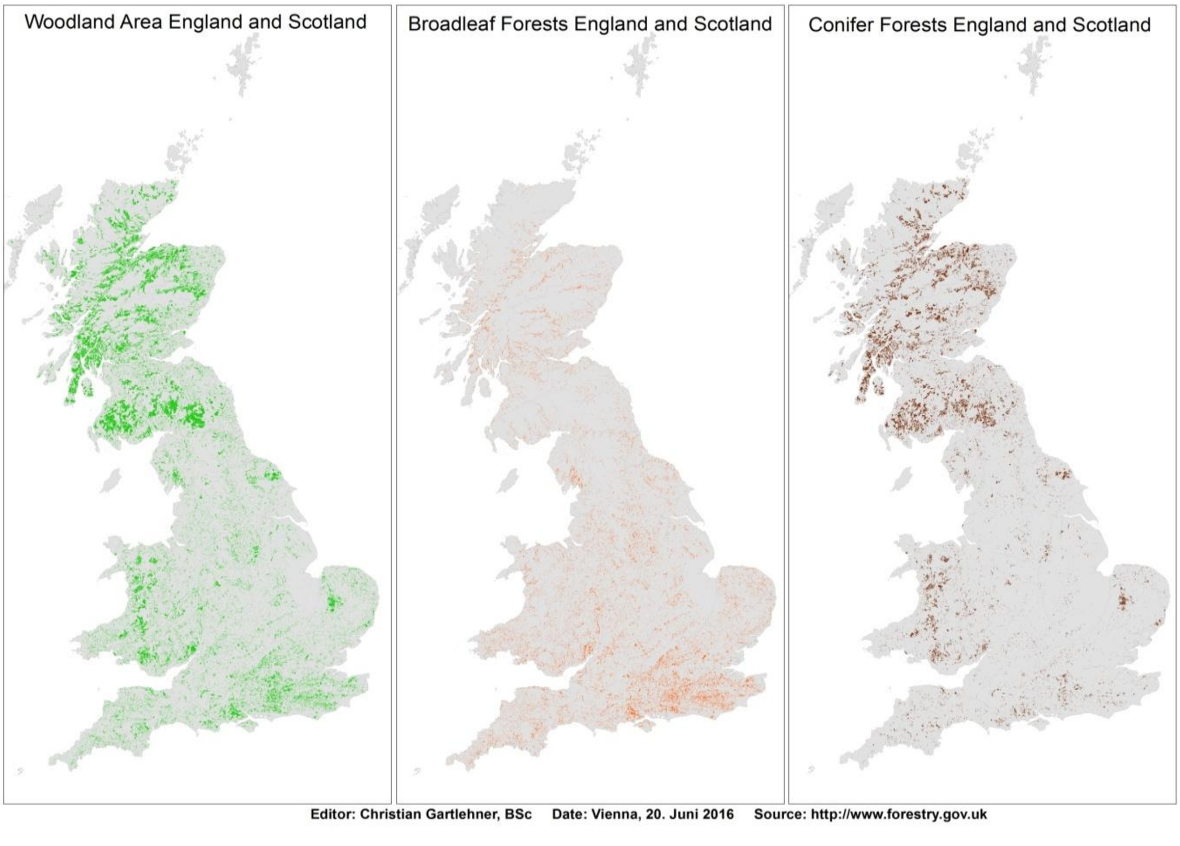

Figure 2: The left figure shows the entire woodland area of England and Scotland. The other figures show the distribution of broadleaf and coniferous forests. The volume of coniferous forests increases in the north, while there is an increase in the area of broadleaf forests in the south (National Forest Inventory 2015).

1.2.2 Provenance

An important factor for the success of a plantation is the selection of an adapted provenance. The genetic resource should respond to the biotic and technical requirements of environment. Genetic resource guarantees an optimized physiological adjustment of the tree species in its site. Another significant factor related to genetics is the high correlation with technical properties. The knot size and frequency in particular affect the quality and value of Sitka spruce timber (MacDonald and Hubert 2002). In 1970, the IUFRO (International Union of Forest Research Organizations) established an international provenance experiment for the Sitka spruce. For Scotland, trees from the provenances of Washington and Queen Charlotte Islands provide the best values (Forest Research 2016).

1.2.3 Plantation Establishment, Spacing and Thinning

Most commercial forest companies harvest their forest by clear-cutting and use young trees from nurseries for restocking. In comparison to natural recruitment, planted trees ensure a well distributed number of trees per hectare. Another benefit is given by selection of the provenance, which influences the growth rate and wood properties significantly (Thompsona et al. 2005). The distribution and number of trees per hectare also have a significant impact on growth, properties and wood quality, as expressed in the annual ring widths (Figure 3) (MacDonald and Hubert 2002).

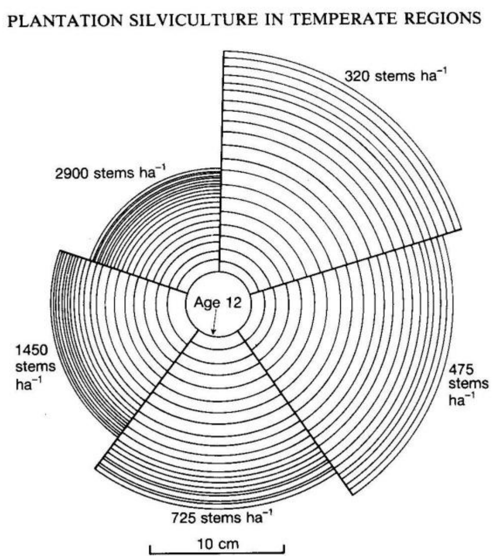

Figure 3: Effects of spacing on mean tree diameter at breast height and annual widths of Sitka spruce 32 years after planting (Savill and Sandels 1983)

In addition to the site quality, these two aspects form the basis of further management activities. Furthermore, spacing also has a substantial effect on the value of the crop. Savill and Evans (1986) distinguish between two main aspects of spacing: effects of early or initial spacing and effects of thinning. Especially in stands where thinning is uneconomic or leads to windthrow, the number of trees can be controlled by early spacing. Spacing and thinning do not influence the top height of a stand, but have a significant impact on other parameters. Three main parameters affected by spacing or thinning are the mean tree volume (Figure 4), stability against windthrow (expressed as height-to-diameter ratio) and the wood quality (MacDonald and Hubert 2002).

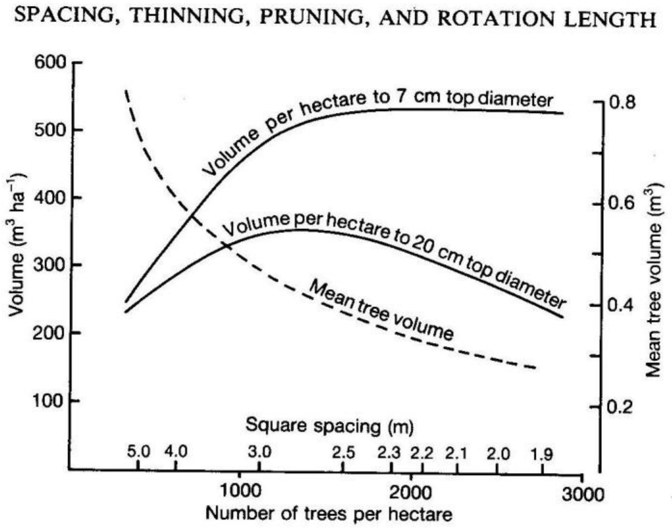

Figure 4: Relationship between spacing and volume production and size distribution in unthinned Sitka spruce of 18.5 m top height (Kilpatrick et al. 1981).

Apart from early spacing, thinning is the main instrument used by silvicultural management to influence the economic value of a stand. Research into spacing and thinning indicated four main influences of thinning (Hamilton 1981, Savill 1991):

- The total production per unit area is not much influenced by the wide range of treatments.
- The removal of suppressed trees does not increase the production in volume per unit area, because the remaining trees are not able to make full use of the resources of the site. Stands are able to make good the production loss when the increment is below normal immediately after thinning.

- Larger standing volume of timber and branches in unthinned stands consumes more assimilated carbon for respiration than thinned stands with lower volume.
- Two factors can have a negative influence on the total cumulative production: removing the most successful trees in the stand and such a high intensity of thinning that the site is not efficiently used.

In addition to Point 2, trees remaining after thinning are able to compensate the loss in increment by using the new resources more efficiently than the suppressed trees. The increment gets disseminated on fewer trees per hectare. Hence, the volume per tree increases constantly with a decrease in the number of trees per hectare.

Point 3 describes the loss in increment at high or maximum stocking densities. A practical approach for estimating the maximum stand density is the Stand Density Index (SDI) given by Reineke (1933) (Comeau et al. 2010). Stand density management tries to control resource competition by regulating the number and spatial arrangement of individual stems per unit area through spacing or thinning events (Newton 1997). Figure 5 shows the correlation between stand density and mean diameter for the Sitka spruce in GB, as given by COMEAU et al. (2010). To prevent loss in increment, actual stand density should be lower than the potential SDI (black line).

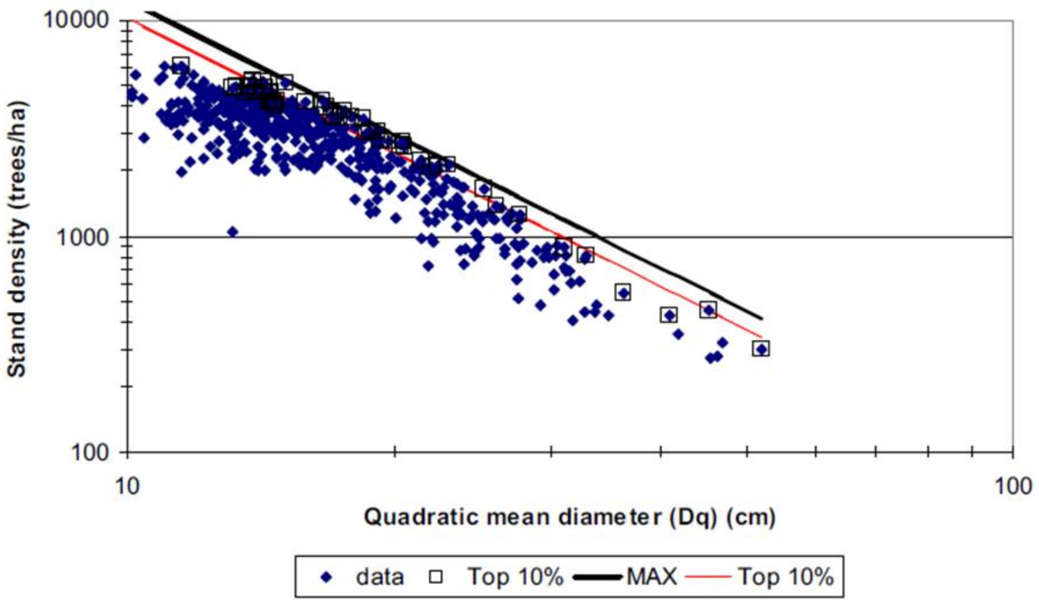

Figure 5: Relationships between stand density and quadratic mean diameter for Sitka spruce. The SDI (black line) is calculated using the formula given by Reineke (1933) SDI = N × (Dq/25)^{1,605}. The red line was calculated with the upper 10 percent of data points by using the regression ln(*N*) = *a* + *b* ln(*D*q), where a = 13.979 and b = -2.063 (Comeau et al. 2010).

If there is an increase in the mean volume per tree, the economic value also increases (Stroede 2003). Therefore, thinning is an efficient way to positively influence the economic value of a stand. For thinning, two main aspects should be considered. The first aspect is the intensity of thinning. Hamilton and Christie (1971) use the example of the Norway spruce with a mean increment of $20m^3ha^{-1}year^{-1}$to show that it is possible to remove $14m^3ha^{-1}year^{-1}$ between the ages of 25 and 55 years without reducing the cumulative production. By thinning at the marginal intensity, about half of the total cumulative volume can be removed without leading to a loss in total production at the end of the rotation time (Figure 6 and Figure 7) (Savill 1991).

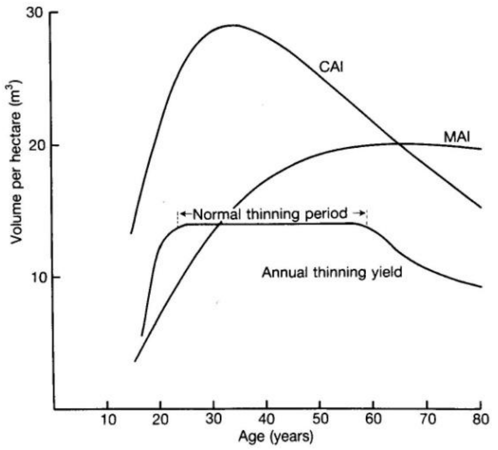

Figure 6: Relationships between age, mean annual increment (MAI), current annual increment (CAI) and annual thinning yields for yield class $20m^3ha^{-1}year^{-1}$ Norway spruce thinned at the marginal intensity (Savill 1991).

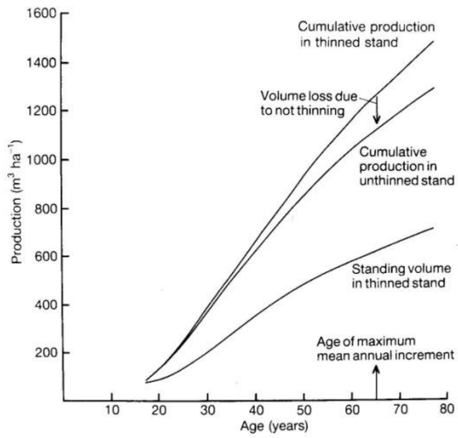

Figure 7: Cumulative production in thinned and unthinned Norway spruce of yield class $20m^3ha^{-1}year^{-1}$ planted at 2500 stems ha^{-1} (Savill 1991).

The second aspect of thinning has to do with the thinning cycle and the time of first thinning. The time of first thinning depends on tree species, standing volume and competition. For most common species, the age of first thinning is about 20 to 35 years in Britain (Savill 1991). The cycle of thinning also depends on tree species and growth rate. In general, the frequency of thinning increases with the growth rate (Savill et al. 1997).

1.3 Forest Management and Tree-Growth Models

Growth models and yield tables are essential tools for forest managers to make informed decisions (Quang 2014). Management decisions are made on the basis of current and future conditions (Peng 2000). The objective of forest management activities is to determine an ecologically and/or economically optimized future stand based on a present stand. Growth models or yield models should help describe the present stand and estimate the future conditions for this stand. Before working with models, it is important to know that a model is an abstract or simplified representation of some aspect of reality (Vanclay 1994). Rozinat et al. (2008) state, that a model that represents certain key characteristics or behaviors of the system can be used to show the eventual real effects of alternative conditions and courses, i.e. to take a look into the future. In forestry, different approaches of models are available. Yield tables assume a specific form of silvicultural management and constant growth conditions over the rotation period. Hence, yield tables assume long growth periods and do not take into account growth conditions (Hasenauer 1994). Because of changes in technique, silviculture and management, dynamic models are required. Dynamic models also enable reaction to changes in conditions due to windthrow, bark beetle or fire. Furthermore, a connection to economic models helps find the optimized age at which to cut down a tree or stand (Loisel and Dhote 2011). The combination of different models in computer-based packages leads to complex growth simulations. Vanclay (1994) classifies models into three main categories based on the level of detail they provide:

- Whole stand models: simple and robust, but may involve complexities not possible in other approaches; no details about individual trees in the stand.

- Size class models: compromise between whole stand models and single tree models
    - Whole stand approach: large class size with only one class
    - Single tree approach: small class width with single classes

- Single-tree models: the individual tree is used as the basic unit of modelling

Single-tree growth models in particular are useful for research and management decisions. As mentioned, in single-tree models, each tree is considered and used as the basic unit of modelling. All values are calculated for the single tree and can be summarized for the stand. Hence, the combination of different tree species is possible. Furthermore, the combination of different age classes inside one area is permitted (Hasenauer 1994).

1.4 Research Objectives

The tree-growth simulator MOSES is a multifunctional tool for silvicultural activities and decision-making for forest management in European stands. After the re-calibration of MOSES for *P. sitchensis*, the practical adaption should be tested with validation. This thesis aims to present a validation of MOSES for *P. sitchensis*, using the re-calibrated coefficients of Jonathan Dash as the starting point. The hypothesis is to validate MOSES through the comparison of incremental data. Therefore, plots in real-grown stands are measured. The aim of this mensuration is the representation of different growing conditions for validation. After validation, the first simulations should provide a connection for the practical use of the model for Sitka spruce. Furthermore, simulations should be used to test the reaction of the model by changing the growth conditions. The simulations are to be based on different management scenarios. In the first part, scenarios of different thinning densities should show how thinning density influences increment and mortality. The second part deals with reforestation and the optimized number of trees. The last part should show the development of managed and unmanaged mature stands without future management.

