Fakultät Umweltwissenschaften

Understanding the dynamics of even-aged stands of Brutia pine (*Pinus brutia* Ten.) in the coastal region of Syria based on a distance-independent individual-tree growth model

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“Understanding the dynamics of even-aged stands of Brutia pine (*Pinus brutia* Ten.) in the coastal region of Syria based on a distance-independent individual-tree growth model”

Tharandt, 07.02.2020

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Declaration

I hereby certify that this thesis entitled **"Understanding the dynamics of even-aged stands of Brutia pine (*Pinus brutia* Ten.) in the coastal region of Syria based on a distance-independent individual-tree growth model"** is my own work and it has not been submitted anywhere else for the award of any other academic degree. All information sources that have been used are clearly acknowledged in the text.

Tharandt 07 02 2020

Tammam Suliman

“The aim of science is not to open the door to infinite wisdom, but to set a limit to infinite error. ”

Bertolt Brecht

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ABBREVIATIONS

Tree level acronyms and abbreviations	
ba	Tree basal area(m^2)
BAL	Basal area of trees larger than the subject tree (m^2 /ha)
CD	Crown diameter (m)
CR	Crown ratio
cl	Crown length(m)
dist	Distance from the center of plot to target tree (m)
distij	Horizontal distance from the ith neighbor tree to the cored tree(m)
θ	Azimuth of the tree
$d_{1.3}$	Tree diameter at breast height (cm)
$d_{1.3}$ (t)	Tree diameter at breast height in current inventory(cm)
$d_{1.3}$ (t-p)	Tree diameter at breast height in previous inventory(cm)
$f_{1.3}$	Form factor at breast height
j	Competitor
i	Subject tree
h	The tree height (m)
I$d_{1.3}$	Periodic mean annual tree diameter increment (cm)
h (t)	Tree height in current inventory (m)
h (t-p)	Tree height in previous inventory (m)
Ih	Periodic mean annual tree height increment (m)
Pi	The probability of tree mortality
RS	Relative spacing index of plot(m)
vi	Tree stem volume(m^3)
Stand level acronyms and abbreviations	
A	Plot size(m^2)
age	Stand age (years)
ASP	Aspect (degrees)
BA	Stand Basal area (m^2 / ha)
CAI	Current annual increment ($m^3.ha^{-1}$ $year^{-1}$)
CCF	Crown competition factor
CF	Conversion factor
Dq	Stand mean diameter (cm)
Dq_{dead}	Quadratic mean diameter of dead trees in each stand(cm)
depth	soil depth in stand (cm)
D_{100}	Stand top diameter (cm)
ELEV	The elevation above sea level (m)
GY	Gross yield ($m^3.ha^{-1}$)
G_{100}	Top basal area per hectare ($m^2.ha^{-1}$)
H	Mean stand height (m)
H_{dead}	Mean height of dead trees in each stand(m)
H_{100}	Stand top height (m)
H_{100} (t_1)	Dominant height at age t_1 (m)
H_{100} (t_2)	Dominant height at age t_2(m)
IH_{pot}	Potential stand top height increment (m)
MAI	Mean annual volume increment ($m^3.ha^{-1}$ $year^{-1}$)
n	Number of trees per plot
n_{100}	Top trees per hectare
N	The number of trees per hectare
N_{dead}	The number of dead trees dead per hectare
OGV	Other geo-climatic variation
P	The period between inventories in years
SI	Site index (m)
SDI	Stand density index
Sl	Slope (%)
V	Stand Volume in current inventory (m^3. ha^{-1})

V_{dead}	Stand volume of dead trees in each stand(m^3 ha^{-1})
V (t)	Volume of the growing stand in current inventory(m^3 ha^{-1})
$V_{(t-p)}$	Volume of the growing stand in previous inventory(m^3 ha^{-1})
Statistical acronyms and abbreviations	
β	Intercept,
$\bar{e}$	Model Bias
e	Euler's number
k	Number of variables in the equation
L	Value of the maximum likelihood function
L_0	Value of the maximum likelihood equation of logistic regression model with no predictors
L_M	Value of the maximum likelihood equation of analyzed model with specified coefficients
ln	natural logarithm
m_x	Model Accuracy
q	Number of observations
RE	Relative error coefficient
RMSE	Root mean square error
ROC	Receiver-Operating-Characteristic
R^2_{adj}	Adjusted R-squared
R^2_{McF}	McFadden's coefficients of determination
R^2_N	Nagelkerkle's coefficients of determination
R^2	R-squared
S_e	Model Precision
Sig	Significance
Std Err	Standard error
VIF	Variance Inflation Factor
X	Independent variables
X_1 to X_n	the independent variables
X_i	Continuous random variable
X^2	Value of Pearson's chi square statistics
$\hat{Y}$	Fitted value
Y_i	Observed value
$\bar{Y}$	Average value of observations
π	Mathematical constant (Pi)

SUMMARY

Introduction and objectives: The correct assessment of resources is a key condition for ensuring the sustainable supply of forest resources. In Syria, sustainable forest management is limited, because there is practically not enough knowledge on how to determine an annual growth, how future developments can be predicted, how the site productivity and the optimal rotation age can be accurately estimated, or which thinning regime is best suitable.

To cover these gaps and to answer the questions, objective of the work is to develop an individual-tree growth model based on real-time series.

Methodology and results: The study analyzed existing inventory data that came from 61 plots (51 for modeling and 10 for validation). The data used to develop the individual tree growth model could be categorized into four groups:

Measured and calculated individual trees, variables describing the growth, measured plot variables, calculated stand variables.e.g. Stand basal area, stand volume, mean stand height….

Plot-wise equations for tree height, crown diameter and crown length were used to model the missing data values.

The also analyzed the factors affecting the individual tree growth: competition and the site index.

The study analyzed the competition using a set of distance-dependent and independent competition indices. The results found it that distance-independent and dependent competition indices have a consistent negative impact on tree basal area increment. On another hand, competition stimulates a little the height increment before start decreasing as competition increases. The best distance-independent indices were candidate for further modeling.

Site index which is a measure of potential site productivity and it is defined in this work as stand dominant height at given age. The study tested 10 equations. Sloboda equation was confirmed as most appropriate for site index characterization of *Pinus brutia* stands in Syria.

Then, the study tested the statistical models for describing the important life processes of single trees which consists of growth and mortality equations.

Growth equations included diameter increment, height increment, crown ratio and generalized height-diameter equation.

The study developed diameter increment equation as function of tree size, site characteristics (site index and geo-climatic variation OGV), and competition variables. The equation showed good performance for explaining the variations in diameter increment, where the coefficient of determination (R2) was 0.58. One supplementary equation for diameter increment equation was fitted without geo-climatic variation (OGV) and showed similar performance.

The study developed two individual tree height increment equations: linearized height increment in similar way to that developed to diameter increment, and the second equation is Modifier-Potential height increment by achieving Nagel's equation (1999). Modifier-Potential height increment is more desirable to be applied in pure even stands of *Pinus brutia* forests because it gave better results than linearized height increment, and requires less information.
The study also developed the crown ratio equation using tree size, competition, and site variables. The exponential equation performed best.
Concerning the height-diameter relationship, the study tested 4 equations. The equation proposed by Mirkovich (1958) provides more satisfactory results as compared to the other tested equations.
Finally, the study developed the mortality equation as function of stand variables, competition and site variables and could be applied deterministically or stochastically.
The study implemented the forest simulation PINUS-SYRIA in NETLOGO. The simulation model allowed us to simulate the behavior of the individual-tree growth mortality dynamics under different conditions (site characteristics and competition) which allowed deep understanding of dynamic of *Pinus brutia* stands in Syria, and it showed that stochastic and deterministic simulations of mortality equation yield different results for the same single-tree model and the same initial conditions. The model applied forest management scenarios to suggest the optimal rotation age and most appropriate thinning regime. Thinning improved the growth rates for diameter at breast height, tree height and tree volume, the improvement on diameter increment is clearer than on height increment, and optimal rotation age was determined upon site index and density. Finally, the study tested the individual-tree growth model by using independent data and applying the global sensitivity analysis.
Conclusions: The PINUS-Syria Model can be applied effectively in several aspects of forest management. Firstly, it can be used for sustainable forest management as determining the rotation length in the absence of thinning and simulating the effect of different scenarios of thinning regimes on the stand development.
Based on the simulation results, this study suggests one thinning scenarios with heavy intensity in good and very good sites, and one or two thinning with moderate, heavy or very heavy thinning in medium and poor sites depending on the density.