1.5 The Single-Tree-Growth Model MOSES

MOSES (MOdelling Stand rESponse) is a potential growth-dependent, tree-growth model developed at the University of Natural Resources and Life Sciences in Vienna. Originally, MOSES was used for mixed spruce-pine and beech-spruce stands. Now the model is calibrated for all major tree species in Europe (Hasenauer 1994, Dash 2006).
MOSES is a computer-based simulation software that is built on several sub-models (Hasenauer 1994):

- Height increment model
- Diameter increment model
- Competition model
- Crown model
- Base of crown model
- Mortality model
- Regeneration model

Dash (2006) describes in his thesis the approach of MOSES given by Hasenauer (2005) as follows: “The increment components within MOSES follow the potential growth concept where current annual diameter (id_{obs}) and height increment (ih_{obs}) are predicted according to pre-defined potential height (ih_{pot}) and diameter increments (id_{pot}).”
The potential height increment (ihpot) is reduced by the crown ratio (CR) and competition index (CIU) (Hasenauer and Monserud 1996). Silviculture interventions are represented in the change of competition (CIDIFF) (Hasenauer et al. 2005). The potential diameter (id_{pot}) is calculated from the relationship between DBH and height in open growth trees and the potential height (ih_{pot}) is calculated from the height increment based on site index curves (Hasenauer et al. 2005). The calculation of the potential increment is shown in Equation 1:

$$\frac{id_{obs}}{id_{pot}}, \frac{ih_{obs}}{ih_{pot}} = CR^{a}\left(1 - e^{\frac{b}{CIU(1+c*CIDIFF)}}\right) + \varepsilon \qquad (1)$$

The MOSES framework was developed for the simulation of tree growth in test areas, chosen stands or relascope sweep points. Single tree data are saved on a database. Through the applications STANDGEN and MOSESbatch, it is possible to simulate the growth of several stands and get numeric and graphical output. (Klopf et al. 2013). The workflow for simulations in the MOSES framework is shown in Figure 8. All the activities of this thesis were done in the MOSES framework.

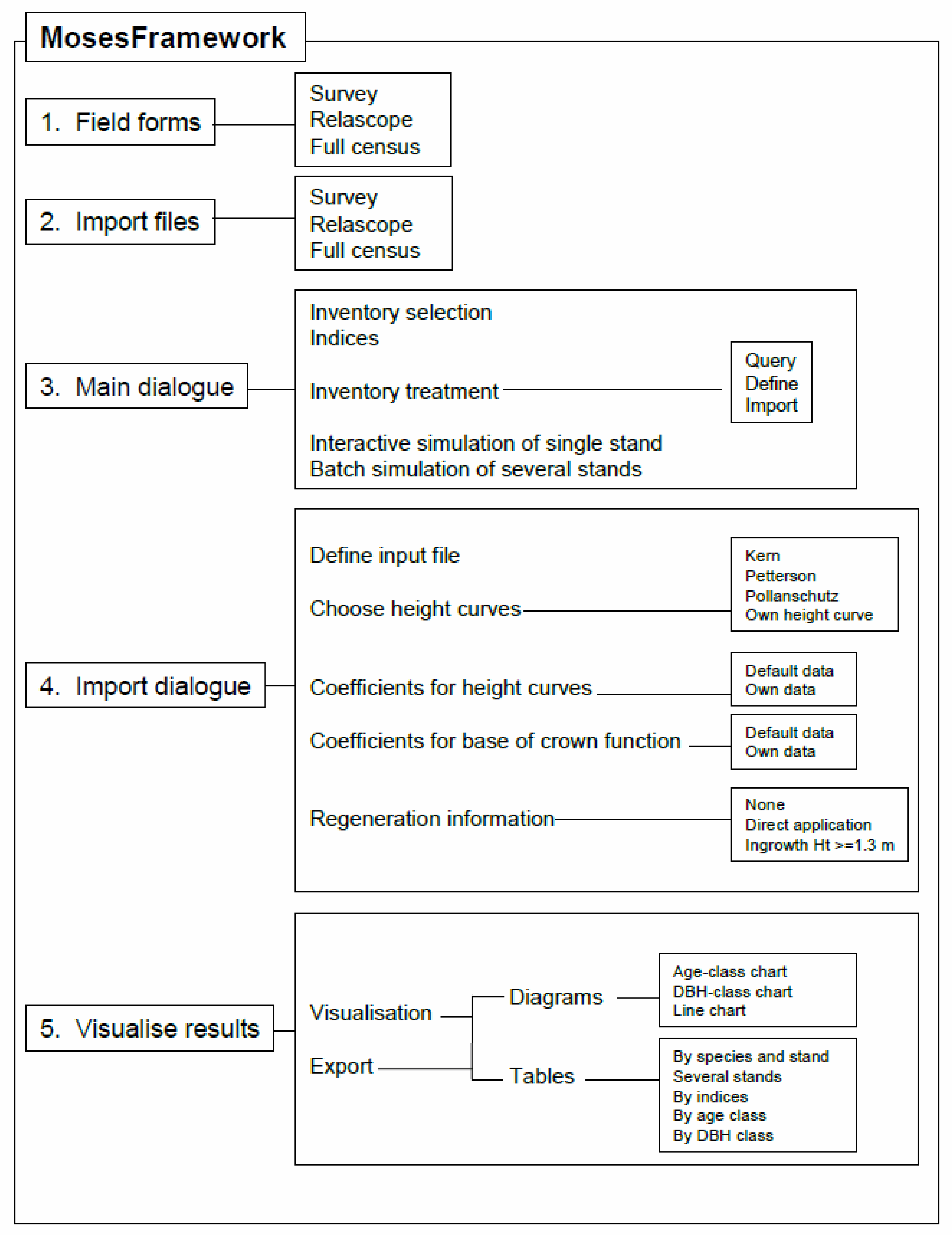

Figure 8: Working steps (1 to 5) from recording at the stand up to visualization of results (Klopf et al. 2013).

1.6 Components of MOSES

The MOSES modelling approach is structurally based on statistically admitted models. Behind these models are well-established functions, that are closely cross-linked. These functions have been adapted to many tree species in different countries by changing their parameters. In order to fit a function, new parameters have to be estimated. In an international study in 2006, Jonathan Dash (University of Wales) first assessed the parameters for *P. Sitchensis.* The summary of activities undertaken is presented in Table 1.

Table 1: The components in the MOSES modelling approach and whether recalibration was attempted as specified by Dash (2006)

Model parameter	Parameters estimated for *P. sitchensis?*
Height increment model	Yes
Diameter increment model	Yes
Generation of HLC	Yes
Static crown model	Yes
Dynamic crown model	Yes
Mortality model	No (inadequate data), parameters for *P.abies* were used

In 2012, Catia Arcangeli (Forest Research UK) made a new parametrization for *P. sitchensis* for the MOSES tree-growth model. Stands from Forest Research UK were used to fit new parameters for the top height model, height increment model, diameter increment model, HLC model and open-grown tree relationships (Arcangeli 2012, Klopf 2016). In this thesis, the estimated set of parameters from Arcangeli (2012) was used. For the mortality model, parameters from Norway spruce (*P. abies*) were used.

1.6.1 Diameter Increment Model

The increment models are based on the height-to-diameter relationship of solitary trees, as shown in Equation 2 (Hasenauer 2007). The difference between the beginning and the ending of one period provides the potential diameter increment.

$$\boldsymbol{dbh = e^{a_0 + a_1 * \ln(H)} \Rightarrow ipot = dbh_{H_0} - dbh_{H_t}} \tag{2}$$

Where:

DBH… diameter at breast height (cm)
H… tree height (m)
a_0, a_1… function coefficients

For the allometric multiplier, the previous competition factors are included in the formula. The current competition, according to management and mortality (CICUT) and changes in competition (CI-CICUT), is considered with overstocking multiplier (Monserud 1975). The estimated parameters are presented in Table 13 (Appendix 1). The increment model has the following form:

$$\boldsymbol{i_i = ipot_i * c_0 * cr_i^{c_1} * \left[1 - e^{\frac{c_2}{CICUT_i * (1 + c_3 * (CI_i - CICUT_i))}}\right] * c_4} \tag{3}$$

Where:

i… increment (DBH or height)
ipot… potential increment of DBH or height
CICUT… competition factor after crown release
CI-CICUT… change in competition factor
$c_0 - c_2$… function coefficients

1.6.2 Height Increment Model

The height increment model follows the diameter increment model and is calculated as shown in Equation 4. The estimated parameters are presented in Table 14 (Appendix 1). Unlike the diameter, the potential height increment cannot be calculated from open-grown trees as is done in the potential diameter increment model. Open-grown trees, unlike forest trees, do not represent maximum potential height development. Forest trees tend to be taller than their open-grown counterparts (Dash 2006). Potential height increment is estimated from site index functions derived from regional yield tables (Spyroglou 2004).

$$i_i = ipot_i * cr_i^{c_0} * \left[1 - e^{\frac{c_1}{CICUT_i * (1 + c_2 * (CI_i - CICUT_i))}}\right] \quad (4)$$

<u>Where:</u>

i…	increment (DBH or height)
ipot…	potential increment of DBH or height
CICUT…	competition factor after crown release
CI-CICUT…	change in competition factor
$c_0 - c_4$…	function coefficients

1.6.3 Potential Height Growth

The potential height increment is derived from the side index (SI) functions. With top height functions, it is possible to estimate the top height from age and vice versa, to estimate an "effective age" from top height (Equation 5) (Hasenauer et al. 2005). The duration of one period is added to the effective age. Equation 6 provides the potential height increment from the extended effective age. For estimation of top height and effective age, the site index function (Equation 7) given by Sterba (1976) was used. Table 15 (Appendix 2) shows the calculated coefficients.

$$\boldsymbol{t = f(TH, SI) \Leftrightarrow OH = f(t, SI)} \tag{5}$$

$$\boldsymbol{ihpot_i = f(SI_i, t_i + LGP) - f(SI_i t_i)} \tag{6}$$

<u>Where:</u>

t…	calculated age of top height tree
TH…	top height
SI…	site index or yield class
ihpot…	potential height increment
LGP…	length of growing period

$$\boldsymbol{Top\ Height = a * \left(1 - e^{-b*t}\right)^{\frac{1}{1-c}} \qquad \Rightarrow t = \frac{ln\left[\frac{1}{1-\left(\frac{h}{a}\right)^{1-c}}\right]}{b}} \tag{7}$$

<u>Where:</u>

$a = a_0 + a_1 * YC + a_2 * YC^2$

$b = b_0 + b_1 * YC + b_2 * YC^2$

$c = c_0 + c_1 * YC + c_2 * YC^2$

Figure 9 graphically presents the estimation of the potential height increment for a given tree at specific heights. Potential height increment is calculated using the estimated effective age and growing period.

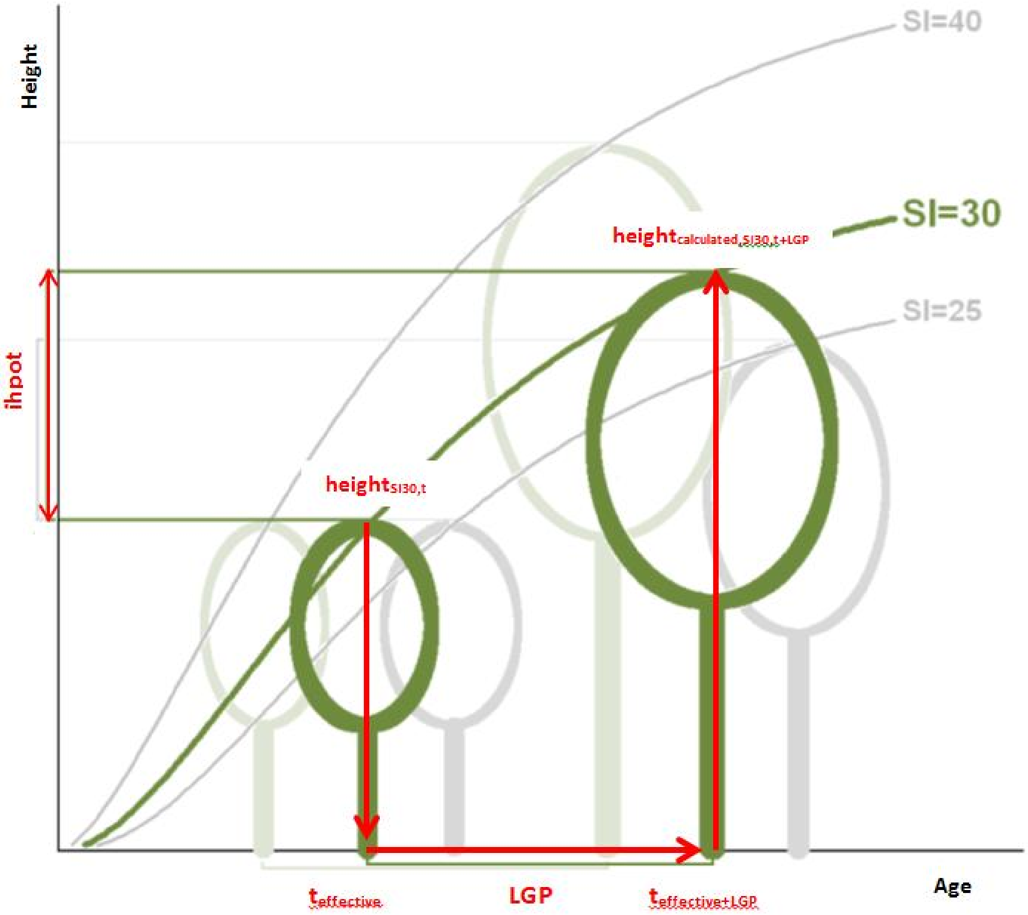

Figure 9: Graphical representation of the calculation of the potential height increment (Klopf et al. 2013). Potential height increment (ihpot) is the difference between the height at $t_{effective}$ and height at $t_{effective+LGP}$ along the side index function.

1.6.4 Crown Model

The crown ratio is estimated within a static crown model. The best fit was obtained using the static crown model given by HASENAUER and MONSURED (1996) (Equation 8). Table 16 (Appendix 2) presents the estimated parameters. Crown ratio (*CR*) is defined as a function of tree size (*bSIZE*) and competition (*cCOMP*). Tree size is calculated as a function of height, height diameter ratio and diameter. The competition is affected by the diameter (*BAL*) and crown competition factor (*CFF*). The model has the following form:

$$\mathbf{CR} = \frac{\mathbf{1}}{\mathbf{1} + \mathbf{e}^{-(a_0 + \mathbf{bSIZE} + \mathbf{cCOMP})}} \qquad \textbf{(8)}$$

<u>With:</u>

$$bSIZE = b_1 * \frac{h}{d} + b_2 * h + b_3 * d^2$$

$$cCOMP = c_1 * BAL + c_2 * \ln(CCF)$$

<u>Where:</u>

h…	tree height
d…	diameter at breast height
BAL…	basal area per ha of trees lager than subject tree [m²/ha]
CCF…	crown competition factor: $CCF = 100 * \frac{1}{A}\sum_{i=1}^{N} R_i^2 \pi$

<u>Where:</u>

i…	index for a tree
A…	plot area [m²]
R…	radius of open-grown trees

$a_0 - c_2$… regression coefficients

1.6.5 Height of Live Crown Model

The height of the live crown (Equation 9) is estimated as reciprocal value from Equation 8 given by Hasenauer and Monserud (2006). For the calculation, the same parameters were used as in the crown model (Table 16, Appendix 2).

$$\boldsymbol{HLC = H * (1 - CR)} \qquad \textbf{(9)}$$

With:

$$\mathrm{CR} = \frac{1}{1 + \mathrm{e}^{-(a_0 + \mathrm{bSIZE} + \mathrm{cCOMP})}}$$

1.6.6 Mortality

Mortality is the probability of tree death, which depends on stand and individual tree characteristics (Hamilton and Edwards 1976). MOSES uses a logistic function (Equation 10) to calculate a probability of death (Monserud and Sterba 1998). The outcome lies between two values: 0 (tree is alive in the next period) or 1 (tree is dead). Parameters have not been estimated at present for this function. Dash (2006) assumes that mortality patterns in *P. sitchensis* in Wales and *P. abies* in Austria are relatively similar, and thus it may be acceptable to use leave the mortality model parameters estimated for *P. abies* in place of *P. sitchensis*. Therefore, the mortality model parameters for *P. abies* were used.

$$\boldsymbol{p_i = \left[1 + e^{\left(a_0 + a_1 * CIR + a_2 * CR + a_3 dbh + a_4 * \frac{1}{dbh}\right)}\right]^{-1}}$$

$$rnd > p_i \begin{cases} yes: tree\ survives \\ no: \boldsymbol{tree}\ dies \end{cases} \qquad \textbf{(10)}$$

Where:

p_i…	probability of tree death in the next five years
CIR…	competition index after crown release
CR…	crown ratio
DBH…	diameter at breast height
a_0 – a_4…	function coefficients
rnd…	uniformly distributed random number

1.6.7 Yield Tables and Open-Grown Tree Relationships

For estimation of the yield class, the yield models for forest management were used (Forestry Commision 1981).

The DBH-height and crown width-height relationships of open-grown trees are essential for potential tree-growth models. MOSES uses the DBH-height relationship in the calculation of the potential diameter increment (Hasenauer et al. 2005). Crown width-height relationship is used to define potential area of influence of a given tree, which is needed for the calculation of the competition index (Dash 2006). Table 17 (Appendix 2) shows the fitted parameters for functions of diameter-height and crown width-height relationships, as given by Arcangeli (2012).

2 Materials and Methods

2.1 Forest Area

The forests of the CKSLC are located in the council areas of Dumfries and Galloway on the south-west side of Scotland. The company's forests are spread over six forest districts: Auchrae, Manquhill and Cornharrow in the north, Margree and Halfmark in the middle near St. John´s Town of Dalry and Garcrogo in the south (Appendix 3). In all, they have a forest area of about 3900 hectare.

The forests in the research area are commercial forests, mostly cropped with Sitka spruce. Two subspecies from different provenances are cropped – Sitka spruce from Washington (USA) with many fine branches between one year leader and the Sitka spruce from Queen Charlotte Island (Canada) with fewer but larger branches.

Most of the forests are well-managed and have a strict management plan. Until the clear cutting, the open areas get replanted with young trees from nurseries. The young trees are planted in lines with an average distance of about two meters between the lines and two meters between the trees in each line. Ultimately there are about 2500 trees per hectare. In most cases, the trees get respaced once, after some years in order to reduce competition from natural recruitment.

Depending on the soil and climatic conditions, the forests first get thinned at an age of about 15 to 20 years. In the research area, thinning mostly took place in forests on dry and good soil, due to the high risk of wind blow. A second thinning is usually not done, because of the short rotation time. The average rotation time for the Sitka spruce is about 30 year. Some mature forests are older, with an age of over 40 years. Thinning and harvesting are done in a fully mechanized manner with harvesters and forwarders.

The research was carried out in the forests of Auchrae, Margree, Garcrogo, Cornharrow and Manquhill, because they are very close together and have nearly the same climatic conditions. In these districts, you can find forests of the same age grown on poor soil as well as on good soil, with and without thinning.

<u>Margree and Auchrae</u>

Margree and Auchrae are mainly stocked with mature and young forests on good as well as on poor soil. Many of the mature forests are thinned and grow on good soil. Some forest units also have a combination of poor and good soil, especially in thinned mature forests (see Appendix 4 and Appendix 5).

<u>Garcrogo</u>

Most of the forests in Garcrogo are in the mid-rotation age. In most cases, they grow on poor wet soil and are not thinned (see Appendix 6).

<u>Cornharrow and Manquhill</u>

Nearly the whole area of Cornharrow was planted in one year (1996). Therefore, it has mid-rotation forests at the same age – about 21 years. Many of these forests grow close together on very good or poor wet soil. The forests in Manquhill were also planted in one year (1992). Trees have nearly the same growth conditions as in Cornharrow (see Appendix 7 and Appendix 8).

2.2 Plot Collection

For validation, it is important to cover different growing conditions on managed and unmanaged stands. Differences should be ensured in terms of age, site quality and management. The first step was to split the stands into groups of same age and same management. Stands were divided by age into young, mid-rotation and mature forests. Young forests had an age of 1 to 15 years, mid-rotation forests of 16 to 30 years and mature forests 30+ years. Another important distribution was the site quality. Stands were subdivided according to site quality into good and poor stands. The division was done by the optical assessment of the top height. Managed forests were characterized by the reduction of trees through thinning, with the important restriction that thinning was not done in the last five years, to ensure that there is no falsification by the competition factor. Table 2 graphically represents the allocation of the plots to the stands. Specific data of the stands were not available, so the allocation was done approximately, using the knowledge of the regional foresters. The second step was the design of the plots. In the following calculations, it was important to have a minimum number of trees (about 20) in each plot. Therefore, circular plots with various radii were chosen. Larger plot area reduces variation.

Table 2: Graphically and numeric allocation of all plots and stands. Basis of allocation was the optical assessment of site quality and top height.

	Radius [m]	managed		unmanaged		∑
Age/ Site		good	poor	good	poor	
young	6			A4,A6;A7;M4;M5; M6	A8;A9;C3	**9**
middle	7			CO3;CO4;CO5;CO6; MA1	C6;CO1;CO2	**8**
mature	10	A3;A4;M7;M8; M11; M12	M1; M13	A1;A2;C2;C10;M9; M10	C1;C4;C5;C7;C8;C9; M2; M3	**22**
∑		**6**	**2**	**17**	**14**	**39**

A…Auchrae	**CO…Cornharrow**
C…Garcrogo	**MA…Manquhill**
M…Margree	

2.3 Data Collection

The parameters for stand description were split into three groups. The first group characterized the stand and the management. The parameters described the site quality, age and management. The second group gave information about the trees in the plot. Single trees were qualified by data about the diameter, height, height of live crown and increment. For determination of the parameters, it was important to have a balance between the number of parameters, their significance and the required time for estimation. Because of this, height, height of live crown and increment were only measured for every fifth tree as well as for the biggest as smallest trees. The last group of parameters described the distribution and competition of the trees in the plot. The selected parameters are listed in Table 3 (see also Appendix 9).

Table 3: Order of selected parameters for description of the plot, stand, trees and distribution.

Parameters about			
plot	**stand**	**trees**	**distribution**
stand	site quality	diameter	tree no.
plot no.	exposition	height	northern angle
radius	age	height of live crown	distance from the central point of the plot
	management	increment	

The diameter of the trees was measured in millimetres using a girthing tape over the bark. To get the diameter at breast height (DBH), a piece of wood with a length of about 1.3 metres was used. Following the usual conventions, the point of the DBH was located from the ground level and not from the top of the tree root (Matthews and Mackie 2006). Dead trees and trees with DBH less than seven centimetres were not measured.

The total tree height is the vertical distance from the base of the tree to the uppermost point. Height of live crown is defined as lowest point of the live crown, where more than three branches are alive. To assess the height of the tree and the spring of the life crown, a VERTEX hypsometer was used.

The coordinates of the trees in the plot were estimated using the distance and the northern angle. The distance and the northern angle from the central point of the plot to the middle of the trunk were measured for each tree inside the plot.

The measurement of the five- and 10- year increment was done within an increment-core driller. Core was taken as the height at DBH in the direction of the centre of the plot. The value was measured in 0.5 millimetres.

In all, 39 plots and 1,115 trees were measured, with a minimum number of 18 (plot M8) and a maximum number of 43 (plot M13) trees per plot. Table 4 gives a summary of the measured dataset. The columns show the ages of the stands in 2015. The first two rows list the number of plots and trees measured. The subsequent rows describe the mean DBH and height for each age class. The mean of DBH is about 17 centimetres with a range from 0.6 centimetres (plot C3) to 61.6 centimetres (plot A3). The mean height is about 14 metres, with a range from 1.5 metres (plot C3) to 32 metres (plot A3). The last rows describe the measurements of five-year increment. Because of small DBH, it was not always possible to measure the increment in young trees. The maximum value of increment was given in age class 11 (plot M5) with a five-year increment of 4.35 centimetres (= 8.7 cm in diameter). The minimum value was about 0.15 centimetres (age class 44) in plot CO1.

Table 4: Summary of measured dataset. The column denotes the age classes in 2015. The rows include the values of measurement for each age class: number of plots, number of measured trees, mean DBH and height, standard deviation of DBH and height as well as number of increment measurements, mean five-year diameter increment and standard deviation of five-year increment.

Age class (2015)	9	10	11	12	21	25	27	30	31	39	43	44	45	46	Sum/ Mean
Number of Plots	1	2	4	2	6	1	1	2	2	1	3	8	1	5	**39**
Number of trees	30	50	117	60	165	22	33	64	63	29	109	221	29	123	**1,115**
Mean DBH [cm]	3.4	5.4	6.2	8.7	14.0	21.3	11.0	14.1	15.1	19.8	25.7	22.9	25.2	27.3	**17.2**
$sd_{DBH\ [cm]}$	1.5	2.6	2.6	4.1	4.3	5.2	5.1	7.6	7.2	5.6	8.8	7.4	7.5	10.4	**10.1**
Mean height [m]	3.0	4.8	5.5	7.8	12.4	17.8	9.7	12.1	12.9	16.7	20.1	18.6	20.0	20.8	**14.1**
$sd_{height\ [m]}$	1.1	2.3	2.4	3.6	3.5	3.6	4.3	6.0	5.4	4.1	4.8	4.6	4.4	5.7	**7.1**
Number of increment measure-ments	0	6	12	12	37	5	7	14	14	6	23	49	6	28	**219**
Mean diameter increment [cm]	0	3.0	3.1	2.8	1.1	1.6	0.8	0.5	0.5	0.7	0.8	0.6	1.0	0.7	**1.3**
$sd_{incr.\ [cm]}$	0	0.3	0.7	0.5	0.6	0.5	0.4	0.3	0.4	0.3	0.3	0.4	0.5	0.5	**3.0**

3 MOSES Data Preparation

The MOSES framework needs a fully completed import data set in order to work. Some of the required data were not available in the measured dataset. To get the missing data, different models and functions from the MOSES framework were used. The functions were transformed and the parameters calculated. The tree height, height of live crown, yield class and coordinates of each tree had to be generated. The import of the completed dataset into MOSES framework was done with EXCEL. All calculations were done with the statistical program R.

3.1 Tree Height Curve

Since only a limited number of trees were measured, the missing tree heights were estimated within height curve functions (Equations 11,12 and 13). In the MOSES framework, three main functions for spruce are available:

$$\boldsymbol{h_{Kern}} = \boldsymbol{e^{a_0 + a_1 * \left(\frac{DBH}{DBH+1}\right)} + 1,3} \qquad \textbf{(11)}$$

$$\boldsymbol{h_{Pollansch\text{ü}tz}} = \boldsymbol{e^{a_0 + \frac{a_1}{DBH}} + 1,3} \qquad \textbf{(12)}$$

$$\boldsymbol{h_{Petterson}} = \boldsymbol{\frac{1}{\left(a_0 + \frac{a_1}{DBH}\right)^2} + 1,3} \qquad \textbf{(13)}$$

In the first step, the measured tree heights of the plots were listed into an EXCEL.CSV- file along with the attributes DBH and height. Using the statistical program R, the specific coefficients a_0 and a_1 were generated for each function. The values of the coefficients are shown in Table 5.

Table 5: Estimated coefficients of the different height curves. All coefficients are significant at 0.1 percent. N = 287

Coefficients	Pollanschuetz	Kern	Petterson
a_0	3.63376	3.65835	0.141218
a_1	-16.51948	17.52111	2.188443
Std. Error a_0	0.02868	0.02902	0.003318
Std. Error a_1	0.59505	0.61985	0.079872
T-Value a_0	126.71	126.04	42.56
T-Value a_1	-27.76	28.27	27.4
Res. Std. Error	2.923	2.908	2.895

In the second step, the deviation between height curves and real-grown trees were compared. To choose the right function, it was important to compare the trends of all the functions, because each function shows a different increase in height. Small and high diameter classes in particular often show differences between the estimated and real growing trend.

Figure 10 shows the trend of the measured tree heights and the trends of the different height functions. The measured tree heights have nearly a linear height increase along the smaller diameters. The bigger diameters show a characteristic deceleration of the positive slope. The function given by Petterson (1955) provides the best results.

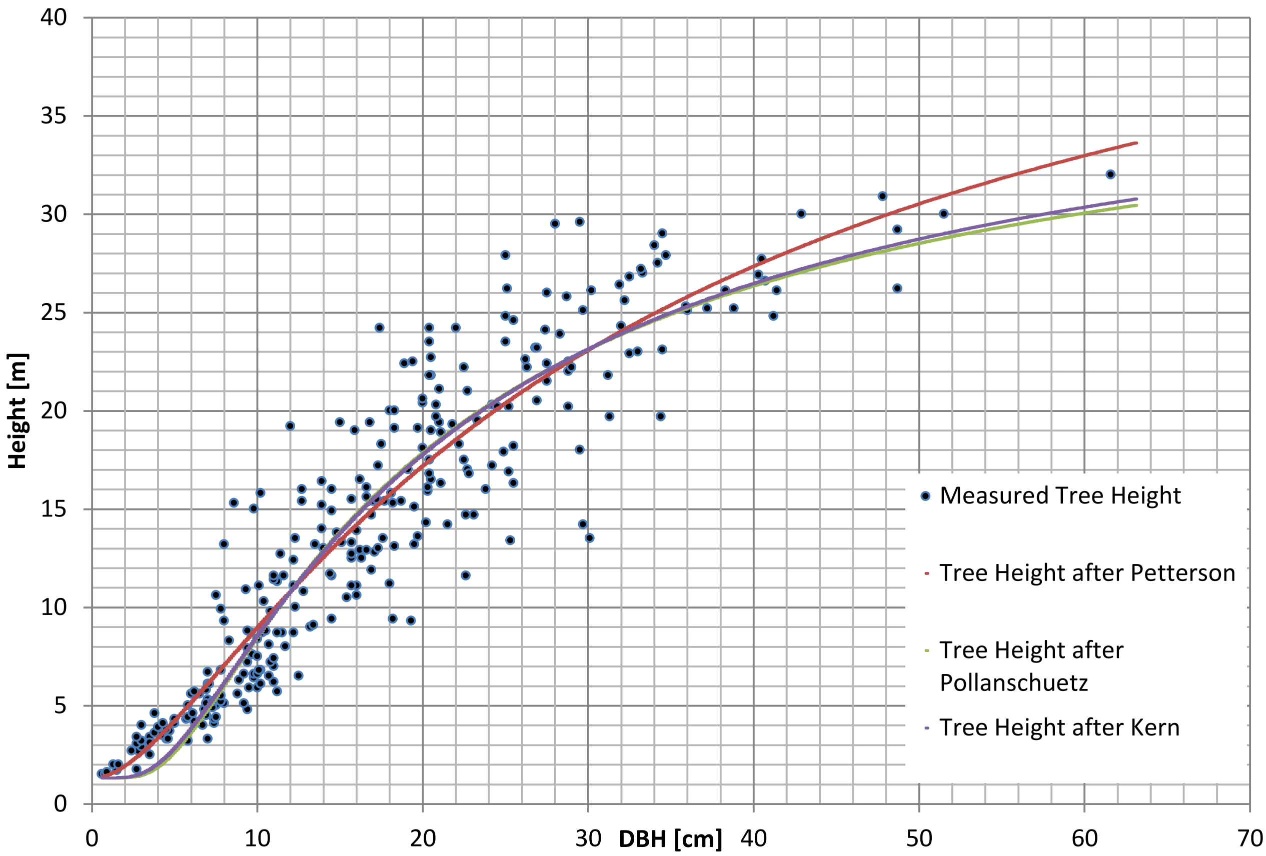

Figure 10: The trends of the different height curves and the measured tree heights of the plots. The function given by Petterson (1955) is nearly similar to the real height growth trend.

3.2 Height to Live Crown Base

To estimate the missing heights of the live crown base (HLC), the function given by Kahn and Pretsch (1997) (Equation 14) was used. The regenerated coefficients of the following function are presented in Table 6. The residuals in Figure 11 show differences of the estimated HLC in comparison to the HLC of the measured trees. Especially in small diameters, the estimated HLC is higher than the observed HLC.

$$hka_p = h * (1 - e^{a_0 + a_1 * \frac{h}{DBH} + a_2 * DBH}) \quad (14)$$

Table 6: The parameters estimated for the height of live crown function. All parameters were significant at 0.1 percent. N = 287 s_d = 1.82

Parameter	Estimate	Std. Error	t-value
a_0	0.953887	0.101589	9.39
a_1	-1.599409	0.100323	-15.94
a_2	-0.017791	0.001525	-11.67

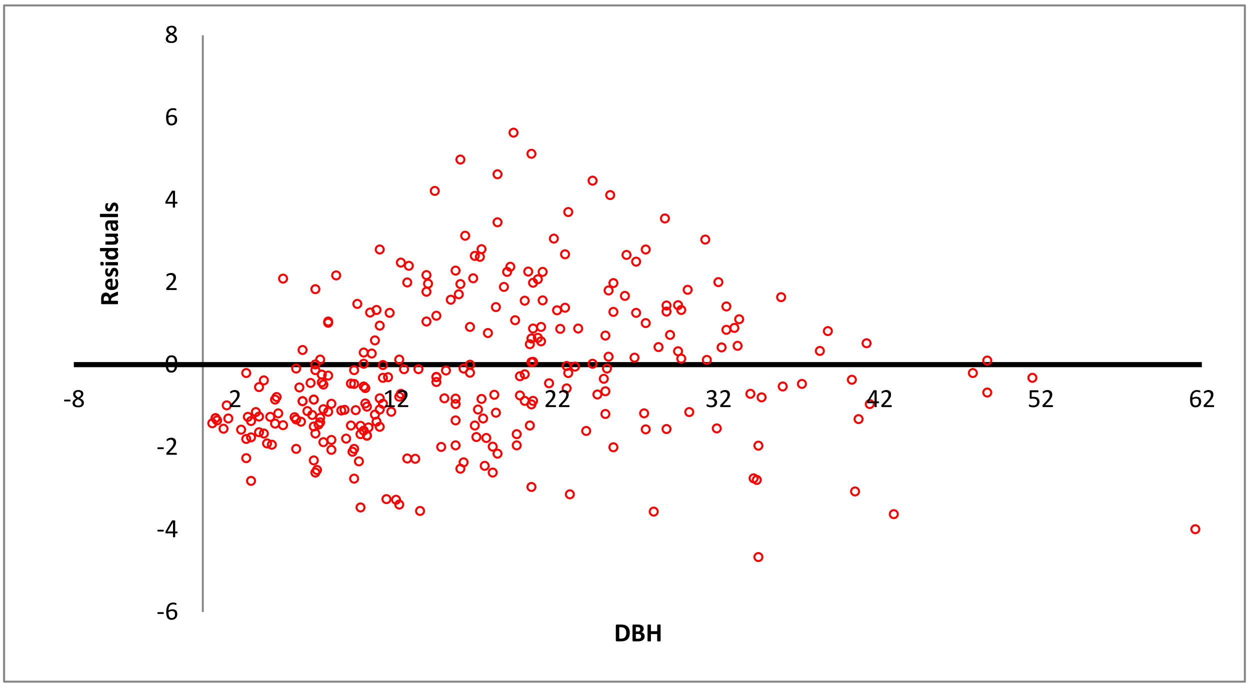

Figure 11: The residuals of the HLC plotted against the DBH. The horizontal axis denotes the DBH in centimetres. The vertical axis shows the differences (predicted-observed) in HLC in metres.