ZUSAMMENFASSUNG

Einleitung und Ziele: Die korrekte Bewertung von Ressourcen ist eine wichtige Voraussetzung für die die nachhaltige Nutzung natürlicher Ressourcen. In Syrien ist die nachhaltige Waldbewirtschaftung eingeschränkt, da praktisch nicht genügend Wissen darüber vorhanden ist, wie der jährliche Zuwachs ermittelt werden soll oder wie zukünftige Entwicklungen, wie z.B. die Produktivität des Standortes oder die optimale Umtriebszeit, prognostiziert werden können oder welche Bestandesbehandlung am besten geeignet ist.

Die vorliegende Arbeit soll einen Beitrag zur nachhaltigen Bewirtschaftung von Brutia-Kiefernbeständen leisten, indem ein auf Zeitreihen basierendes Wachstumsmodell auf Einzelbaumebene entwickelt wird.

Methodik und Ergebnisse:

Diese Dissertation kombiniert Inventurdaten von Waldmessungen, empirischer Wachstums- und Ertragsmodellierung (61 Probeflächen) sowie Computersimulationstechniken zur Realisierung der Zielstellungen.

Im ersten Schritt mussten Inventurdaten erstellt und anschließend für die Modellierung ausgewertet werden. Zu diesem Zweck besteht die Datenbank aus zwei Teilen: Modellierungs- (zur Erstellung des Einzelbaumwachstumsmodells) und Validierungsdaten (zur Bewertung des Einzelbaumwachstumsmodells).

Der zweite Schritt der Analyse der Daten bestand darin, je Untersuchungsfläche eine Gleichung für die Baumhöhe, den Kronendurchmesser und die Kronenlänge zu berechnen.

Dieser Schritt ist notwendig, um fehlende Datenwerte zu modellieren.

Der nächste Schritt bestand darin, die Faktoren zu untersuchen, die das Wachstum einzelner Bäume beeinflussen: Der Einfluss der Konkurrenz und Schätzung des potentiellen Standort-Leistungsvermögens., der durch den Standortindex dargestellt wurde.

Zur Abschätzung der Effekte von Konkurrenz um Wuchsraum auf den Grundflächen- und Höhenzuwachs von Einzelbäumen wurden distanzabhängige und distanzunabhängige Indizes analysisert.

Bei der Untersuchung des Konkurrenzeinflusses konnte festgestellt werden, dass distanzabhängige und -unabhängige Indizes mit einer Ausnahme einen konstant negativen Einfluss auf den Grundflächenzuwachs hatten. Reineke-Index, BAL-Index, CCF, BA und BAL / $d_{1.3}$ lieferten die besten Ergebnisse und waren die Kandidaten für die weitere Analyse zur Modellierung der Durchmesser-Zuwachs-Gleichung. Auf der anderen Seite hat die Konkurrenz einen ähnlichen Effekt auf den Baumhöhenzuwachs. Reineke-Index, BAL-Index, BA und BAL / $d_{1.3}$ waren auch hier die Kandidaten für die Modellierung des linearisierten Höhenzuwchses.

Standortindex, der ein Maß für die potenzielle Standortproduktivität darstellt und in dieser Arbeit als standdominante Höhe in einem bestimmten Alter definiert wird. Die Studie testete 10 Gleichungen. Die Sloboda-Gleichung wurde als am besten geeignet für die Standortindexcharakterisierung von Pinus brutia-Beständen in Syrien bestätigt.

Nach der Untersuchung der Konkurrenz und der Entwicklung des Standortindexes entwickelte die Studie die Durchmesserzuwachsgleichung als Funktion der Baumhöhe, der Standortmerkmale (Standortindex und geoklimatische Variation OGV) und der Konkurrenzvariablen. Die Gleichung zeigte eine gute Eignung zur Prognose der Variationen im Durchmesserzuwachs, wobei das Bestimmtheitsmaß (R2) 0,58 betrug.

Eine ergänzende Gleichung für die Durchmesserzuwachsgleichung wurde ohne geoklimatische Variation (OGV) angepasst und zeigte eine ähnliche Eignung.

In der Studie wurden zwei Baumhöhezuwächse entwickelt: linearisierter Höhenzuwach als Funktion der Baumhöhe, der Standortmerkmale (Standortindex und geoklimatische Schwankungen) und Konkurrenzvariablen, wobei das Bestimmtheitsmaß (R^2) 0.36 betrug. Für die zweite Gleichung gilt der Modifier-Potential-Höhenzuwachs mit einem Bestimmtheitsmaß (R^2) von 0.54. Der Höhenzuwachs des Modifikatorpotentials ist für gleichaltrige Reinbestände der Brutia-Kiefer geeigneter, da er bessere Ergebnisse als der linearisierte Höhenzuwachs liefert und weniger Informationen benötigt.

Darüber hinaus wurde der Kronenanteil unter Verwendung von Baumhöhe-, Konkurrenz- und Standortvariablen berechnet, wobei diese üblicherweise für homogenere Bestände verwendet werden. Die Exponentialgleichung lieferte die besten Ergebnisse unter den getesteten Funktionen und erfüllte die Annahmen der nichtlinearen Regression.

In Bezug auf die Höhe-Durchmesser-Beziehung haben die Kandidaten der Höhen-Durchmesser-Gleichungen ein bis vier Parameter. Für alle Gleichungen wurden die Parameter ermittelt und es wurde festgestellt, dass alle Gleichungen signifikant (bei einem Signifikanzniveau von 0.05) am besten für die Daten geeignet waren.

Die von Mirkovich (1958) vorgeschlagene Gleichung liefert die besten Ergebnisse.

Die Gleichung für die Mortalität war die letzte in dieser Studie entwickelte Funktion. Die Variablen für die Baumhöhe, die Konkurrenz und Variablen auf Bestandesebene wurden getestet und anschließend bei der Erstellung der beiden Mortalitätsgleichungen ausgewählt, die mithilfe der logistischen Regressionsanalyse abgeleitet und analysiert wurden. Es wurden drei Grenzpunkte (der Abfangpunkt für Sensitivität und Spezifität, die durchschnittliche beobachtete Sterblichkeitsrate und eine Zufallszahl) verwendet.

Nach der Entwicklung der Wachstums- und Mortalitätsgleichungen wurde NETLOGO für die Simulation des entwickelten Einzelbaumwachstumsmodells verwendet.

Schlussfolgerungen: Das PINUS-Syrien-Modell kann in verschiedenen Aspekten der Waldbewirtschaftung effektiv angewendet werden. Erstens kann es für eine nachhaltige Waldbewirtschaftung verwendet werden, um die Rotationslänge ohne Ausdünnung zu bestimmen und die Auswirkungen verschiedener Szenarien von Ausdünnungsregimen auf die Standentwicklung zu simulieren. Basierend auf den Simulationsergebnissen schlägt diese Studie ein Ausdünnungsszenario mit hoher Intensität an guten und sehr guten Standorten und ein oder zwei Ausdünnungen mit mäßiger, schwerer oder sehr starker Ausdünnung an mittleren und schlechten Standorten vor, abhängig von der Dichte. Zweitens kann das PINUS-Syrien-Modell verwendet werden, um Schüler in Waldwachstum und -modellierung zu unterrichten, und es kann auch verwendet werden, um Personen zu schulen, die für Entscheidungen über die Waldbewirtschaftung verantwortlich sind.

Die Modellausgabe, die aus Diagrammen und Tabellen besteht, kann Waldverwaltern eine Vielzahl von Informationen und Visualisierungen zur Verfügung stellen, um sie bei der objektiven Planung zu unterstützen.

1 INTRODUCTION

1.1 Background

Pinus brutia Ten., commonly known as Turkish red pine, Brutia pine or Calabrian pine, is a coniferous tree species dominating the forests of the eastern coast of the Mediterranean sea which constitute one of the most important coniferous ecosystems in the Mediterranean region. These forests cover about 5,800,000 ha in Turkey, 175,000 ha in Cyprus, 196,000 ha in Greece, 55,000 ha in Syria and 17,000 ha in Lebanon (Pantelas, 1986; Schiller and Mendel, 1995; Skordilis and Thanos, 1997; Barbéro et al., 1998; Quézel, 2000; IPGRI, 2001; Dalsgaard, 2005; MFWA, 2012). Of the 145,000 ha coniferous forests in Syria (Nahal, 2012), *Pinus brutia* forests are the most important and abundant species. They are concentrated particularly in the Baer-Bassit region on the western slopes of the coastal area, in Jiser Al-Shoghour hills, small spots in Wastani Mountains, some locations on the eastern slopes of the Coastal Mountains and in the southern part of Al-Akrad Mountain (Nahal, 1977).

Pinus brutia is an ecologically flexible species. It is distributed in the humid, sub-humid and semi-arid bioclimatic zones (Nahal, 1977; Quézel, 1985). It grows on brown soils, including Serpentine, Amphibolites and Gabbro, which are derived from green rocks, Rendzina and calcareous soils. The elevation range varies from 0 up to 1,600 m above sea level (Zohary, 1973). The mean rainfall in the natural distribution area of *Pinus brutia* is between 400 mm and 2000 mm and the mean annual temperature varies between 10-12 °C and 20-25 °C. The forests are fragile, instable and suffer from frequent degradation (Palahi et al., 2008a). For many years, they have been subject of deforestation and over-exploitation (Nahal, 1977). Climate change, intensive use of wood for timber and firewood, overgrazing, as well as repeated forest fires (Central Bureau of Statistics, 2002) are the common drivers of this incessant deforestation. Nonetheless, these *Pinus brutia* forests are valued for multiple objectives in most cases. They are used for hunting, as a source of firewood and construction materials and for the collection of various non-wood forests products such as resin, honey, mushrooms, as well as the environmental importance e.g. soil protection, water regulation and providing various services (Nahal and Zahoueh, 2005). In the same manner, the increasing demand for different equations and products of forests has led to continuing pressures and changes upon forest areas. Only a forests management system, which put the sustainable use of the forest resources as a priority can put an end to this situation.

In 2007, the Syrian government issued a new law of forest policy, which considers implementing sustainable forest management policy and practices indispensable (Forest Legislation, 2007). The Ministry of Agriculture focused on the forest protection and plantation with priority of the environmental perspectives accompanied with establishing the permanent plots to estimate correct assessment of resources. This is considered one of the main points highlighted by this forest policy and law. The correct assessment of resources, e.g. current stock levels, is a key condition for ensuring the sustainable supply of forest resources. In Syria, sustainable forest management is limited, because there is practically not enough knowledge on how to determine an annual growth, how future developments can be predicted, how the site productivity and the optimal rotation age can be accurately estimated, or which thinning regime is best suitable. To date, only a few *Pinus brutia* stands are properly thinned, partly due to the lack of science-based information. Past management of forests was based on experience and simple calculations, which in turn propagated errors that resulted in serious ecological and economic damages (Nahal and Zahoueh, 2005). Therefore, in view of the economic and environmental importance of *Pinus brutia* stands in Syria, with more than 55,000 hectares planted, there is a need for a management system that enables reliable growth and yield predictions to support proper planning and management.

The work has an intent to provide a contribution to the sustainable management of *Pinus brutia* stands by developing an individual-tree growth model based on real-time series (long-term observation). Its main purpose is to simulate future forest management scenarios (Weiskittel,2011). Because they provide detailed information on manifold output variables, individual tree growth models have the ability to predict future yields and to explore silvicultural options and management options and silvicultural alternatives. For example, foresters may want to know the long-term effect on both the forest and on future harvests, forecasts of the nature and timing of future harvests, and estimates of the maximum sustainable harvest. With a growth model, they can examine the likely outcomes, both with the intended and alternative cutting limits, and can make their decision objectively (Vanclay, 1994).

1.2 Forest growth and yield models

Growth models have a major role in forest management and in shaping the forest policy, so in the following, the definition of the growth model, its purpose and its classifications will be presented. Vanclay (2003) states that a model is an abstraction or a simplification of some aspect of reality. In this sense, growth and yield models are considered a brief way to represent growth and yield relationships. Vanclay (1994) defines a forest growth and yield model as a model which draws the status of the forest at some future time. Hasenauer (1999) refers that a growth and yield model may consist of a series of mathematical equations which generally allow forest managers to predict the growth and yield of a forest stand under different conditions.

In general, researchers consider a forest growth model as an attempt to quantify the growth of a given forest. These models are commonly used for two essential purposes: (1) to estimate the future status of a forest, and (2) to choose and check the effect of alternative silviculture treatments (Weiskittel et al., 2011).

Forest growth and yield models can be classified into four main models: empirical models, physiological models, ecological models, and hybrid models.

I. Empirical models are the most commonly applied in forestry. They are normally derived by executing a set of processes such as observing, recording and generalizing how forest stands respond to different conditions e.g. soil and climatic variations, or competition (Tomé and Verwijst, 1996). Empirical models are mainly used to predict wood production and to simulate different forestry management treatments on the short and long-term. They can be divided into whole stand level and the individual-tree level. The models, which only are based on stand-level information, are called whole stand models. Pretzsch et al. (2007) divided the whole stand growth models, based on their concept and structure, into three groups: Differential equation models that predict the change of stem number, basal area and volume within a given diameter class dependent upon initial stand characteristics (Clutter and Bennett,1965; Pretzsch et al, 2007); distribution prediction models that have characterized the condition of a tree population by its diameter and height distribution and described stand development by extrapolation of these frequency distributions (Bailey, 1973; Pretzsch et al, 2007), and stochastic evolution models that assume that stand development evolves from an initial frequency distribution, e.g. from diameter distribution known from forest inventory, and predict individual stem dimensions rather than mere distributions of tree properties (Kouba, 1973; Pretzsch et al, 2007). While the models, which are based on individual-tree data and use single trees as a cornerstone to predict yield, are called single tree growth models. In forestry, single tree growth models usually include a system of equations which predict the increment, the mortality rate, crown ratio, and the ingrowths in a stand based on single tree data like tree diameter or basal area, height, and crown.

II. Process-based models (Physiological) models are photosynthesis-based. Process models predict the behavior of a system such as a forest stand based on a set of functional components and their interactions with each other and the system environment (Matala, et al., 2003). In these models emphasis is on understanding the nature of processes of growth such as light interception, photosynthesis, respiration and evapotranspiration, and modelling these processes as a function of the physical environment (Larocque, 2002). In spite of attempts to explain the the changing phenomenon, it does not accurately describe the forest tree and stand structure, and that makes it less correlated with respect to practical forestry if compared with the empirical models (Kimmins, 1988).

III. Ecological models (succession or gap) models are used to simulate the dynamics of forest ecosystems (Larocque, 2002). These models imply that the death of dominant tree results in a gap, and thus improve the growth conditions of understory trees and natural regeneration occurs. With growing trees successively, the gap will close again and a new overstorey develops. The process is repeated with further deaths of dominant trees (Evans, 2001). The gap models are a clear representation of key ecological processes in contrary to the empirical models which predict the potential growth which mainly affected by competition and site characteristics.

IV. Hybrid models are new approaches that combine both process-based and empirical models for predicting forest yield and growth (Waterworth et al., 2007).

The model, the study will achieve it (PINUS-SYRIA), must provide detailed information about each individual-tree dimensions in a stand and sum the resulting individual-tree estimates to produce stand level values, it must be usable with data available, it should be sufficiently flexible in terms of stand management, able to offer the possibility to calibrate the model with data from standard research plots, and to be flexible as possible to a broad range of coniferous species, and describe accurately the forest tree and stand structure, and test alternative silviculture treatments. From the criteria defined here and considering the models already discussed above, the suitable model approach for this study is the empirical model, in particular, the single-tree model that encompasses in this research five dynamic submodels (Figure 1-1): tree diameter, height increment, natural mortality equation, tree crown ratio, height-diameter relationship, and that will not be possible unless studying the main factors on growth which are the site productivity and competition that will be highlighted in detail in the following subsections along with evaluation and application of the model.