3.3 Yield Class Model

MOSES uses top height functions to calculate the effective age of a tree with a given height. The Function (15) defines top height as function of the age and side index (SI) (Hasenauer et al. 2005).

$$\mathbf{Top\ Height} = \mathbf{f(t, SI)} \Rightarrow \mathbf{t} = \mathbf{f(Top\ Height, SI)} \Rightarrow \mathbf{SI} = \mathbf{f(Top\ Height, t)} \quad \textbf{(15)}$$

Transformation of these functions enables the calculation of the side index. Furthermore, empirical studies showed that the function for the side index is implementable for the yield class. The yield class (YC) of each stand was calculated by transformation of the side index functions. The focus of the calculation was to estimate the yield class using the age and top height.

The following steps describe the estimation of the yield class using the top height function given by Sterba (1976). The paramters were taken from the MOSES framework .

$$\mathbf{Top\ Height} = \mathbf{a} * (\mathbf{1} - \mathbf{e}^{-\mathbf{b}*\mathbf{t})})^{\mathbf{1/(1-c)}} \quad \textbf{(16)}$$

Where:

$a = a_0 + a_1 * YC + a_2 * YC^2$

$b = b_0 + b_1 * YC + b_2 * YC^2$

$c = c_0 + c_1 * YC + c_2 * YC^2$

Using Equation (16, it was possible to calculate a relative age (t_{calc}) (Equation (17) based on top height and estimated YC.

$$\boldsymbol{t_{calc}} = \frac{\mathbf{ln}\left(\frac{\mathbf{1}}{\mathbf{1} - \left(\frac{\boldsymbol{h}}{\boldsymbol{a}}\right)^{\mathbf{1}-\boldsymbol{c}}}\right)}{\boldsymbol{b}} \quad \textbf{(17)}$$

The restriction was to minimize the difference between the calculated age and the stand age.

$$\mathbf{min}\ \mathbf{t}_{\mathbf{calc.}} - \mathbf{t}_{\mathbf{stand}} \qquad \textbf{(18)}$$

The yield class was calculated by optimizing the functions after YC, according to Equation 16 and 17.

$$\textbf{Yield Class}:\ \ \mathbf{minimze}\ \mathbf{t}_{\mathbf{calc.}} - \mathbf{t}_{\mathbf{stand}} \Rightarrow \mathbf{optimize\ YC} \qquad \textbf{(19)}$$

Figure 12 graphically presents the generated yield class curves. The uppermost point shows the side index of plot C10 with an age of 50 years. The left upper point is the actual height and the brown line is the generated yield class curve with a calculated yield class of 18.97. The plot C9, in comparison to plot C10, has a lower SI and a lower yield class curve, with a yield class of 12.98.

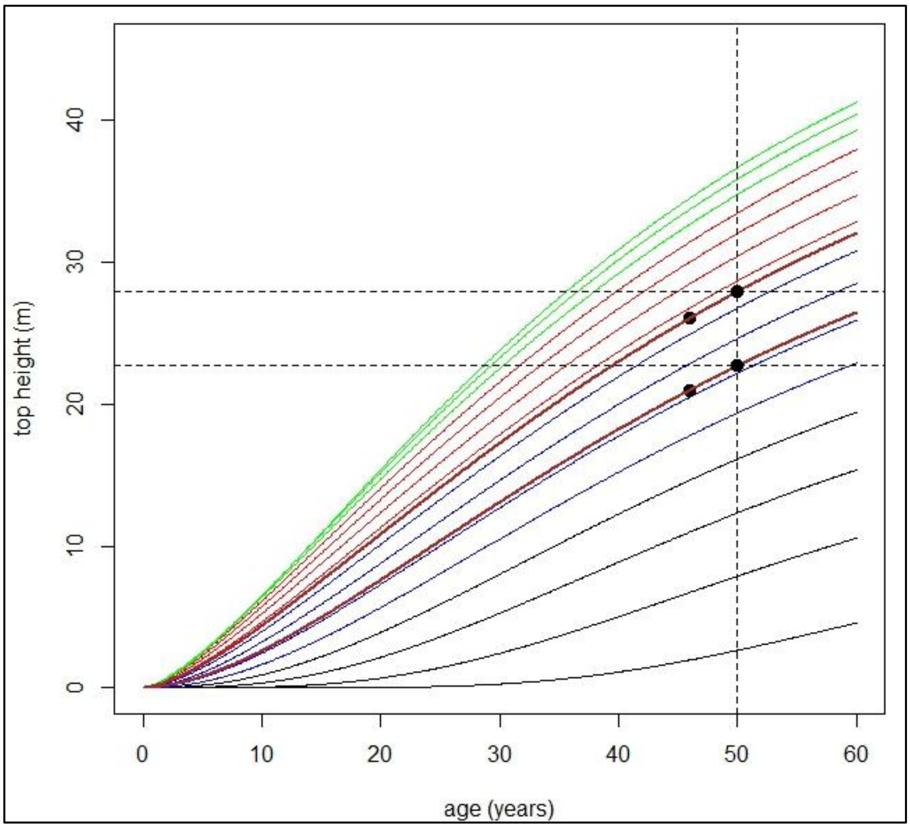

Figure 12: Graphical representation of the yield class curves from 2.5 to 35. The upper two points on the curve are from plot C10 with an estimated yield class of 18.97. The lower points are on the yield class curve of plot C9 with a yield class of 12.98.

3.4 Tree Coordinates

For the crown models and the competition index – according to the mortality model – MOSES needs exact tree positions. Unfortunately, MOSES needs for coordinates of trees a rectangular design of plots. Because of the circular design of the plots, coordinates of the trees were not available. An alternative approach was to generate the missing coordinates with R. First, a square with the same area as the circular plots was visualized. Using the knowledge that the trees in the observed stands were planted in rectangular ranks, a rectangular grid inside the square was created. The number of trees in the square is the same as in the circular plot. Following this method, exact coordinates have been generated for each tree in the plots. Figure 13 shows the generation of coordinates for plot M2.

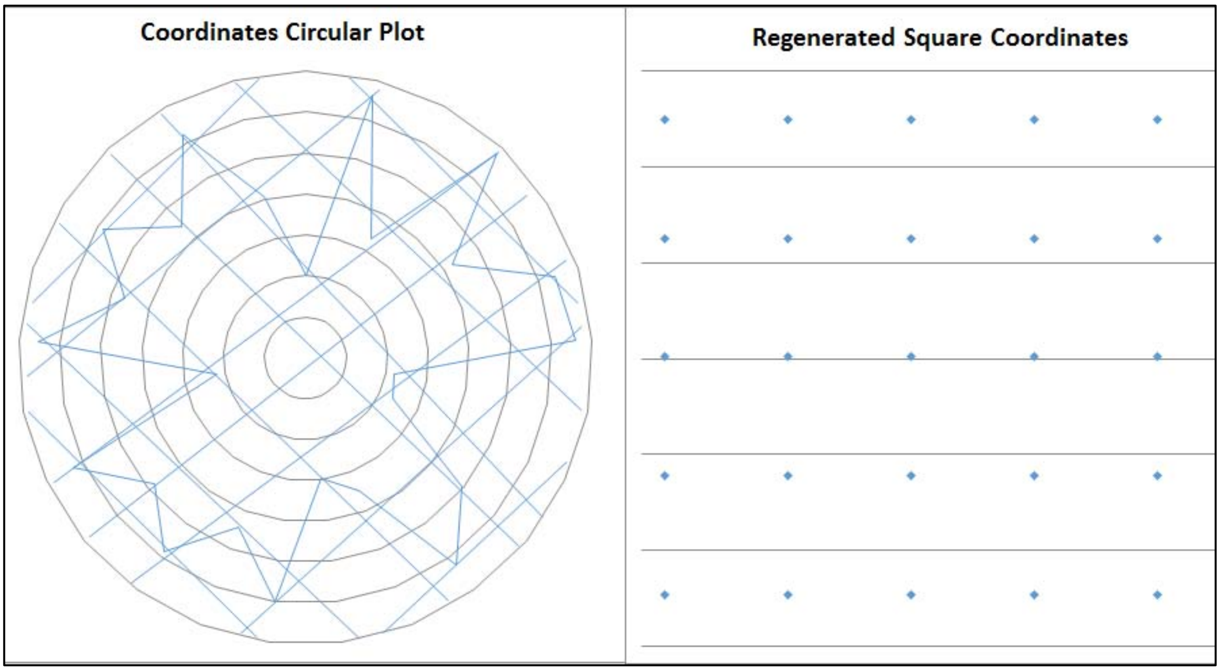

Figure 13: Regeneration of coordinates for plot M2. The left plot shows the real distribution of trees, while the right plot shows the regenerated distribution. The coordinates of the circular plot supposed to have a nearly rectangular distribution of trees.

3.5 MOSES Data Import

MOSES works with a specific excel formation to import the dataset. This file needs detailed information about the trees and plots. The import-file consists of three different layers:

tree: specific information's about each tree, like DBH, height, etc.
stand: information about the plot, like site index, size of the plot, etc.
regeneration: information about the regeneration

In order to use the MOSES model, stands were arranged in the order of their exact age and management as shown below:

Young forests: age lower than 16 years
Mid-rotation forests: age 16 to 30 years
Mature forests: age over 30 years

The plots were divided into groups of same yield classes (Appendix 10). The range of one yield class group was about +/- one yield class. The following table shows the systematic order of the dataset for mature managed forests.

Table 7: Systematic order of the plots in mature managed forests. Same colour shows different plots covered in the same stand. M11 is listed separately, because of the difference in trees per hectare.

Mature Forests managed											
Group	Class	Plot Nr.:	Age	managed	Exp.:	Rad. [m]	Top H.	Yield Class	SI [m]	T.i.P	N/ha
1	26	A3	46	yes	NW	10	30,64	26,03	32,66	18	573
	26	M12	43	yes	SW	10	28,98	25,96	32,62	30	955
2	21	A4	46	yes	NW	10	27,57	21,1	29,49	35	1114
	21	M7	43	yes	W	10	26,29	21,49	29,76	36	1146
	21	M8	44	yes	NNW	10	26,67	21,27	29,61	35	1114
3	21	M11	44	yes	SW	10	26,59	21,15	29,52	28	891
4	19	M1	45	yes	flat	10	25,52	18,9	27,88	29	923
5	13	M13	43	yes	flat	10	19,34	12,77	22,47	43	1369

4 Analyses and Results

4.1 Validation of MOSES

Validation is essential in order to verify the suitability of application of MOSES for *P. sitchensis*. The international organization of standardization (ISO) in its norm 9000 defined validation as confirmation that the requirements for a specific intended use or application have been fulfilled.

“The objective evidence needed for a validation is the result of a test or other form of determination such as performing alternative calculations or reviewing documents. The use conditions for validation can be real or simulated.” (ISO 2015)

Law and Kelton (1991) give a specific description of validation in models: “Validation is concerned with determining whether the conceptual simulation model (as opposed to the computer models) is an accurate representation of the system under study.” The aim of validation for computer-based simulations is the verification of application in real-size problems. Considerations are made for the entire output. Interim results give a short, but relevant value of a restricted system. The focus of validation is not on the single computed values, but on the entirety of the model. Kleijnen (1995) states that validation cannot be assumed to yield in a perfect model, since the perfect model would be the real system itself.
For MOSES, validation can be done by testing the results of essential models, such as the increment model.
For validation, a set of predicted and observed data was compiled. The basis was the comparability of the predicted with the observed data. In the observed dataset, values should be measured directly and without derivations. Especially in forest mensuration, measurement error is an important factor that has to be minimized. All observed data have to be based on a growing period of five years. The predicted dataset should be composed of values with high significance to further computed models. Predicted data must have the same initial parameters as the observed data. For increment, initial parameters are summarized in the yield class.

The best data for validation provides the potential height increment. Hence, the observed five-year height increment is required. In the observed data, the potential height increment is not available, because height increment was not measured and heights were calculated with the formula given by Petterson (1955). Because of this, the potential diameter increment was used for validation. The basis of diameter increment is the potential height increment (Chapter 1.6.1). Thus, the diameter increment guarantees significant data for the validation of MOSES. The observed increment also provides independent and exact values of the real increment, because of direct measurement.

The validation was done by comparing the observed and predicted diameter increment. In the first step, the growth of all stands was simulated in the MOSES framework for a single period of five years. After simulation, data of trees whose increment was measured were picked out of the predicted dataset. In sum, the data of 88 trees were available. Because of the inaccurate increment measurements of very small trees, the dataset was modified by removing trees with DBH smaller than 12 centimetres. In the second step, the differences between the predicted and observed data for each tree were calculated. In Table 8, the summary of the differences is given. However, it is necessary to verify with statistical methods whether a computer model is valid. Therefore a graphical assessment was done and statistical intervals were calculated.

Table 8: Summary of differences between the predicted and observed data, where: n = sample size, $\bar{D}$ is the mean, $\sigma_{\bar{D}}(n-1)$ the variance and $s_{\bar{D}}$ the standard deviation of the differences (predicted-observed). All values are scaled in centimetres.

Statistic	n	D_{Min}	D_{Max}	1st Quartile	Median	3rd Quartile	$\bar{D}$	$\sigma_{\bar{D}}(n-1)$	$s_{\bar{D}}$
YC_standard	55	-1.600	0.930	-0.483	-0.195	0.045	-0.238	0.223	0.472

4.1.1 Graphic Assessment

For the graphical assessment, deviations between the observed and predicted data were plotted against a qualitative scale. The vertical axis denotes the deviations and the horizontal axis denotes the quality, which is represented by DBH, height and yield class. Differences and group effects are shown by the distribution of the deviations. However, graphical assessment should show if there is an under- or overestimation of the real increment. Figure 14 and Figure 15 represent a slight underestimation of the real increment. Moreover, the trend shows an increase of underestimation in small diameters and heights. Generally, positive values (n = 15) are less given as negative values (n = 40). The highest values of positive deviation are between 10 and five millimetres. In contrast, lowest values of underestimation are about 15 millimetres.

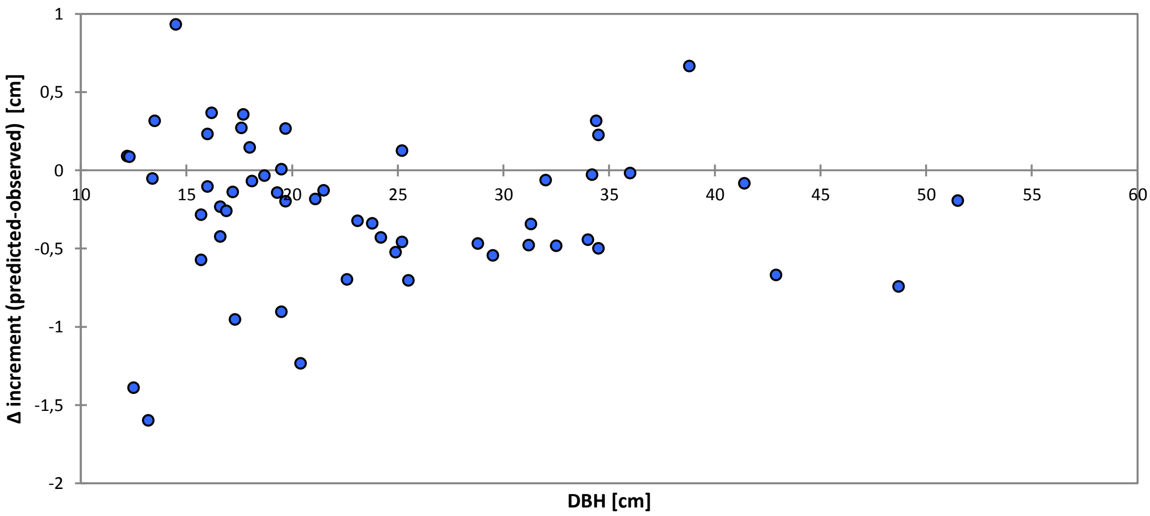

Figure 14: The vertical axis denotes the deviations (∆increment) and the horizontal axis denotes the DBH. (N = 55; $N_{positive}$= 15; $N_{negative}$= 40)

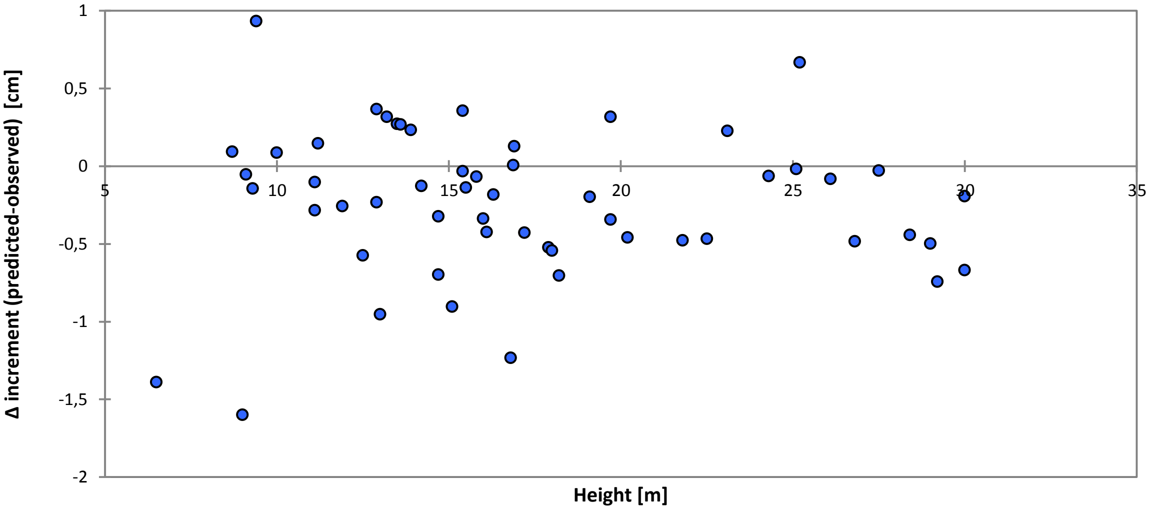

Figure 15: The vertical axis denotes the deviations (∆increment) and the horizontal axis denotes the height. (N = 55; $N_{positive}$= 15; $N_{negative}$= 40)

The same procedure was used for the yield classes. Figure 16 shows that negative residuals increase with the yield class. In addition to knowledge about the distribution of yield classes and ages (see also Appendix 10), the observations are similar to Figure 14 and 15. Height yield classes were observed in young stands with small diameters and heights.