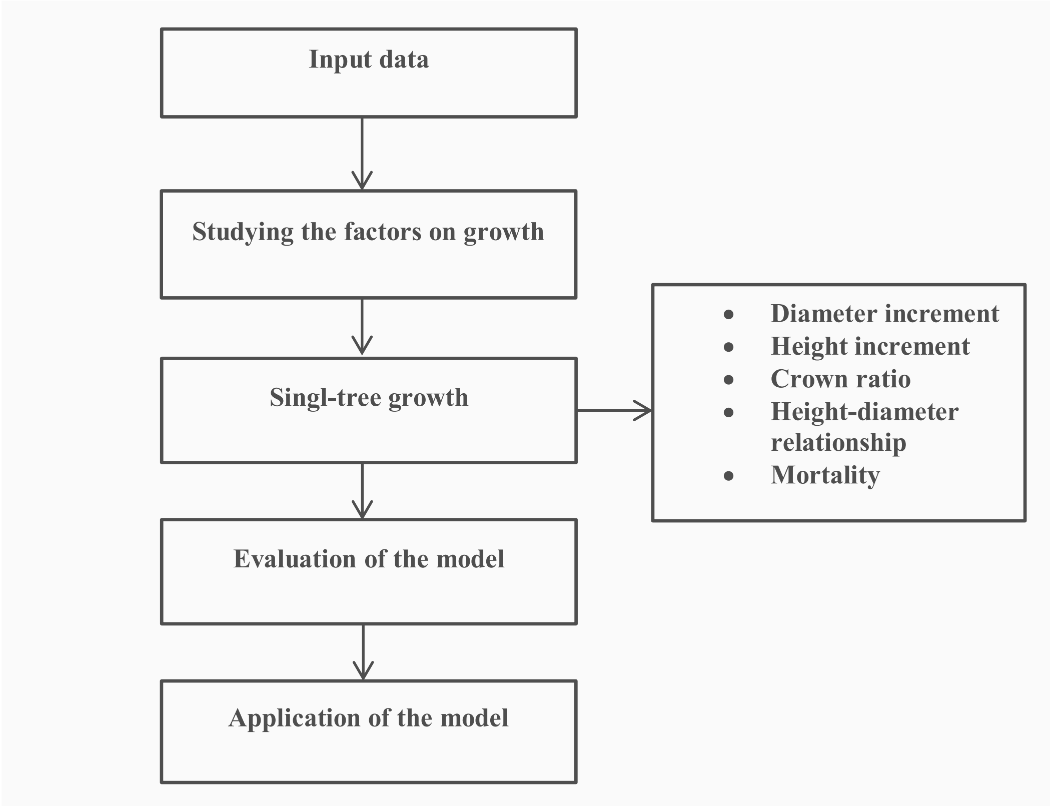


Figure 1-1: Flowchart of proposed single-tree growth model components

1.2.1 Site productivity

The classification of forest stands regarding its productivity is an important question for forest managers. This classification is also an indispensable component for the modeling growth and yield over time. It enables foresters to predict the maximum potential productivity which can be produced from particular sites under given conditions at a specified age (Vanclay, 1994). It can also be used for the process of stratifying the forest land for purposes of forest inventory (García, 1983). Different environmental conditions (rain, soil, slope, and aspect) lead to different wood productions obtainable from stands among sites.

Earlier, in the eighteenth century the site classification was based on standing volume (Pretzsch, 2009). With the change to more intensive management concepts in the nineteenth century, stand mean height is introduced as an alternative to the former indicator, because it is less dependent on stand density and thinning (Pretzsch, 2009). This concept was used to classify the productivity sites into seven classes in Al-Bayer and Al-Basit region in northern Syria (Nahal, 1982). In the mid-twentieth century with the intensification of thinning from below, which greatly influenced the mean height, the reference height measure was switched to top height (dominant height) as an indicator of site quality (Pretzsch, 2009), where top height is affected by site rather than density effects (Gadow and Hui, 1999).

Site index often represents the relationship between top height and age of upper-story trees, and is defined as the average height of a specified number of dominant trees (and co-dominant or the largest and tallest trees per unit area) at an index age. The site index became the most commonly used measure of site productivity, which is applicable only to an even-aged stand of uniform development.

Three main methods are commonly used to fit site index curves: (1) guide curve, (2) parameter prediction, and (3) differential equation methods (Clutter et al., 1983). The guide curve represents the height development for the average site index in the data. It is used to generate a set of anamorphic site productivity index curves. In all site classes, heights at all ages are normally supposed to be proportional to that of the guide curve (Burkhart and Tome, 2012), and it is usually used when only temporary plots are available. The parameter prediction method is based on fitting a growth function tree-by-tree or plot-by-plot and linking the parameters of the fitted curves with the site index. The differential equation approach can be applied to any height-age equation to produce families of anamorphic or polymorphic curves (Burkhart and Tome, 2012). This method requires permanent plots or stem analysis data.

Data used for site index modeling can be derived from three sources:

(1) Measurement of height and age on temporary plots. Site index has been developed in this case by measuring height-age pairs in stands of different site qualities and ages. This method is considered inexpensive and should represent the full range of ages and heights in the forest (Burkhart and Tome, 2012).

(2) Measurement of height and age over time on permanent plots (Garcia, 2004; Dieguez-Aranda et al., 2005). Despite this method is expensive and it requires many years, site index curves from remeasurement plots are generally preferred because it provides good dynamic data (Burkhart and Tome, 2012).

(3) The reconstruction of height/age through stem analysis. Stem analysis can be carried out by making intermodal measurements for trees that have a determinate growth pattern, or splitting the main stem along the pith so the heights at different ages can be measured directly or by taking cross-sectional cuts at given heights and rings counted to determine tree age at that height (Burkhart and Tome, 2012). This method is expensive but it is possible to be carried out immediately and offers good dynamic data (Suliman, 2013; Garcia, 2004).

1.2.2 Competition

In order to access and acquire the main resources required for growth, a tree has to compete with other individuals; this process is called the competition. Competition is "*an interaction* *between individuals, leading to a reduction in the survivorship, growth, and reproduction of the competing individuals concerned*" (Begon et al., 1996), and according to Allaby (2006) „*an interaction between individuals of the same species, or between different species populations at the same trophic level, in which the growth and survival of one or all species or individuals are affected adversely*".

There are various criteria to classify competition, which can all be divided in four different subtypes (Figure 1-1):

A) The mode of competition:

(1) Aboveground: competition for light, and

(2) Belowground: competition for water and nutrients (Mudrák et al, 2016).

B) Species competition:

(1) Inter-specific competition between trees of different tree species

(2) Intra-specific competition, between members of the same species.

C) The symmetry of competition:

(1) One-sided competition / asymmetric competition; if the division of resources between the individuals is not proportional to their size resources (Weiner, 1990).

(2) Two-sided competition / symmetric competition between two individuals; occurs when both individuals use a number of resources proportional to their size. If one plant accounts for 30% of the biomass of the population, it also uses 30% of the resources.

To further complicate the matter, there is controversy about a mix of both models of competition. Namely, there are studies that suggest that aboveground competition is dominated by asymmetry, whereas belowground competition would function more symmetrically (Weiner, 1990; Schwinning and Weiner, 1998).

D) Tree position: Competition indices could be classified as

(1) Distance-independent (non-spatial), and

(2) Distance-dependent (spatial) (Munro, 1974; Wykoff et al., 1982).

Distance-independent indices do not require individual-tree coordinates, while distance-dependent indices do. In addition, sometimes "semi-distance-independent indices" are applied (Lederman, 2010).

Many papers studied the degree of the effect of distance-dependent and distance-independent competition indices on predicting tree growth. There are three different points of view recorded in answering which approach is better to predict tree growth.

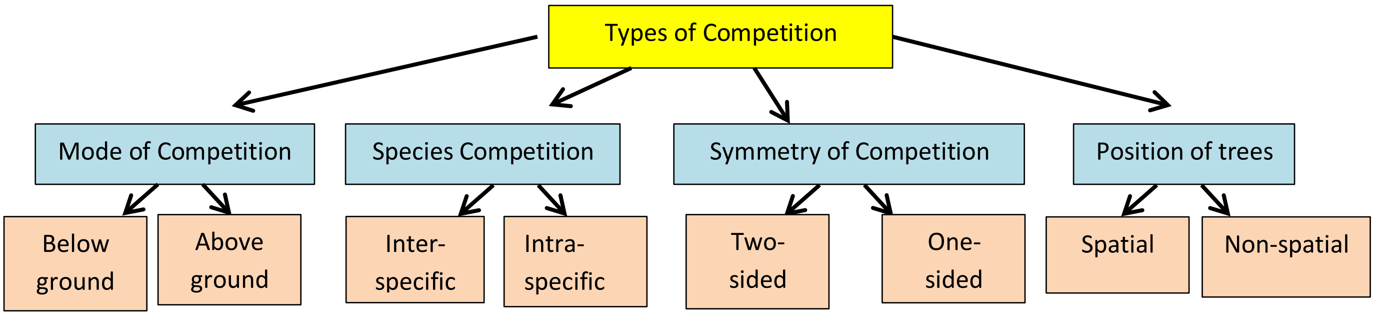


Figure 1-1: Schematic overview of different types of competition

1) The first one is that that distance-independent competition indices are superior over more advanced distance-dependent competition indices (Castagneri et al.,2008). Supporters of this viewpoint see that distance-independent indices are easy to calculate and less demanding in data and computer time (Tomé and Burkhart., 1989) and that the initial tree size alone can explain the variation (Mitsuda and Yoshida, 2007).