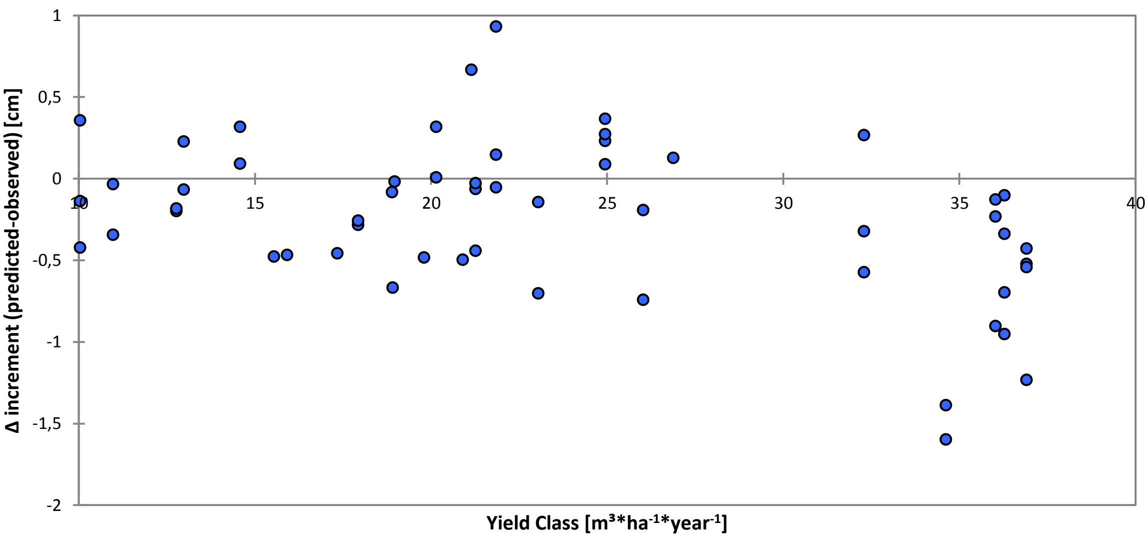

Figure 16: The vertical axis denotes the deviations (∆increment) and the horizontal axis denotes the yield classes. (N = 55; $N_{positive}$= 15; $N_{negative}$= 40)

As the basic input parameter of the increment model, yield class has the highest influence on output data. To check if there is a "Type I" error (rejection of the model though it is valid), the standard value of yield class was modified up and down six classes (Kleijnen, 1995). The output is represented graphically in Figure 17. As expected, there is an increase of positive residuals with the rise in the yield class ($N_{positive;YC\_standard-6}$=10; $N_{positive;YC\_standard}$=15; $N_{positive;YC\_standard+6}$=21). Furthermore, there are differences in the value of residuals along the horizontal axis. Small diameter classes show higher differences than higher diameter classes by changes in yield class.

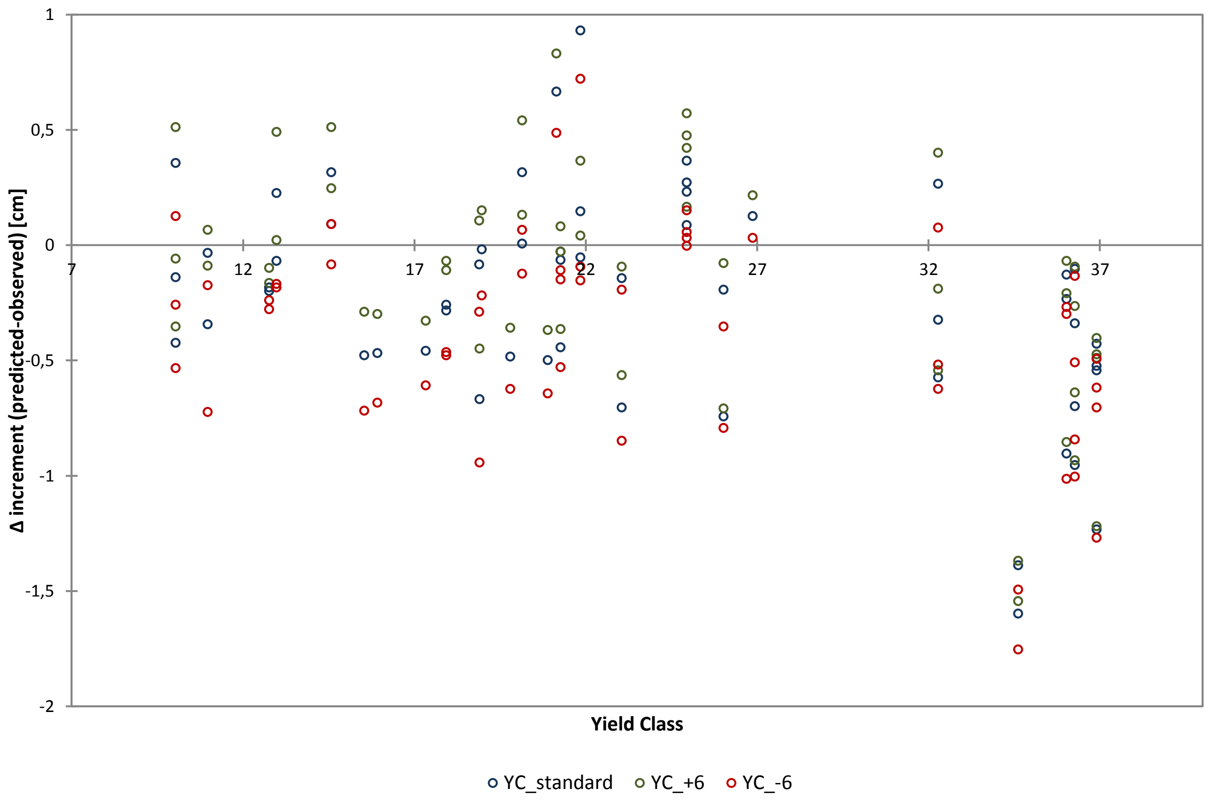

Figure 17: The vertical axis denotes the deviations (∆increment) and the horizontal axis denotes the yield classes. Blue points ($YC_{standard}$; N = 55; $N_{positive}$= 15; $N_{negative}$= 40) mark the initial yield classes. Green ($YC_{standard+6}$; N = 55; $N_{positive}$= 21; $N_{negative}$= 34) and red ($YC_{standard-6}$; N = 55; $N_{positive}$= 10; $N_{negative}$= 45) points represents the modified yield classes.

4.1.2 Prediction, Confidence and Tolerance Interval

The prediction, confidence and tolerance interval mentioned by Reynolds (1984) is an approach to evaluate the limits and range in the errors of predictions (Pötzelsberger 2015). The prediction interval PI presents the array of the differences (Di) between the predicted and the estimated increment. The confidence interval CI scales discrepancies between the expected difference and the estimator $\bar{D}$. If the model is used repeatedly, the tolerance interval TI evaluates the limit that includes a specified proportion (e.g. 95 percent) of the distribution of differences (Reynolds 1984).

Table 9: Results of the error analyses for the simulations in five-year increment. All values are scaled in centimetres.

n	$\bar{D}$	$S_{\bar{D}}$	t	$\rho_{1-y;n;1-\alpha}$	PI			CI			TI		
55	-0.238	0.472	2.005	2.354	-1.194	to	-0.717	-0.366	to	-0.111	-1.350	to	0.873

$$PI = \bar{D} \pm \sqrt{1 + \frac{1}{n}} * S_{\bar{D}}$$

$$CI = \bar{D} \pm * \frac{S_{\bar{D}}}{\sqrt{n}} * t_{1-\alpha/2;n-1}$$

$$TI = \bar{D} \pm S_{\bar{D}} * \rho_{1-y;n;1-\alpha}$$

$\bar{D}$ is the mean and $S_{\bar{D}}$ the standard deviation of the differences (predicted-observed)

n the sample size and **t** the 1-α quartile of the t-distribution with n-1 degrees of freedom

$\rho_{1-y;n;1-\alpha}$ is the tolerance factor for the normal distribution accounting for the probability that (1-γ)100 percent of the distribution of *D* is within a probability of $1\text{-}\alpha$

The values of the prediction, confidence and tolerance interval are given in Table 9. A Shapiro-Wilk test (p=0.05) confirms that the variables from which the sample was extracted follows a normal distribution. The prediction interval supposes that most of the differences (95 percent probability) in five-year increment of future simulations are between -1.194 and -0.717 centimetres. With a probability of 95 percent, the mean bias is between -0.366 and -0.111 centimetres and thus significantly different from zero. It can be assumed that there is a low underestimation of increment in the samples. The tolerance interval confirms that the true value of the estimator $\bar{D}$ is, with a 95 percent probability, between -1.350 and 0.873 centimetres.

4.2 Management Scenarios

After validation, the model was used to simulate different management scenarios based on practised management activities. Thinning, as a basic management treatment, is the central point of consideration in part one. The second part of management scenarios includes six scenarios with different numbers of trees in reforestation. The last part considers the simulation of growth of managed and unmanned mature stands.

4.2.1 Thinning Effects

The parameters of thinning are described by the scheme of thinning and the given limits. Hence, six thinning scenarios with different limits were simulated. Each scenario represented a different thinning density. Five different unthinned real-grown stands of the plot sample (see Appendix 10; CO1, CO2, CO3, CO4, CO5) were chosen, with an age of 21 years and different only in yield class (18 to 36). All stands were in the Cornharrow forest district and had had no management treatment in the past. The simulation started in 2015 and will end after five periods (2040), with the first thinning at the beginning of simulation in Period 1. Second thinning is to be done after 10 years in Period 3. The assumption was that twice as low thinning is done with same density of removal. For low thinning, trees are sorted by DBH. Trees with smaller DBH get removed first. The removal stops when the given limit is reached (Klopf et al. 2013).

Figure 18 represents the value of volume of the different thinning scenarios. The scenarios without thinning show a fast increase in the remaining volume in the first period, whereas scenarios with high thinning density show a rapid increase at the end of simulation. An interesting effect is seen in the last two periods. All scenarios nearly reach the same value of remaining volume. Another important difference in thinning density is given by mortality. Generally, the mortality increases with age. Scenarios with low thinning density in particular show a high increase of mortality early. It seems that the mortality can reach an equal level at the end of simulation. Only scenarios with a high thinning density show no or little mortality in the first periods.

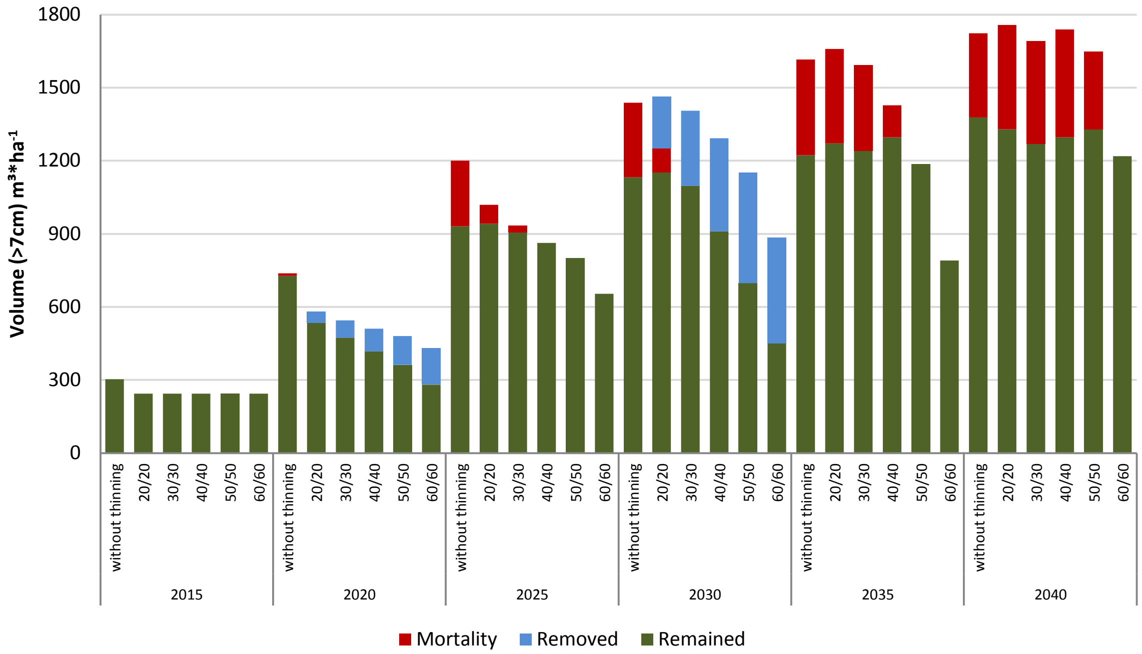

Figure 18: Representation of the values of different thinning scenarios. The vertical axis denotes the volume of stems greater than seven centimetres in diameter. The horizontal axis shows the simulation period and the thinning density. The first and second number presents the percentage of removed volume in the first and second thinning.

Table 10 presents the values of the different thinning scenarios. The maximum mean of remaining volume at the end of simulations is given without thinning. There is only a small difference (about 158 m³) between unthinned and massively thinned (60_60) scenarios. A Friedman´s test also shows no significant (p = 0.05) differences between the mean remain volume.

Table 10: Values of different thinning scenarios. All values are cubic metre of trunks greater than seven centimetres in diameter.

Variable	Observations	Minimum	Maximum	Mean	Std. deviation
without thinning	5	952.966	1882.404	1377.429	401.653
20_20	5	794.972	2113.815	1329.806	509.823
30_30	5	832.572	1574.866	1270.267	287.647
40_40	5	778.567	1896.218	1295.959	460.096
50_50	5	902.447	2427.244	1327.354	621.248
60_60	5	704.386	1942.618	1219.060	471.742
Asymptotic p-value 0,995			alpha	0.05	

H0: The samples come from the same population.
Ha: The samples do not come from the same population.
As the computed p-value is greater than the significance level alpha=0.05, one cannot reject the null hypothesis H0. The risk of rejecting the null hypothesis H0 while it is true is 99.45 percent.

4.2.2 Planting Effects

To simulate planting effects, stands with different number of trees per hectare were generated. All the stands were not real-grown model stands with identical growth conditions. Stands only differed in terms of the number of trees per hectare. All trees were similar with an age of five years, a DBH of 1.7 centimetre and a height of 1.8 metre. The assumed yield class was 20 $m^3ha^{-1}year^{-1}$. The simulation was done over eight periods (40 years). Two scenarios were simulated. The first scenario was without thinning. In the second scenario, two low thinnings activities for the same density (remove of 40 percent of standing volume) were carried out. The first thinning was done in Period 3 (2025 to 2030) while the second thinning was done in Period 5 (2035 to 2040).

The values of simulations are presented in Table 11. The first scenario offers the highest value of remaining volume, at 2,000 to 2,500 trees per hectare. It seems that in the second scenario, the same stands also provide the best remaining volume values. Low and high stocked stands with 1,200 and 3,600 trees are present in both scenarios with only a low variance in volume and mortality. Generally, the two scenarios differ in terms of remaining volume and mortality. A students t-test for two paired samples shows a significant difference ($p = 0.05$) in remaining volume and mortality between two scenarios. There is also a significant difference ($p = 0.05$) between stands with 2,000 and 3,600 trees per hectare without thinning.

Table 11: Results of plantation simulations. The remaining volume shows the volume of standing trees with diameter greater than seven centimetres at the end of simulations in 2055. The volume of removed and dead trees is summarized over the simulation periods (40 years).

Scenario 1 (without thinning)						
Trees per hectare	**1200**	**1600**	**2000**	**2500**	**3000**	**3600**
V [m^3>7cm*ha^{-1}] remaining t_{2055}	866	1136	1296	1287	1066	770
V [m^3>7cm*ha^{-1}] removed $t_{2015-2055}$	0	0	0	0	0	0
V [m^3>7cm*ha^{-1}] mortality $t_{2015-2055}$	1550	1385	1373	1377	1530	1833
Scenario 2 (with thinning)						
Trees per hectare	**1200**	**1600**	**2000**	**2500**	**3000**	**3600**
V [m^3>7cm*ha^{-1}] remaining t_{2055}	883	661	803	756	787	761
V [m^3>7cm*ha^{-1}] removed $t_{2015-2055}$	287	330	421	417	380	434
V [m^3>7cm*ha^{-1}] mortality $t_{2015-2055}$	1089	1180	1153	1241	1281	1397
Differences (Scenario 2 – Scenario 1)						
Trees per hectare	**1200**	**1600**	**2000**	**2500**	**3000**	**3600**
V [m^3>7cm*ha^{-1}] remaining t_{2055}	16.4	-474.8	-493.2	-530.5	-278.9	-9.5
V [m^3>7cm*ha^{-1}] removed $t_{2015-2055}$	286.8	330.0	420.7	417.5	379.6	433.5
V [m^3>7cm*ha^{-1}] mortality $t_{2015-2055}$	-460.9	-204.8	-219.4	-136.3	-249.2	-436.5

Figure 19 and Figure 20 present the development of remaining volume and mortality over the simulation time. In Scenario 1 (Figure 19), the mortality and the remaining volume increases constantly while Scenario 2 (Figure 20) only shows a continuous increase in remaining volume and a discontinuous increase in mortality. In Scenario 2, the effect of thinning can be observed. During the first (Period 3) and second (Period 5) low thinning, the potential of mortality decreases. Low thinning with a density of 40 percent has only a low influence on remaining volume in comparison to the mortality. The same can be observed in chapter 4.2.1.

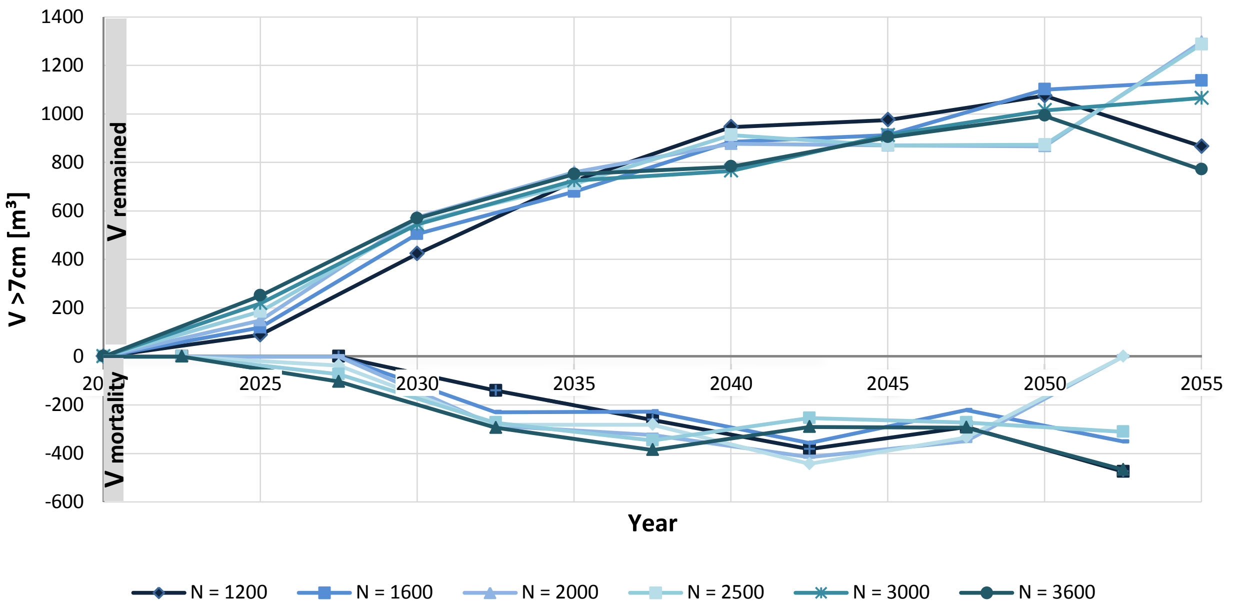

Figure 19: Scenario 1; remaining volume and mortality in simulated stands without thinning. The upper field denotes the increase in remaining volume. The lower field shows the increase in mortality.

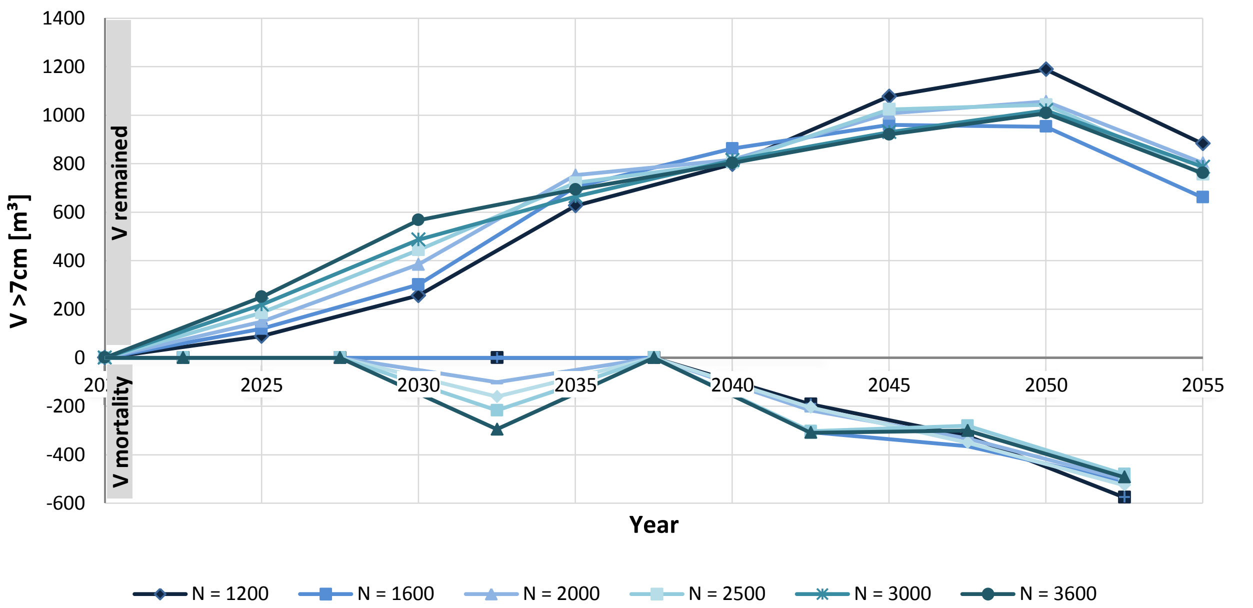

Figure 20: Scenario 2; Remaining volume and mortality in simulated stands with thinning. The upper field denotes the increase in remaining volume, while the lower field shows the increase in mortality.

4.2.3 Growth Simulations of Mature Stands

The last part of the simulations was the observation of growth of mature stands. Four real-grown mature stands, with and without management in the past, were chosen. The simulations were done over 10 periods (50 years) without any management activities. The point of consideration was the development of volume, basal area, stocking and mortality. Because of different ages and yield classes and the non-availability of data from past management activities, a statistical verification was not possible.

Table 12 presents the values of growing simulations for mature stands at the end of the simulation. The mortality volume presents the sum of mortality over the simulation periods. As assumed, unmanaged stands show a higher number of trees per hectare. In comparison to the other values from thinning scenarios, managed stands have a higher volume and basal area. In addition to the volume, the mortality in managed stands also shows higher values. Generally, the simulations show a strong increase in volume in mature stands. Mean tree volumes of managed stands are about 12 m³ per tree while mean tree volumes of unmanaged stands are about 6 m³ per tree.

Table 12: Values of simulation of mature stands. Values of trees per hectare, basal area and remaining volume are related to the end of simulation in 2065. The volume of mortality is summarized over all simulation periods (50 years).

Trees per hectare					
Variable	Observations	Minimum	Maximum	Mean	Std. deviation
managed	4	127	159	151	16.000
unmanaged	4	130	260	195	53.072
Basal area [m^2*ha^{-1}]					
Variable	Observations	Minimum	Maximum	Mean	Std. deviation
managed	4	99.275	118.359	112.447	8.954
unmanaged	4	66.124	90.351	78.954	10.636
Remained volume [m³>7cm*ha^{-1}]					
Variable	Observations	Minimum	Maximum	Mean	Std. deviation
managed	4	1580.356	2158,076	1940,620	249.850
unmanaged	4	1020.843	1438.740	1193.556	187.626
Mortality volume [m³>7cm*ha^{-1}]					
Variable	Observations	Minimum	Maximum	Mean	Std. deviation
managed	4	1776.010	2835.692	2477.541	476.577
unmanaged	4	1092.182	1946.803	1641.387	387.407

5 Discussion

5.1 Plot Collection

The validation of MOSES was done with samples of 39 real grown stands. Therefore stands from the forest portfolio of the Czernin-Kinsky Scottish Ltd. Company in the southwest of Scotland were chosen. The point of consideration is the range of growing conditions and not the representation of the area. All stands were chosen subjective to the knowledge of the regional foresters. Plots allow a validation of MOSES for Sitka spruce in the research area, but do not guarantee valid values for other regions.

5.2 Methodology

Because of time limitations, circular plots with different diameters were used. Unfortunately, MOSES needs quadratic plots in order to work with tree coordinates. Hence, the measured plots had to be transferred to quadratic plots. Further plots in research should follow the quadratic plot concept of MOSES.
For validation and simulation, estimated parameters for *P. sitchensis* given by Arcangeli (2012) were used. The mortality model was not recalibrated for Sitka spruce, so parameters for *P. abies* were used. It can be assumed that the two species are sufficiently similar (Dash 2006). Simulations in this thesis also show no immoderate values of mortality, but the mortality model should be recalibrated according to refereed stand concepts.
First simulations show that the maximum five-year increment was restricted to three centimetres. Good sites exceed this constraint, so the limit has to be removed. All the simulations in this thesis were made without an increment limit. The estimated increment data for this thesis do not show an extreme increase in increment, but a specific limit should be determined for further simulations.

5.3 Validation

According to the structure of MOSES, potential height increment would offer the best values for validation. Height increment data were not available, so the potential increment was used. The validation in this thesis is based on the comparison of the predicted and observed increment. Generally, predicted values are very close to observed data. The prediction interval offers a maximum negative deviation (95 percent probability) of about 1.194 centimetres. The confidence interval also provides a negative mean bias and thus differs significant from zero. For this reason, we can assume that there is a slight underestimation of the real increment. Young stands in particular show an underestimation in increment. One reason for this could be the complexity of yield class estimation in young stands and the increase in the high curve at a young age. Another important issue is the range of the deviation in annual increment. For example, the range of values is about -16 to 9.3 millimetres (Table 8). Thus, the range of annual deviation is about -3.2 to 1.8 millimetres. Most of the values are very close to zero. Therefore, it can be assumed that validation also shows a significant error of measurement. The comparison between predicted error in model and measurement is not possible. In all, the validation provides excellent values for the plots in this thesis, but more research is necessary for its advanced use.

5.4 Applied scenarios

The applied scenarios with MOSES offer two important outcomes. First, it is important to see how MOSES responds to changes in growth parameters. Growth should follow empirically known rules. It is important to consider changes in basal area or stocking density. The second output comes from the test of new scenarios for management activities. The values of the scenarios should help to find answers for planting and thinning decisions.

Generally, the applied scenarios are close to reality and offer good values, but all values and results are only valid for the plots in the study area. It is important fact that all scenarios have been simulated under regular conditions. To ensure validation of management scenarios, a refereed stand concept under different conditions is required.

5.4.1 Thinning Effects

Thinning as a basic management activity was the central point of consideration. The simulations were made with real-grown stands from Cornharrow forest. In comparison to other mid-rotation forests, the chosen forests were on very good sites. Therefore, the values of simulation cannot be transferred to poor sites. Furthermore, a thinning cycle of 10 years with first thinning at the age of 21 years was assumed. All thinning activities were simulated as low thinning, wherein trees with smaller DBH were removed first. In practice, the thinning cycle and scheme of thinning differ from simulations. The forest manager Tom Clark describes the thinning scheme as follow:

"Assuming a site is suitable for thinning, the trees are usually thinned between 17-21 years of age, with a mean top height of between 10 and 12m. The first intervention is wholly mechanical with racks being cut every 14m into the crop, to establish extraction routes. Suppressed and sub-dominant trees between the racks are usually removed at this intervention. In the first intervention, we look to reduce total stand volume by approximately 20-25%. Future interventions are generally on a seven year cycle following first thinning, and can expect to reduce stand volume by around 15-20% at each intervention. Typically in South Scotland, most thinnable crops will be thinned up to three times prior to final clearfelling"

Unfortunately, the common thinning scheme for *P. sitchensis* is not available in MOSES, but the programmed values also provide a good idea about different thinning scenarios. The values of the high thinning density scenarios show a strong increase in increment after thinning (Figure 18). This effect is also observed by Savill (1991). He describes the effect of high thinning density for a stand stocked with *P. abies*. The annual increment is 20 $m^3*ha^{-1}*year^{-1}$. SAVILL (1991) postulates that it is possible to remove 14 $m^3*ha^{-1}*year^{-1}$ (i.e.70 percent of increment) between the ages of 25 and 55 years without prejudicing future production. In Figure 18 it can be observed that the ratio of mortality also decreases with thinning density. The main reasons for this effect are less competition and more efficient use of resources of by the remaining trees (Savill 1991). Furthermore, the removed volume covers the potential mortality.

5.4.2 Planting Effects

Virtual stands have been generated for the simulation of different planting scenarios. Trees are similar and distributed in an optimally quadratic manner. The stands do not represent real conditions. In reality, trees are not identical and do not have optimized distribution. Also, the growth conditions are not similar over the rotation time. The simulations should only show the effect of different stocking densities. In both scenarios (without and with thinning), stands with a stocking density of 2,000 to 2,500 trees per hectare provides the best values in volume. The same stocking densities are recommended in literature as well (see Savill, The Silviculture of Trees used in British Forestry, 1991). Stands show a significant difference between low and high stocking densities in terms of remaining volume, but there are no significant differences in volume between Scenario 1 and 2 (Table 11). Scenarios differ only in mortality. This effect could be caused by the scheme of thinning. All thinning activities were done as low thinning. Low thinning densities do not have a significant influence on the remaining trees. The removed trees correspond to natural mortality. In practice, stands without thinning and high stocking densities (3,000+ trees ha^{-1}) provide less volume compared to medium stocked (2,000 to 2,500 trees ha^{-1}) stands. To reach the same volume, high thinning densities (see Chapter 1.2.3) are required. As mentioned, long-term stand concepts in association with different thinning activities are required for validation.

5.4.3 Old Growth Stands

Growth simulations in mature stands show primary differences between managed and unmanaged stands. Furthermore, the simulations show how MOSES manages simulations in age classes without measured data. The simulations indicate an enormous increase in volume and mortality. The main reason for this could be that the assumed high curves overrate the potential increment at high ages. The predicted parameters for high curves include a maximum age of 46 years. In all, MOSES does not provide exact values for long-term simulations with mature stands. Therefore, more research work is necessary, especially in mature and old growth forests.

5.5 Adaptability of MOSES

Dash (2006) states in his thesis that the MOSES modelling approach is highly versatile and with further work could be fully adapted to the UK. Further research has been done by Arcangeli in 2012 with new recalibration of the Model for *P. sitchensis* in the UK. Referring to the estimated parameters of Arcangeli (2012) and the positive validation results in this thesis, the MOSES model can be fully adapted to the research area. Using MOSES it is possible to estimate the annual increment and create management simulations for commercial use in the research area. Furthermore, it can be assumed that the model is also valid for stands around the research area in the district of Galloway and Dumfries.

5.6 Recommendations for Further Research

This thesis gives a first point of validation of MOSES for *P. sitchensis* in a closely restricted area around St. Johns Town of Dalry in Scotland. If MOSES is to be used for common research and management activities in Great Britain, more research in validation should be carried out. Further recommendations for the plot design include a standardized quadratic plot design for exact tree coordinates. Moreover, Dash (2006) also states in his thesis that time series data should be determined on a cycle of one growing period within five years along with the recording of tree height and height to live crown base for each tree as standard in sample plots. For validation of management effects, it is necessary to place a refereed stand concept over a wide range of sites. Future validation should also include research in mature and old-grown stands.

6 Summary

6.1 English Version

MOSES (MOdelling Stand rESponse) is a potential growth-dependent tree-growth model developed at the University of Natural Resources and Life Sciences in Vienna. Originally, MOSES was used in mixed spruce-pine and beech-spruce stands (Hasenauer 1994). Jonathan Dash (University of Wales) assessed the parameters for *P. sitchensis* in an international study (Tyfian Coed Project at the University of Wales) in 2006.
The approach of MOSES follows the potential growth concept, wherein current annual diameter (id_{obs}) and height increment (ih_{obs}) are predicted according to pre-defined potential height (ih_{pot}) and diameter increments (id_{pot}) (Hasenauer et al. 2005). The potential height increment (ihpot) is reduced by crown ratio (CR) and competition index (CIU) (Hasenauer and Monserud 1996). The potential diameter (id_{pot}) is calculated from the relationship between DBH and height in open-growth trees and the potential height (ih_{pot}) is calculated from the height increment based on site index curves (Hasenauer et al. 2005).
The aim of this thesis is to validate the application of the MOSES model for the Sitka spruce. In addition to validation, the study also aims to give a practical connection for the application of dynamic tree-growth models in forest management. Therefore, plots were made in selected forests of the portfolio forests of the Czernin-Kinsky Scottish Ltd. Company. The Validation was carried out through the comparison of predicted and observed increment parameters.
The validation was done with the potential diameter increment. Generally, validation shows a slight underestimation of increment, especially for young stands. Because of very small deviations between observed and predicted data, it is not possible to identify significant errors in the model or mensuration. After validation, different management scenarios were generated to test common and new silvicultural arrangements for *P. sitchensis*. An important outcome was the virtual testing of new forest treatment strategies for practical use. On the one hand, data from simulations were used to test MOSES under changing conditions. On the other hand, data were used to compare different thinning and planting scenarios in practice.
In all, the first validation and simulation provide very good values for the considered stands. To evaluate the validation and simulations for other areas of Great Britain, more research with a refereed stands concept is necessary.