2) The second viewpoint is the distance-dependent competition indices improve the estimates of individual-tree growth when compared with the distance-independent indices (Cole and Lorimer, 1994; Biging and Dobbertin, 1995).

Pretzsch (2009) indicates that "if stem coordinates and stem and crown size are known, then position-dependent indices may be used for a more detailed characterization of resource availability". Distance-dependent indices would also be more reliable in mixed forests with much more diversity (Pretzsch, 2009).

3) The last viewpoint found that there is no difference between distance-dependent indices of competition and distance-independent ones (Martin and Ek,1984; Cole and Lorimer,1994; Wimberly and Bare,1996), that is noticed in particular in pure stands (Daniels et al., 1986; Biging and Dobbertin, 1995; Rivas et al.,2005). To complete the cycle of discussion about this point, some researchers attribute the superiority of distance-independent indices to distance-dependent ones to some limitation of distance-dependent indices (Weiskittel et al., 2011): 1) distance-dependent tree models are often difficult to use because they require a map of the stand, which is not only very costly but also impracticable in a routine management context (Munro, 1974; Wimberly and Bare, 1996), furthermore the distance-dependent indices generally need to apply the edge correction method, 2) Distance-dependent indices mainly generally take the one-sided competition into account and ignores below-ground competition (Larocque, 2002).

Due to the general lack of obtaining all the data needed for distance-dependent competition indices, distance-independent competition indices for modeling the individual-tree growth model will be sufficient in this study, this trend is supported by Weiskittel et al (2011), and the study will provide an analysis of distance-dependent competition indices based on the data available as a step toward broader studies in the future.

To sum it up: The part defined the competition and classified it according to 1) The mode of competition 2) Species competition 3) Symmetry of competition,4) spatial and non-spatial competition. Comparisons between distance-dependent and independent competition indices did not give an advantage to approach over another.

1.2.3 Individual-tree diameter increment

Diameter increment equations are a fundamental component of forest growth and yield frameworks since the diameter is the primary determinant of stem volume.

Single-tree growth may be modeled as basal area increment or as diameter increment. It has been discussed that it is more suitable to model basal area increment than diameter increment, as basal area increment would resemble the individual-tree volume growth more closely than diameter increment does (Hökkä and Groot, 1999). However, tree diameter increment and basal area increment are related mathematically, and if any differences in the goodness of fit have appeared, that is attributed to differences in the error structure and a developed functional relationship, rather than the superiority of one sub-model over the other (Vanclay, 1994). Empirical studies have not offered any evidence of differences in estimation precision between the diameter increment and basal area increment equations (West, 1980), and there were also no differences found between the two approaches for short-term simulations (<10 years) (Russel et al., 2011). Nevertheless, many authors have used diameter increment (e.g. Cole and Stage, 1972; Dolph, 1988; Wykoff, 1990; Dolph, 1992; Palahi et al., 2003; Calama and Montero, 2004; Trasobares and Pukkala, 2004; Zhao et al., 2004; Carus, 2004; Uzoh and Oliver, 2008; Palahi et al., 2008; Shater et al., 2011; Assaf et al., 2012), and only a few basal area increment (e.g. Opie, 1968; Mailly et al., 2003). Individual-tree diameter or basal area increment is often modeled using one of the following two approaches:

1) A potential/modifier model (maximum potential increment multiplied by a modifier).

Potential modifier is a method to determining individual-tree growth. This method assumes that the potential diameter increment is obtained usually from potential diameter-age curves of dominant trees of a given site (Pretzsch, 2009). The potential diameter increment represents the growth of a tree in the absence of competition, then the actual diameter tree growth is obtained by multiplying the potential increment by a modifier which reduces the potential growth, represents the competition state of the individual-tree. Many studies used the potential/modifier model (Wensel et al., 1987; Soares and Tome, 2002) and the potential/modifier model is adopted in most ecological gap models (Bugmann, 2001).

2) A composite model (a unified equation that predicts realized increment directly), which models tree growth directly as a function of individual-tree and stand characteristics. Many authors have used this approach (Dolph, 1988; Hann and Larsen, 1991; Monserud and Sterba, 1996; Hökkä et al., 1997; Zhao et al., 2004). The differences between the two methods are mostly semantic because they both result in a reasonable model behavior (Wykoff and Mensured, 1988). In such a composite model, the independent variables are divided into three classes of covariates: tree size, competition, and site (Wykoff, 1990). Each model uses a set of independent variables (tree and stand variables) to predict diameter increment (Table 1-1).

Table 1-1:Stand variables used in developing diameter increment equations in forestry literature

Stand Variable	
Variables	**Reference**
Stand basal area	Ritchie andHann, 1985; Dolph, 1988; Pukkala, 1989; Hann and Larsen, 1991; Cao, 2000; Andreassen and Tomter, 2003; Palahi et al., 2003; Carus , 2004
Quadratic mean diameter	Pukkala, 1989; Andreassen and Tomter, 2003
Stand density index	Uzoh and Oliver, 2008; Berrill et al., 2013
Site index	Ritchie and Hann, 1985; Wykoff, 1990; Monserud and Sterba, 1996, Pretzsch et al., 2002; Andreassen and Tomter, 2003; Palahi et al, 2003; Uzoh and Oliver, 2008; Shater et al., 2011; Carus ,2004; Assaf et al., 2012
Physiographic and topographic variables like elevation, slope, and aspect and soil depth	Wykoff, 1990; Monserud and Sterba., 1996; Shater et al., 2011; Assaf et al., 2012
Tree Variables	
Variables	**Reference**
Basal area of trees larger than the subject tree	Wykoff, 1990; Shater et al., 2011; Assaf et al., 2012
Crown dimensions	Pretzsch et al., 2002; Schröder et al., 2007
Tree basal area	Pukkala., 1989; Andreassen and Tomter, 2003
Crown ratio	Ritchie and Hann, 1985; Dolph, 1988; Wykoff, 1990; Hann and Larsen, 1991; Monserud and Sterba, 1996
Diameter at breast height and squared diameter at breast height	Monserud and Sterba, 1996; Carus,2004; Assaf et al., 2012
Natural logarithm of diameter at breast height	Wykoff, 1990; Shater et al., 2011
Reverse of diameter at breast height	Zhao et al., 2004

1.2.4 Individual-tree height increment

Besides a sub-model for diameter increment, a sub-model predicting individual-tree height increment should be included in an individual-tree growth model (Wykoff, 1986; Hester *et al*., 1989). Compared with the modeling of diameter increment, which requires the simply-to-measure diameter at breast height as input, modeling height increment is more difficult because it is not easy at all to obtain good height increment data (Hasenauer and Monserud, 1997).. There are three options to obtain height increment data for modeling purposes:

(1) Stem analysis of felled trees. Stem analysis is the common procedure in forestry by which the past growth can be determined by directly measuring the accumulated stem increments of height and diameter. This method is accurate but it has some critical shortages as trees must be felled. Therefore, it is not practical or appropriate on permanent sample plots. Moreover, it is quite time-consuming and expensive (Hasenauer and Monserud, 1997).

(2) Re-measured heights of trees. This method is equally time-consuming and difficult, especially in mountainous terrain and in dense forest stands. Height measurement may lead to large errors relative to the increment especially for relatively slow growing species found in boreal and most temperate forests (Hasenauer and Monserud, 1997). Some height increment equations used this method based on re-measured trees heights in permanent plots (Burkhart et al., 1987; Pretzsch, 1992; Hasenauer, 1994).

(3) Heuristic functions of diameter. Growth and yield modelers develop a height increment equation based on heuristic functions of diameter instead of measuring all tree heights. Representative trees are selected and both tree height and diameter at breast height ($d_{1.3}$) are obtained. Then, a height-diameter equation is developed. Heights for other trees, of which only $d_{1.3}$ measured, are predicted based on the height-diameter relationship (Curtis, 1967; Curtis et al., 1981; Wykoff et al., 1982; Nagel, 1994, 1995; Hasenauer and Monserud, 1997; Linkivicius, 2014).

Two different modeling approaches for height increment have been commonly used in literature: (1) The realized height increment approach, which is parallel approach used for predicting the diameter increment (Lemmon and Schumacher, 1962; Beck, 1974; Wykoff et al., 1982; Dolph, 1992; Hasenauer and Monserud, 1997; Uzoh, 2001; Uzoh and Oliver, 2006). An advantage of this approach is, "*that the competition is estimated correctly because it doesn't depend on possibly wrong growth potentials out of improperly selected yield tables*" (Nachtmann, 2006). The main shortage is the unsuitable mathematical methods for predicting may cause unreasonable tree height increments (Nachtmann, 2006).

(2) The potential height increment equations with modifiers is more common in literature (Hegyi, 1974; Burkhart et al., 1987; Wensel et al., 1987; Hann and Ritchie, 1988). The potential height increment obtained by the dominant tree height increment which represents the growth in the absence of competition. To estimate the potential height increment (dominant tree height increment), both age-dependent and independent approaches are used. The age-dependent approach is applicable to even-aged, homogeneous stands only (Weiskittel et al., 2011). The potential height increment is then reduced by competition indices (modifier) to get the individual-tree height increment. Clear differences were noticed in the way that researchers introduce the modifier to reduce potential tree growth to the single tree growth.

Arney (1972) employed live crown length and total height ratio as modifiers. Ritchie and Hann (1986) used the function of tree height, dominant stand height ratio and crown ratio. Wensel et al. (1987) used the tree crown ratio as modifier to adjust potential height increment. Nagel et al (2002), Schröder (2004) and Nachtmann (2006) employed the ratio between stand top height and tree height to develop the height increment model. Pretzsch et al (2002) achieved their study by using crown surface area. Nunifu (2009) used basal area of trees larger than the subject tree, total tree height, dominant tree height, stand density as variables in the modifier. The disadvantage of this approach is that a wrong potential tree height increment (dominant tree height increment is not equivalent to the tree height increment in the yield table) leads to a wrong competition impact, that is why the potential tree height increment is always reduced by competition indices, but it nevertheless gives reasonable predictions for height increment (Nachtmann, 2006). In this thesis, both approaches will be tested which may help to determine which approach is more suitable for even-aged stands.

1.2.5 Individual-tree mortality

Mortality is an essential component of models predicting growth and yield of trees, and stand development patterns. It is one of the most difficult processes to model because of a variety of factors such as environmental, physiological, pathological, and entomological factors, as well as some random events (Adame et al., 2010). For this complexity, it is considered one of the least understood processes in forest modeling (Hamilton, 1986).

Two major categories of natural mortality can be distinguished: regular and catastrophic (irregular) mortality (Lee, 1971). Regular mortality, or self-thinning, can be described as density-dependent and occurred by competition for light, water, and soil nutrients within a stand (Lee, 1971; Peet and Christensen, 1987), the probability of individual-tree mortality increases with competition (Teck and Hilt, 1990). Irregular mortality, on the other hand is independent of stand density. It occurs because of external events or hazards such as wind, snow, wildfire, landslides or pest and disease outbreaks (Vanclay, 1994), where the probability of survival is very low at the tree and stand level but not necessarily at the landscape level (Alenius et al., 2003). Generally, most growth and yield models focus only on regular mortality (Amateis et al., 1997; Monserud and Sterba, 1999; Weiskittel et al., 2011).

Forest survival following a mortality event is usually modeled at the whole stand or at the individual-tree level. Whole-stand survival models predict the future trees per unit area when an initial number of trees and corresponding age are given. They have been applied in pure and mixed stands (Bailey et al., 1985; Eid and Øyen, 2003) and appear to be more effective for early stand age (Amateis et al., 1997). Forest survival modeling at the individual-tree level is more common (Hamilton and Edwards, 1976; Buchman, 1979; Hamilton, 1986; Vanclay, 1995; Monserud and Sterba, 1999). According to Schröder et al (2007), the mortality likelihood functions modify the values of probabilities of natural tree mortality ranging from 0 to 1 into likelihood values generating mortality as observed in the field for given intervals of probability of natural tree mortality. The most common methodology for estimating individual-tree mortality is statistical. Researchers widely used weighted nonlinear regression or multivariate maximum likelihood procedure to estimate the parameters of a flexible nonlinear function which is bounded by 0 and 1. A dead tree is expressed by 1 and a live tree is expressed by 0 (Neter and Maynes, 1970). The most popular is the logistic, Weibull, Gamma, Richards's function, Exponential and the Normal (Richards, 2010).

Mortality sub-models can be applied either deterministically or stochastically, like in many statistical models, or these two methods may be combined in one model (Table 1-2). A deterministic model provides the expected growth, whereas a stochastic model attempts to illustrate the natural variability of the growth by including random components (Vanclay 1994). Some researchers found that there was no practical difference in mean stand values for a number of trees, basal area, volume, or diameter distributions (Weber et al., 1986; Vanclay, 1991).

Table 1-2: Developed individual-tree mortality based on deterministic and stochastic approaches

Deterministic	Stochastic	Combination
Staebler, 1953; Lee, 1971;	Monserud, 1976; Hamilton, 1986; Avila and Burkhart, 1992; Vanclay, 1995; Yao et al., 2001; Zhao et al., 2007	Woollons, 1998; Eid and Øyen, 2003; Zhao et al., 2007; Adame et al,2010

In relation to competition, individual-tree mortality sub-models are divided into distance independent and distance-dependent sub-models (Pukkala, 1988; Vanclay, 1994). Mortality is dependent on tree size, vigor, species, stand density, species composition, site quality, and available growing space (Peet and Christensen, 1987; Oliver and Larson, 1990). So the selection of better predictors requires more efforts, especially when building individual-tree mortality to estimate the mortality from a range of variables (Guan and Gertner, 1991). In literature the mortality usually is a function of three groups of factors (Table 1-3):

(I) Size-related variables such as diameter at breast height or tree height,

(II) Growth-related variables such as competition and measures of stand density (Monserud and Sterba, 1999; Eid and Tuhus, 2001; Bigler and Bugmann, 2003),

(III) Stand variables such as Stand basal area, Mean stand height,..etc

Table 1-3:Most commonly variables used in individual-tree moertality equation representing tree, competition and stand level variables

Tree Variables	
Variables	**Reference**
Diameter at breast height	Monserud, 1976; Hamilton and Edwards, 1976; Wykoff et al.,1982; Hamilton, 1986; Wykoff, 1986; Hann and Wang, 1990; Crow and Hicks, 1990; Vanclay, 1991; Dursky, 1997, Murphy and Graney, 1998; Monserud and Sterba, 1999; Zhao et al., 2004; Bravo-Oviedo et al., 2006; Schröder et al., 2007
Transformations of diameter at breast height	Wykoff et al., 1982; Hamilton, 1986; Monserud and Sterba, 1999; Palahi et al., 2008
Tree height	Hamilton and Edwards, 1976; Dursky, 1997; Schröder et al., 2007
Diameter increment and basal area increment	Monserud, 1976; Hamilton, 1986; Wykoff, 1986; Yao et al., 2001; Pretzsch et al., 2002; Montero et al., 2002; Schröder et al., 2007
Predicted diameter increment/ basal area increment) divided by diameter at breast height	Hamilton, 1986; Pretzsch et al., 2002
Crown ratio	Hann and Wang, 1990; Monserud and Sterba, 1999
Tree diameter at breast height and tree height ratio	Schröder et al., 2007
Competition	
Basal area of trees larger than the subject tree	Hann and Wang, 1990; Murphy and Graney, 1998; Monserud and Sterba, 1999; Montero et al., 2002; Palahi and Grau, 2003
Tree diameter and quadratic mean diameter ratio	Hamilton, 1986; Wykoff, 1986; Misir et al., 2006
Tree height and mean stand height ratio	Avila and Burkhart,1992
Ratio of the height of the subject tree and the top stand height	Palahi and Grau, 2003
Stand Variable	
Stand basal area	Zhao et al., 2004; Bravo-Oviedo et al., 2006; Misir et al., 2006; Palahi et al., 2008
Site index	Murphy and Graney, 1998; Bravo-Oviedo et al., 2006; Misir et al., 2006
Mean stand age	Jurkonis, 2004; Juknys et al., 2006
Mean stand height	Lynch et al., 1998

To conclude: There are two kinds of natural mortality: Regular and Irregular mortality, two approaches are applied statistically to model the mortality: deterministic models are applied to model mortality at stand level and stochastic models at individual-tree level. Tree and stand level variables are used in building the mortality equation representing the tree size and competition.