6.2 German Version

MOSES (MOdelling Stand rESponse) ist ein Einzelbaumwachstumsmodell, das ursprünglich für die Verwendung in mitteleuropäischen Wäldern konzipiert wurde (Hasenauer, 1994). Grundlage von MOSES bildet das potentielle Wachstumskonzept. Aus dem potentiellen Höhen- und Durchmesserwachstum einer Wachstumsperiode ergeben sich die beiden Hauptkomponenten Durchmesser- und Höhenzuwachs. Basis der Berechnung bildet die Site Index Kurve des jeweiligen Bestandes. Durch Bestimmen eines relativen Alters und Addition der Wachstumsperiode zu diesem wird der potentielle Höhenzuwachs errechnet (Hasenauer et al. 2005). Mit Hilfe von Einzelbaum- und Konkurrenzmodellen kann aus diesem der Durchmesserzuwachs ermittelt werden (Hasenauer and Monserud 1996). Entscheidend dabei ist, dass MOSES auf Basis allgemeiner Wachstumsformeln arbeitet, welche eine Adaption des Simulators für nahezu jede Baumart ermöglicht. Aus diesem Grund wurde im Rahmen des Tyfiant Coed Projektes der Universität Wales, Bangor und Forst Research 2006 von Jonathan Dash eine erste Parametrisierung von MOSES für *P. sitchensis* in Wales (Schottland) durchgeführt.

Ziel der vorliegenden Masterarbeit ist es eine erste Validierung von MOSES für *P. sitchensis* zu realisieren. Im Rahmen der Validierung wurden auch Szenarien mit verschiedenen Management-Konzepten simuliert. Grundlage der Validierung bildeten Bestandeserhebungen, welche in den Wäldern der Czernin-Kinsky Scotish Ltd. Company im November 2016 durchgeführt wurden. Mit Hilfe des Programms EXCEL wurden die erhobenen Daten aufbereitet und in das MOSES Framework eingespielt. Basis der Validierung war der einzelbaumweise Vergleich gemessener Durchmesserzuwächse mit errechneten Zuwächsen für eine Simulationsdauer von fünf Jahren. Die statistische Auswertung der Differenzen weist auf eine sehr gute Validität des Models, trotz geringer Unterschätzung des errechneten Zuwachses, hin. Aufgrund der teils marginalen Abweichungen ist es jedoch schwierig, die Differenzen eindeutig als Fehler des Models oder als Messungenauigkeiten bei den Zuwachsbohrungen zu identifizieren. Anzuführen ist auch die gute Performance des Models, die bei den Simulationen verschiedener waldbaulicher Behandlungskonzepte erzielt werden konnte. Einerseits lieferten die Simulationen Werte für die Überprüfung des Models bei veränderten Wachstumsbedingungen, andererseits konnten wertvolle Daten für praktische Behandlungskonzepte gewonnen werden.

Als Resümee kann festgehalten werden, dass MOSES für die Bestände, die im Zuge dieser Arbeit erfasst wurden, sehr exakte Werte liefert und sich somit als ein wertvolles Tool für waldbauliche Behandlungen erweist. Für eine allgemeine Feststellung der Gültigkeit der Validierung und Simulationen sollten jedoch weitere Untersuchungen in Verbindung mit Langzeitversuchen vollzogen werden.

7 References

Arcangeli, C. 2012. Estimated parameters for PP.sitchensis in UK for the Moses Tree Growth Model. *unpublished, personal communication with Thurnher C*. (25.07.2016).

Bernhardt, T. 2000. Canadian Biodiversity Web Site. From Canadianbiodiversity: http://canadianbiodiversity.mcgill.ca/english/species/plants/plantpages/pic_sit.htm. Retrieved Juni 23, 2016.

Burkhart, H. E. 2012. Comparison of maximum size-density relationships based on alternate stand attributes for predicting tree number and stand growth. Forest Ecology and Management 289: 404-408.

Clark, T. 2016. CKSC Thinning scheme. *unpublished, personal communication* (08.06.2016).

Comeau, P. G., White, M., Kerr, G., and Hale, S. E. 2010. Maximum density-size relationships for Sitka spruce and coastal Douglas-fir in Britain and Canada. Forestry 83 (5): 461-468.

Dash, J. 2006. An Assessment of the suitability of the Austrian tree growth model MOSES for application to Sitka spruce (Picea sitchensis) in Wales. School of Agricultural and Forest Sciences, University of Bangor. Bangor. 92 pp.

Forest Research. 2016. Forestry Commission. From Forest Research: http://www.forestry.gov.uk/fr/infd-8cyjlu. Retrieved Juni 25, 2016.

Forestry Commission. 1981. Yield Models for Forest Management. Baxter Ltd. Edinburgh. 120 pp.

Griffith, R. S. 1992. Picea sitchensis. From Fire Effects Information Systeme (FEIS): http://www.fs.fed.us/database/feis/plants/tree/picsit/all.html#BOTANICAL%20AND%20ECOLOGICAL%20CHARACTERISTICS. Retrieved Juni 22, 2016.

Hamilton, D., and Edwards, B. 1976. Modelling the probability of individual tree mortality. Forest Service - U.S. Department of Agriculture. Utha. 32 pp.

Hamilton, G. J. 1981. The effect of high intensity thinning on yield. Forestry 54: 1-15.

Hamilton, G. J., and Christie, J. M. 1971. Forest Commission Booklet Vol. 34: Forest Management Tables (Metric). HMSO. London. 212 pp.

Hasenauer, H. 1994. Ein Einzelbaumwachstumssimulator für ungleichaltrige Fichten-Kiefern- und Buchen-Fichtenmischbestände. Forstliche Schriftreihe der Universität für Bodenkultur 8. 162 pp.

Hasenauer, H. 2007. Dimensional relationship of open-grown trees in Austria. Ecology and Management 96: 197-206.

Hasenauer, H., and Monserud, R. 1991. A crown ratio model for Austrian forests. Forest Ecology and Management 84: 49-60.

Hasenauer, H., Kindermann, G. E., and Steinmetz, P. 2005. The Tree Growth Model MOSES 3.0. In: Hasenauer, H. (ed) Sustainable Forest Management - Growth Models for Europe. Springer. Berlin. 398 pp.

ISO, 2015. ISO 9000:2015 - Quality management systems: Fundamentals and vocabulary. From International Organization for Standardization: https://www.iso.org/obp/ui/#iso:std:iso:9000:ed-4:v1:en. Retrieved Mai 29, 2016.

Kahn, M., and Pretzsch, H. 1997. Das Wuchsmodell SILVA - Parametrisierung der Version 2.1 für Rein- und Mischbestände auf Fichte und Buche. Allgemeine Forst- und Jagdzeitung 168: 115-123.

Kern, (n.d). Tree height function. In: Manual MosesFramework. Department für Wald- und Bodenwissenschaften - Universität für Bodenkultur. Vienna. 119 pp.

Kilpatrick, J. M., Sanderson, J. M., and Savill, P. S. 1981. The influence of five early respacing treatments on the growth of Sitka spruce. Forestry 54: 17-19.

Kleijnen, J. P. 1995. Verification and validation of simulated models. European Journal of Operational Research 82: 145-162.

Klopf, M. 2016. Used dataset for estimated parameters for PP.sitchensis in UK for the Moses Tree Growth Model. *unbublished, personal communication*. (2016, July 29)

Klopf, M., Thurnher, C., and Hasenauer, H. 2013. Manual MosesFramework. Department of Forest- and Soil Sciences - University of Life Sciences. Vienna. 119 pp.

Law, A. M., and Kelton, W. D. 1991. Simulation, Modelling and Analyses. MCGraw-Hill. New York. 299 pp.

Loisel, P., and Dhote, J. F. 2011. Real World Applications: A tree-growth model to optimize silviculture. Nonlinear Analyses 12: 2784-2793.

MacDonald, E., and Hubert, J. 2002. A review of the effects of silviculture on timber quality of Sitka spruce. Forestry 75 (2): 107-138.

Matthews, R., and Mackie, E. 2006. Forest Mensuration - A handbook for practitioners. Forestry Commission. Edinburgh. 330 pp.

Monserud, R. A. 1975. Methodology for simulating Wisconsin northern hardwood stand dynamics. University of Wisconsin. Madison. 156 pp.

Monserud, R. A., and Sterba, H. 1998. Modelling individual tree mortality for Austrian forest species. Forest Ecology and Management 113: 109-123.

Moore, J. 2011. Research Report: Wood properties and uses of Sitka Spruce in Britain. Forestry Commission. Edinburgh. 60 pp.

National Forest Inventory. 2015. National Forest Inventory 2014. From Forestry Commission: http://www.forestry.gov.uk/datadownload. Retrieved June 23, 2016.

National Statistics. 2015. Forestry Commission. From Forestry Statistics and Forestry Facts & Figures: http://www.forestry.gov.uk/forestry/infd-7aqdgc. Retrieved June 18, 2016.

Newton, P. F. 1997. Stand density management diagrams: Review of their development and utility in stand-level management planning. Forest Ecology and Management 98: 251-265.

Peng, C. 2000. Growth and yield models for uneven-aged stands: past, present and future. Forest Ecology and Management 132: 259-279.

Petterson, H. 1955. Die Massenproduktion des Nadelwaldes. Mitteilung der forstlichen Versuchsanstalt Schwedens 45 (1B): 1-189.

Pollanschuetz, J. 1974. Formzahlfunktionen der Hauptbaumarten Österreichs. Allgemeine Forstzeitung 85 (12): 341-343

Pötzelsberger, E. 2015. Management of dynamic forest functions based on carbon, nitrogen and water cycles (Diss.). University of Life Sciences. Vienna. 92 pp.

Quang, C. V. 2014. Linking individual-tree and whole-stand models for forest growth and yield prediction. From Forest Ecosystems: http://www.forestecosyst.com/content/1/1/18: Retrieved Juni 19, 2016.

Reineke, L. H. 1993. Perfecting a Stand density index for even-aged forests. Journal Agric Research 46: 627-638.

Reynolds, M. 1984. Error in Model Predictions. Forest Science 30: 454-469.

Rozinat, A., Mans, R. A., Song, M., and Van der Aalst, W. M. 2008. Discovering simulation models. Information Systems 34: 305-327.

Savill, P. S. 1991. The Silviculture of Trees used in British Forestry. CAB International. Wallingford. 160 pp.

Savill, P. S., and Sandels, A. J. 1983. The influence of spacing on the wood density of Sitka spruce. Forestry 56: 109-120.

Savill, P., Evans, J., Auclair, D., and Falck, J. 1997. Plantation Silviculture in Europe. Oxford University Press. New York. 312 pp.

Spyroglou, G. 2004. A growth model for Quercus frainetto (Ten) in Greece (Diss.). University of Life Siences. Vienna. 122 pp.

Sterba, H. 1976. Ertragstafeln der ÖBF 1976. Universität für Bodenkultur. Wien. 179 pp.

Stroede, P. 2003. Analyse des wirtschaftlichen Potentials forstwirtschaftlicher Produktionsverfahren innerhalb einer interdisziplinären Landnutzungsprognose. Cuvilier Verlag Goettigen. Gießen. 191 pp.

Thompsona, D., Lallyb, M., and Alistair, PP. 2005. Washington, Oregon or Queen Charlotte Islands? Which is the best provenance of Sitka spruce (Picea sitchensis) for Ireland? Irish Forestry 62: 19-32.

Vanclay, J. K. 1994. Modelling Forest Growth and Yield: Applications to Mixed Tropical Forests. CAB International. Wallingford UK. 330 pp.

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11 Appendix

Appendix 1: Estimated parameters for *P. sitchensis* – Part 1

The following tables give an overview of the estimated parameters for *P. sitchensis*. Parameters were estimated from the work of ARCANGELI (2012) from Forest Research UK. Basic datasets were presented by the stands of the Forest Research UK (Klopf 2016).

Diameter Increment Model

Formula:

$$i_i = ipot_i * c_0 * cr_i^{c_1} * \left[1 - e^{\frac{c_2}{CICUT_i*(1+c_3*(CI_i-CICUT_i))}}\right] * c_4$$

Table 13: Estimated coefficients for the diameter increment model given by Arcangeli (2012)

Parameters	Estimate	Std. Error	t value	Pr(>│t│)
c0	2.370e-01	8.219e-04	288.41	<2e-16***
c1	2.738e-01	5.727e-03	65.26	<2e-16***
c2	-2335e+02	2.476e+00	-94.30	<2e-16***
c3	-1.302e-03	1.189e-04	-10.94	<2e-16***
c4	2.332e+00	3.211e-02	72.64	<2e-16***

Significant codes: 0 *** ; 0.001 ** ; 0.01 * ; 0.05 . ; 0.1

Residual standard error: 0.0603 on 118560 degrees of freedom

Height Increment Model

Formula:

$$i_i = ipot_i * cr_i^{c_0} * \left[1 - e^{\frac{c_1}{CICUT_i*(1+c_2*(CI_i-CICUT_i))}}\right]$$

Table 14: Estimated coefficients for the height increment model given by Arcangeli (2012)

Parameters	Estimate	Std. Error	t value	Pr(>│t│)
c0	7.484e-01	1.142e-02	65.529	<2e-16***
c1	-3.083e+02	2.004e+01	-15.383	<2e-16***
c2	3.127e-03	2.378e-03	1.315	0.189

Significant codes: 0 *** ; 0.001 ** ; 0.01 * ; 0.05 . ; 0.1

Residual standard error: 0.2583 on 5250 degrees of freedom

Number of iterations to convergence: 5

Achieved convergence tolerance: 6.61e-06

Appendix 2: Estimated parameters for *P. sitchensis* – Part 2

Top Height Function

Formula:

$$Top\ Height = a * (1 - e^{-b*t})^{\frac{1}{1-c}}$$

Table 15: Estimated coefficients for the top height function given by Arcangeli (2012)

Parameter	a0	a1	a2	b0	b1	b2	m0	m1	m2
Value	13.3	2.63	-0.040	0.039	-0.00136	0.0000302	0.905	-0.0441	0.000811

Crown Model

Formula:

$$\mathrm{CR} = \frac{1}{1 + \mathrm{e}^{-(a_0 + \mathrm{bSIZE} + \mathrm{cCOMP})}}$$

Where:

$$bSIZE = b_1 * \frac{h}{d} + b_2 * h + b_3 * d^2$$

$$cCOMP = c_1 * BAL + c_2 * \ln(CCF)$$

Table 16: Estimated coefficients for the crown model given by Arcangeli (2012)

Parameters	Estimate	Std. Error	t value	Pr(>│t│)
c0	5.0908905	0.1471612	34.59	<2e-16***
b1	-0.0074145	0.0005773	-12.84	<2e-16***
b2	-0.0497847	0.0013156	-37.84	<2e-16***
c1	-0.0131281	0.0006521	-20.13	<2e-16***
c2	-0.5673036	0.0254504	-22.29	<2e-16***

Significant codes: 0 *** ; 0.001 ** ; 0.01 * ; 0.05 . ; 0.1

Residual standard error: 0.1184 on 5197 degrees of freedom

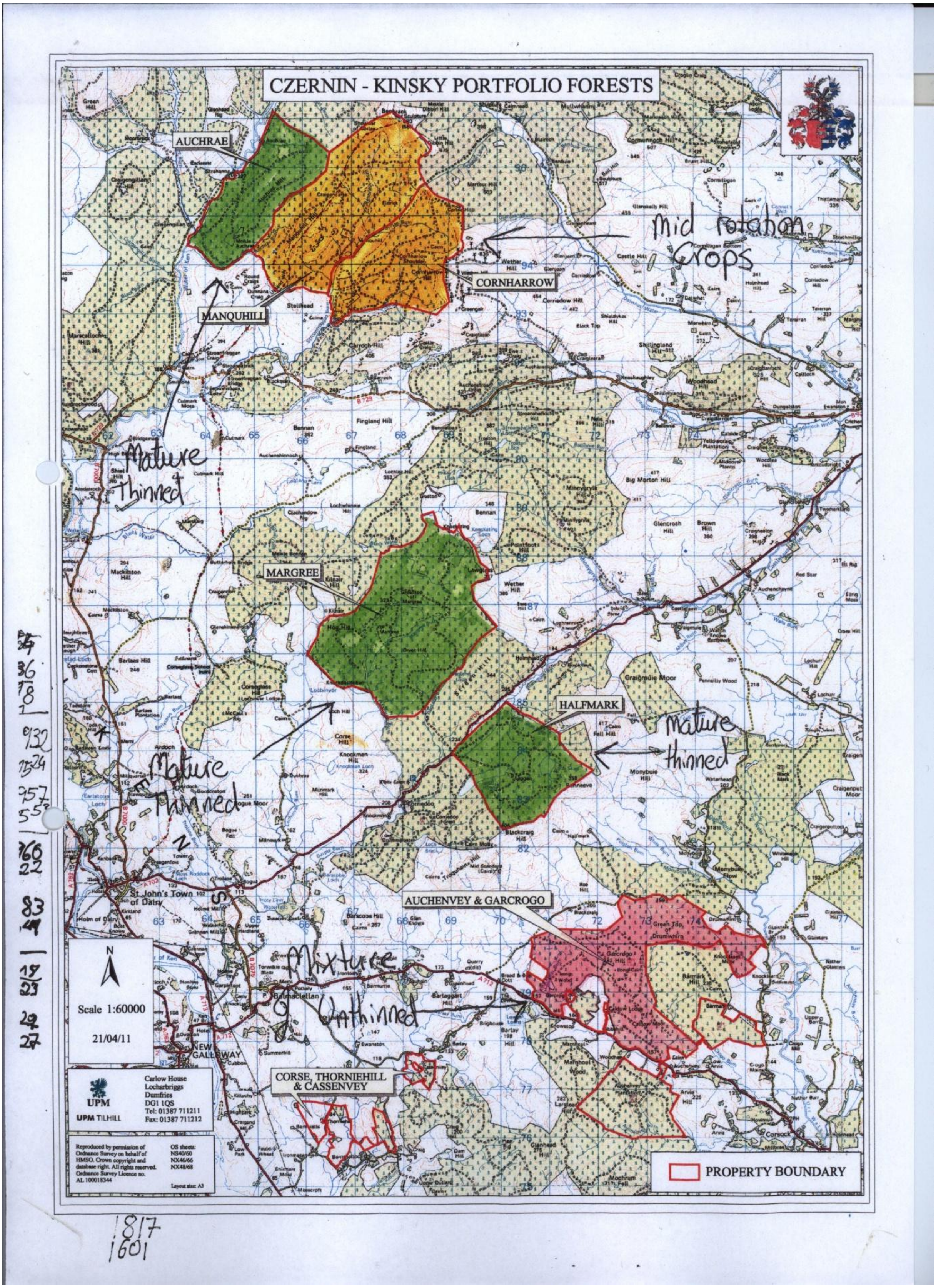
Parameter b3 is not significant

Open-grown tree relationships

Table 17: Formula and parameters fitted for diameter height and crown width height relationships given by Arcangeli (2012)