1.2.6 Individual-tree crown ratio

Crown ratio, which is the ratio of live crown length to the total height of the tree, is an important variable that is commonly involved in growth and yield models used as decision-support tools in forest management (Daniels and Burkhart, 1975; Monserud, 1975; Shifley, 1987; Wykoff, 1990; Hasenauer, 1994). It is an important measure of tree vigor (Assmann, 1970; Spurr and Barnes, 1980; Valentine et al., 1994). Some researchers referred that crown ratio can be considered an indicator for competition and probability of survival. Crown measures are also important for evaluating the wood quality of tree (Abetz and Unfried, 1983), and it is an advantage to the management of many non-timber resources including wildlife habitat and recreation (Mcgaughey, 1997). Dense and large crowns are correlated with actual and predicted growth rates (Kozlowski et al., 1991). Predictions of tree crown ratio have been based on the allometric relationship between stand and tree variables, and finding this relationship allows forest managers to accurately predict tree crown ratio in future with less possible effort (Temesgen et al., 2005). Many researchers have developed crown ratio equations based on logistic functions (Hasenauer and Monserud, 1996; Temesgen et al., 2005), an exponential function (Dyer and Burkhart, 1987) or Chapman Richard function (Soares and Tome, 2007; Adesoye and Oluwadare, 2008). Most of these models were developed for either even aged single species stands or multi-species stands comprising trees of different ages.

1.2.7 Height-diameter relations

The height-diameter relationship is commonly used in forest inventories to estimate the heights of trees for which only diameter was measured. The height-diameter relationship is a common precursor when using inventory and sample plot data to calculate volume and other stand attributes, e.g. site index, growth, yield and biomass.

A height-diameter relationship is obtained by the relationship between tree heights and their corresponding diameters. Diameter at breast height is measured easily and accurately for all trees in a stand, whereas tree height is relatively difficult, time-consuming and costly, and these factors often result in inaccurate measurements (Sharma and Parton, 2007).

This relationship can be expressed in mathematical functions. Most papers use generalized diameter-height relations; and at least 30 different functions have been used to describe the relationship. Korsun (1935), Michailow (1943), Assmann (1943), and Freese (1964) have developed some of the more important functions.

Every forest stand has its own height curve. The relationship between tree diameter and tree height differs among stands, related to site index, stand density, tree species, tree age, stand structure, competition and time (Curtis, 1967; Pretzsch, 2009). Because of these factors, height-diameter relationships are often not easy to describe (Oliver and Larson, 1990; Temesgen and von Gadow, 2004), so the best alternative is to develop a generalized height-diameter relationship, which includes stand variables as predictors such as dominant height, quadratic mean diameter, dominant diameter, number of trees per hectare, stand basal area, etc. (Temesgen and von Gadow, 2004; Sharma and Parton, 2007).

1.2.8 Model evaluation

After shedding the light on the factors influencing on growth and components of the individual-tree growth model, it is necessary to discuss some points related to the model evaluation. Model evaluation (or model validation) is an important part of forest growth modeling that answers how closely the model's behavior fits the real world, and to what extent logically and biologically the model agrees with actual forest growth (Zhao, 1999). While evaluation and validation are often used synonymously in forest growth modeling, Pretzsch (2009) deeply explained the difference between the two terms. Pretzsch (2009) considered the evaluation to mean checking the efficiency and success of a model being tested; it includes qualitative as well as quantitative examinations of the model (Soares et al., 1995). Similarly, validation is one aspect of evaluation, which is defined only by quantitative comparisons of model simulations to actual growth behavior (Pretzsch, 2009).

The qualitative evaluation examines the biological aspects of every single module and the logical structure of the model as a whole, and whether it is compatible with current understanding of biological processes and the expected response of a forest to various silvicultural treatments (Vanclay, 1994; Zhao, 1999; Gadow and Hui, 1999). In other words, the model properties should be examined for consistency. Some researchers included other aspects; for example, the estimated parameter values and signs should agree with the normal understanding of growth processes, approaches to parameter estimation should comply with the theories of statistical assumptions and predict sensible responses to management actions (Vanclay, 1994). After the qualitative evaluation is carried out, models can be evaluated quantitatively.

Quantitative examination should include a characterization of errors in terms of their magnitude and the distribution of residuals against the predictions, observations or other variables in the model by using graphical analysis (Vanclay, 1994; Soares et al., 1995; Zhao, 1999; Gadow and Hui, 1999), in addition to other tests for the model ,e.g. bias, precision, root mean square error. Furthermore, there is a sensitivity analysis, which aims to investigate how input factors affect the outputs of the model (i.e., usually output), in other words, the sensitivity analysis explores how sensitive a model's outputs are to changes in parameter values (Railsback and Grimm, 2012).

Sensitivity analysis procedures can be categorized as local sensitivity and global sensitivity analysis depending upon how parameter values are perturbed. Local sensitivity analysis perturbs one parameter at a time in a small range (Railsback and Grimm, 2012), while Global sensitivity analysis perturbs multiple parameters simultaneously over a large range (Railsback and Grimm, 2012).

1.2.9 Thinning treatment

The developed forest growth model can be applied effectively in several aspects of forest management. for example, to simulate the effect of different scenarios of thinning regimes on stand development, and this is what will be worked on in this thesis, therefore it is important to shed light on thinning treatments.

A thinning could be defined as a cultural treatment made to enhance forest health, to improve the growing space for production of maximum volume and stand quality by reducing the competition, and to provide an intermediate financial return (Evans and Turnbull, 2004). If the stand remains un-thinned, the growth rate slows down, stagnation develops, and many dead trees eventually occur.

Thinning intensity includes various correlated aspects, namely: The timing of the first thinning, the proportion of trees removed, how frequently it is done and the timing of the last thinning (Piper, 2008). Thinning has different impacts on the mean height and diameter of the residual stand.

Four distinct methods of thinning were introduced in forestry literature:

1) Thinning from above (Crown thinning) is a commercial thinning which removes dominant and co-dominant trees from the canopy to favor residual trees in the same classes (Graham et al,1999).
2) Selection thinning removes dominant height trees to favor the smallest trees (Graham et al,1999).
3) Thinning from below is a noncommercial thinning which was applied by cutting on a diameter basis, removing the smallest sizes, leaving large trees (Marquis and Ernst, 1991).

4) Free thinning releases selected trees while not treating the rest of the stand.

Regarding with the thinning of *Pinus brutia* forests, it is often carried out as an operational practice of plantation management (Carus and Catal, 2009) using different methods. In Syria and Turkey and where even-aged stands exist, thinning from below are used (Boydak, 2004). Selective cutting or thinning from above with the aim of harvesting the dominant and most profitable trees (Pantelas, 1986) are used in Cyprus and Lebanon.

1.3 Individual-based simulation tools

Individual-based modeling (IBMs) (in social science also referred to as Agent-based models) , has gained increasing attention in the last two decades. IBMs are "models where individuals or agents are described as unique and autonomous entities that usually interact with each other and their environment locally" (Railsback and Grimm, 2012). IBMs are applied when one or more of the following single-level aspects are considered necessary in order to explain the system-level behavior: heterogeneity among individuals, local interactions, and adaptive behavior based on decision making (Grimm, 2008).

IBMs have become a substantial tool in social, ecological and environmental sciences (Gilbert, 2007; Thiele et al., 2011; Railsback and Grimm, 2012), and "could augment traditional deductive and inductive reasoning as discovery methods" (Axelrod, 1997).

IBMs have a long history in forest modeling where an understanding the development and function of forests is a significant research challenge. They have proven to be an effective approach toward understanding key factors that influence or control the long-term behavior of a system of interest owing to "new software tailored to IBM analysis and increases in computing power" (Grimm and Railsback, 2005).

Despite the excellent empirical studies related forest which have been carried out, for example in tree growth, climate, and vegetation composition over time, it is still limited to much shorter time intervals, which makes it difficult to predict forest development and to explain which causes resulted in this development. On the other hand, long-term monitoring of forests is labor intensive and requires great commitment over long periods of time from individuals and institutions (Botkin, 1993). To address these points and answer different types of forest research questions, forest researchers often turned to simulation modeling (Bugmann, 2001) which is a useful approach to address the limitations of empirical models, and an important tool allows to understand the dynamics of forests and address different types of complex forest research questions.

A wide variety of modeling frameworks has been developed in forestry literature based on individuals that represent changes in forest structure and composition. Most models can be readily classified into some of general model classes for example empirical, gap model and process-based (Taylor et al. 2009). Table 1-4 provides a few examples of models in each of the major model classes.