$D_{1.3} = a_0 * H \wedge a_1$		$C_w = a_0 * D_{1.3} \wedge a_1$		$C_w = a_0 * H \wedge a_1$	
a0	a1	a0	a1	a0	a1
2.11	1.17	0.71	0.67	1.04	0.82

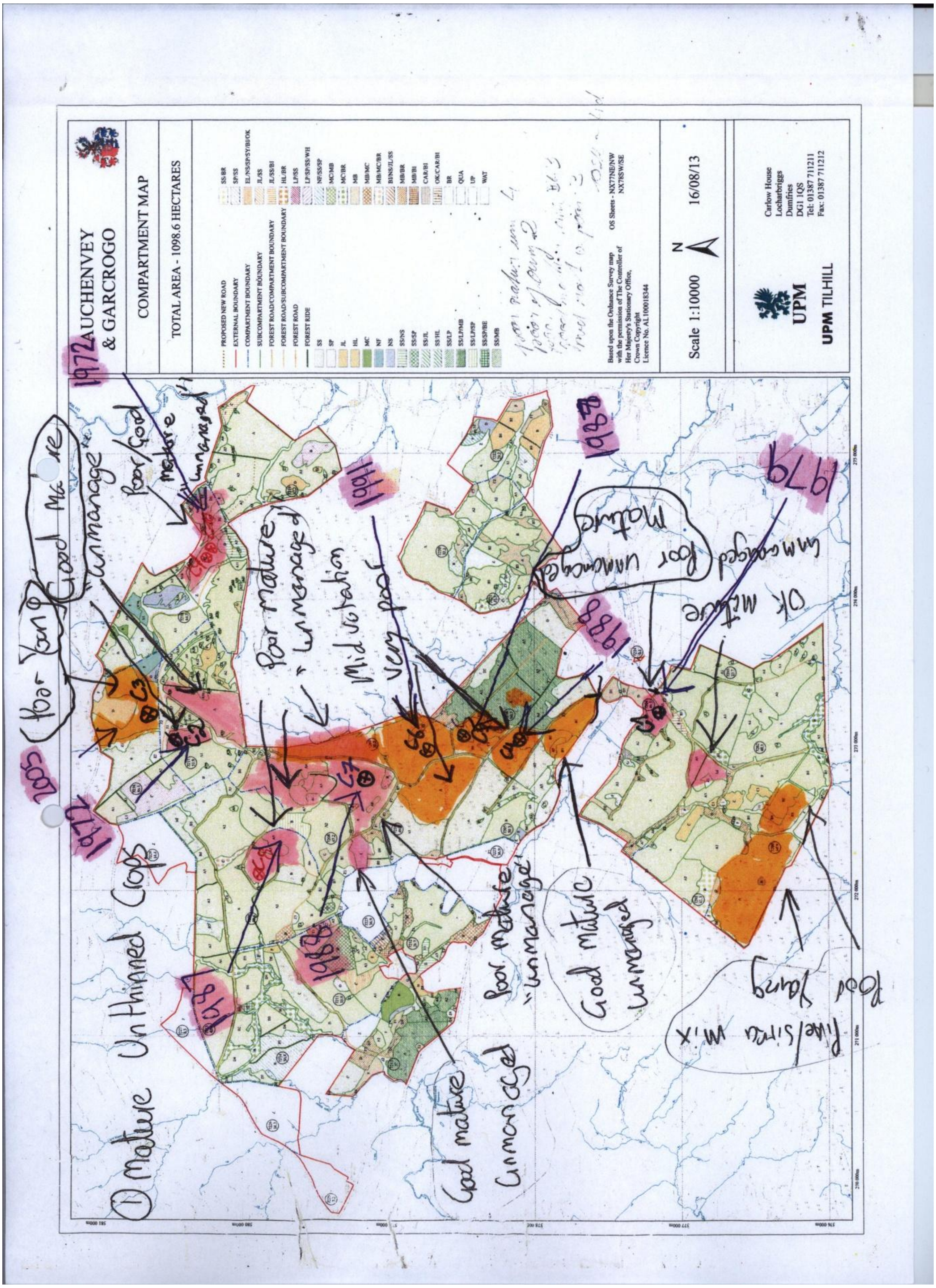
Appendix 3: Czernin-Kinsky Portfolio Forests



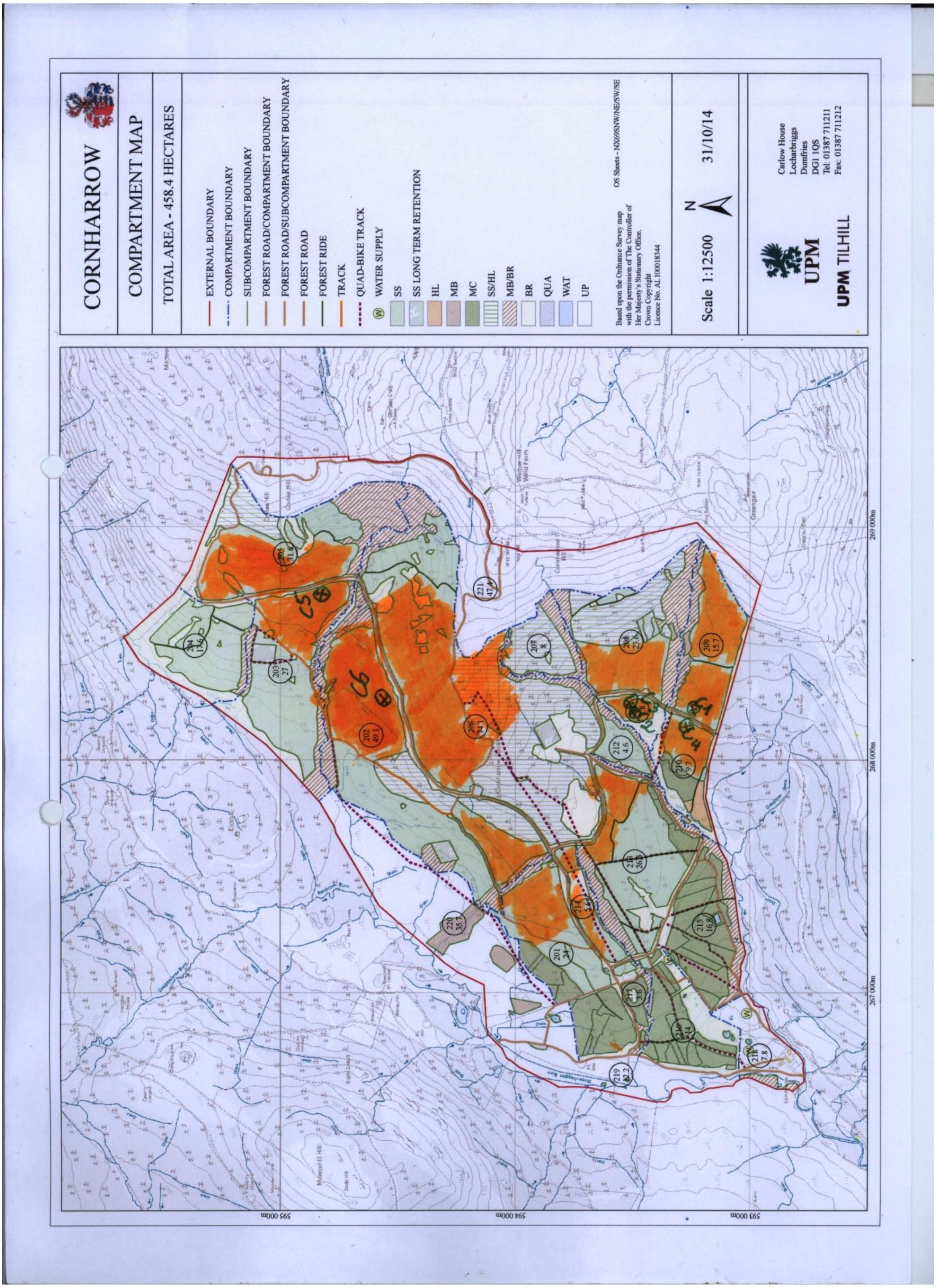
Appendix 4: Margree Forest District

Appendix 5: Auchrae Forest District

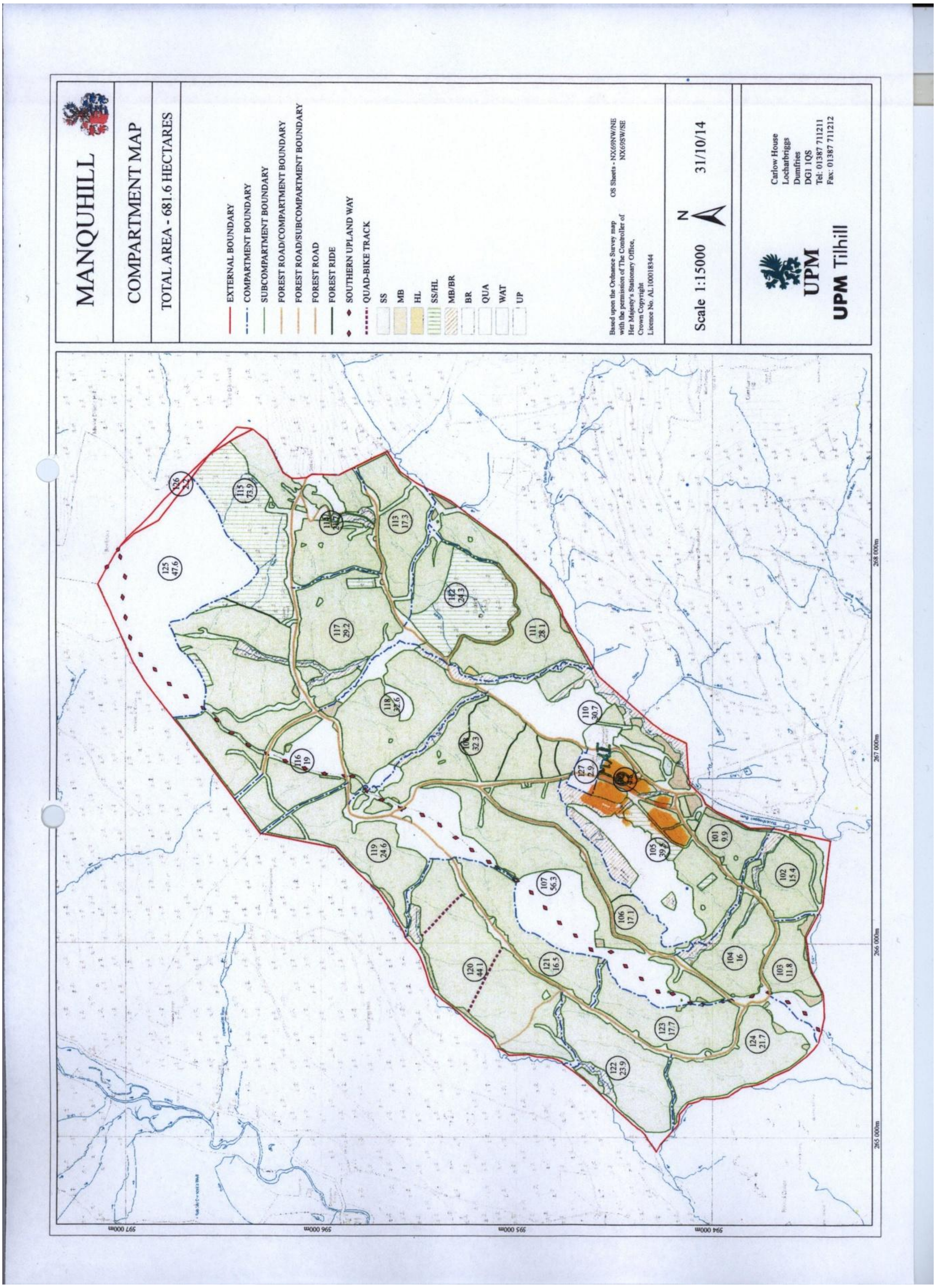
Appendix 6: Garcrogo Forest District



Appendix 7: Cornharrow Forest District



Appendix 8: Manquhill Forest District



Appendix 9: Admission form

Plot Data

Stand Data

Stand:		Plot Nr.:		Age:		Stand Qual.:	
H.a.S		Exp.:		Management.:		Radius:	

Tree Data

Tr. Nr.:	DBH	NA	Dis.	Height	SoC	Incr. 5y	Incr. 10y
	[cm]	*[°]*	*[m]*	*[m]*	*[m]*	*[cm]*	*[cm]*
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
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Appendix 10: Overview of Plots

Young Forests unmanaged

Group	Class	Plot Nr.:	Age	managed	Exp.:	Rad. [m]	Top H.	Yield Class	SI [m]	T.i.P	N/ha
1	34	A6	12	no	NW	6	11,59	34,62	36,58	30	2653
	34	A7	10	no	SE	6	7,15	33,21	36,13	27	2387
	34	M4	11	no	SW	6	8,48	33,66	36,29	29	2564
	34	M5	11	no	S	6	9,57	34,01	36,4	31	2741
2	28	C3	12	no	flat	6	7,87	28,58	34,08	30	2653
3	24	A5	12	no	W	6	4,93	24,54	31,76	30	2653
	24	A9	11	no	WSW	6	6,17	23,54	31,13	24	2122
4	20	M6	11	no	S	6	5,51	20,84	29,3	33	2918
5	18	A8	10	no	SE	6	4,1	17,94	27,13	23	2034

Mid-Rot. Forests

Group	Class	Plot Nr.:	Age	managed	Exp.:	Rad. [m]	Top H.	Yield Class	SI [m]	T.i.P	N/ha
1	37	CO3	21	no	NW	6	17,98	36,28	36,98	23	2034
	37	CO6	21	no	NNW	6	16,95	36,03	36,93	20	1768
	37	MA1	25	no	E	6	20,83	36,91	37,09	22	1945
2	32	CO5	21	no	W	6	16,01	32,29	35,79	35	3095
3	25	CO4	21	no	N	6	14,03	24,95	32,01	30	2653
4	22	CO2	21	no	N	6	12,81	21,85	30	29	2564
5	18	C6	27	no	flat	6	14,78	17,93	27,12	33	2918
5	18	CO1	21	no	N	6	11,13	18,22	27,35	28	2476

Mature Forests managed

Group	Class	Plot Nr.:	Age	managed	Exp.:	Rad. [m]	Top H.	Yield Class	SI [m]	T.i.P	N/ha
1	26	A3	46	yes	NW	10	30,64	26,03	32,66	18	573
	26	M12	43	yes	SW	10	28,98	25,96	32,62	30	955
2	21	A4	46	yes	NW	10	27,57	21,1	29,49	35	1114
	21	M7	43	yes	W	10	26,29	21,49	29,76	36	1146
	21	M8	44	yes	NNW	10	26,67	21,27	29,61	35	1114
3	21	M11	44	yes	SW	10	26,59	21,15	29,52	28	891
4	19	M1	45	yes	flat	10	25,52	18,9	27,88	29	923
5	13	M13	43	yes	flat	10	19,34	12,77	22,47	43	1369

Mature Forests unmanaged

Group	Class	Plot Nr.:	Age	managed	Exp.:	Rad. [m]	Top H.	Yield Class	SI [m]	T.i.P	N/ha
1	27	C7	30	no	E	7	21,31	26,88	33,15	37	2404
2	23	C8	31	no	flat	7	20,17	23,05	30,81	42	2728
3	20	A2	44	no	NW	7	26,42	20,9	29,34	23	1494
	20	C5	31	no	flat	6	18,57	20,15	28,81	21	1857
	20	M9	44	no	NNW	7	25,67	19,8	28,56	25	1624
4	19	C2	46	no	flat	7	26,02	18,91	27,89	23	1494
	19	C10	46	no	flat	7	26,06	18,97	27,93	25	1624
5	17	C1	39	no	NNO	7	21,31	17,34	26,65	29	1884
6	15	A1	44	no	NW	7	22,4	15,54	25,12	31	2014
	15	C4	30	no	flat	6	14,32	14,58	24,24	27	2387
	15	M10	44	no	SW	7	22,72	15,92	25,45	24	1559
7	13	C9	46	no	flat	7	20,99	12,98	22,69	22	1429
8	10	M2	44	ns	NWN	7	18,04	10,97	20,53	25	1624
	10	M3	44	no	ESE	7	17	10,04	19,44	30	1949