Table 1-4: Examples of the models used in forestry in each of the major model classes

Model	Class	Relevant citations
BWINpro	Empirical	Nagel (2003)
BWINPro-S	Empirical	Schröder (2004)
SILVA	Empirical	Pretzsch (2002)
CACTOS	Empirical	Wensel et al 1986
JABOWA	Gap model	Botkin et al. (1972)
FORET	Gap model	Shugart and West (1977)
FORMIND	Gap model	Armstrong et al (2018)
FORTNITE	Gap model	Aber et al (1978)
SOEL	Gap model	Kellner and Swihart (2017)
ZELIG	Gap model	Urban (1990)
BALANCE	Process-based	Grote and Pretzsch (2002)
SORTIE	Process-based	Pacala et al (1996)

Understanding the development and function of forests is a significant research challenge, and this motivated the researchers to develop a wide variety of simulation models has been developed in forestry literature. Simulation experiments with forest models address the limitations of empirical models, and the tool allows to understand the dynamics of forests and address different types of complex forest research questions.

In the following sub-section, thinning treatments which are considered one of the most important applications of developing the individual-tree growth model will be discussed.

1.4 Objective and research questions of this thesis

For making sustainable forest management plans, forest managers require much information about tree growth, mortality and how these processes are affected by alternative silviculture treatments on the short and long term. To clear these issues, this study presents a new forest growth model based on individual-trees using real time series in the Mediterranean region. In this region, information on height increment is scarce, none of the existing publications has addressed the crown ratio. Studies that address diameter increment based on real time series data are virtually nonexistent. Only one paper developed an individual-tree mortality equation for *Pinus brutia* in the Mediterranean Sea region (Palahi, 2008 b). In terms of estimating the site productivity, this thesis presents for the first time a site index equation based on data comes from long-term observation (Amaro et al., 1998).

So the objective of the study is to develop a distance-independent individual-tree growth model based on real time series of even-aged *Pinus brutia* stands in the coastal region of Syria

designed to simulate management regimes in these forests. Thereby, such a model would support decision makers and foresters to improve forest management in Syria.
The research questions of this study are categorized in three groups of questions, related to growth, mortality and the simulation of tree growth.
Growth:

- How does the growth of *Pinus brutia* (diameter, height, crown ratio) develop over time under different site conditions?
- How does competition affect growth of *Pinus brutia*?

Mortality:

- How does the probability of mortality develop over time and how does it respond to competition, different densities and different site indices?

Simulation of the individual-tree growth model is necessary to overcome the limitation of empirical models to predict the general behavior in the medium and long-term, and the difficulty of simulating the effects of alternative management practices in the field. It allows developing long-term strategies for forest management and ensuring resource sustainability in Syria by creation of scenarios, compare outcomes, test competing alternatives and find forest management options that best meet the objectives of the decision makers for even-aged stand dynamics.
In addition to investigating and evaluating the behavior of the individual-tree growth mortality dynamics under different conditions (site characteristics, competition), the simulation model allows us to address the following questions:

- Stochastic or deterministic single-tree models: is there any difference in growth predictions for the same single-tree model and the same initial conditions?
- What is the optimal rotation age when wood production is maximized in the absence of thinning in stands under different site index values?
- What is the impact of thinning on tree growth? What are the appropriate timing, intensity, and type of thinning of *Pinus brutia* stands?

2 MATERIAL AND METHODS

This main section of the present work comprises the methodological approach through which the points formulated in the objective are to be fulfilled. In addition to sections that help to understand, the main focus is on the methodology for data collection and analysis that is followed by data modeling of the growth for *Pinus brutia*.

2.1 Study area and sites

This study is based on data collected from study sites in Syria, which geographically belongs to the latitude 32°,61 - 37°,07 'N and longitude 35°,79 - 40°,91 'E. The coastal region, where the study area is situated, is located in west of Syria on Mediterranean Sea (Figure 2-1 A, B). The region can be viewed as a major source of natural resource, as well as "transitional" in character, being the link between the Mediterranean Sea with arid zones of the interior Syria and the Arab world. The coastal region comprises three regions: the coastal plains, covering the seashore up to 300 m height, the Coastal Mountains, and the Baer and Bassit Mountains. Administratively, the coastal region is divided into two provinces: Latakia, which occupies the northern part of the coastal region with 2,300 km^2 total area, and Tartous, which is in the south, with area of 1,900 km^2.

The coastal region has 190 km of coastline and covers 2% of the national territory and contributes about 11% to the Gross Domestic Product (Annual agricultural static's abstract, 2003). In general, the coastal region accounts for 38.7% of the Syrian forests, mainly coniferous forests.

REFERENCES

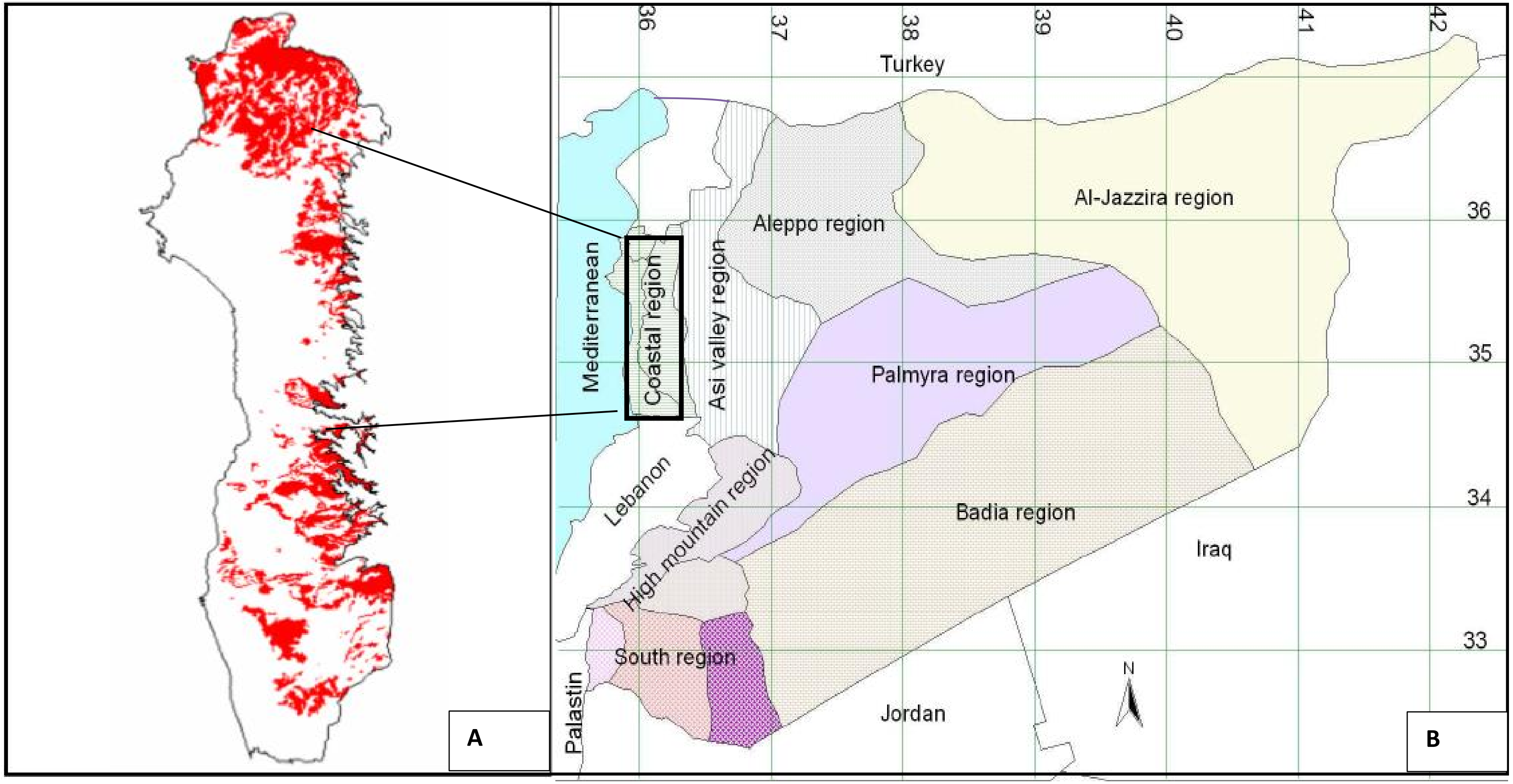


Figure 2-1: A: Distribution of coniferous forests in the coastal region; B: Major regions and sub-regions of Syria, the coastal region is located in the west of Syria

With regard to climate, the Mediterranean climate dominates the entire study area. The coastal areas have a mild climate, with four distinct seasons in the year.
Characterizing the rainfall pattern in this region is the irregular distribution of precipitation over the year. The annual precipitation in the coastal region (Tartous and Latakia) varied between minimum 600 mm and 1200 mm maximum during the past 10 years (Figure 2-2), (Figure 2-3). The annual dry period is usually less than four months (between June and October).

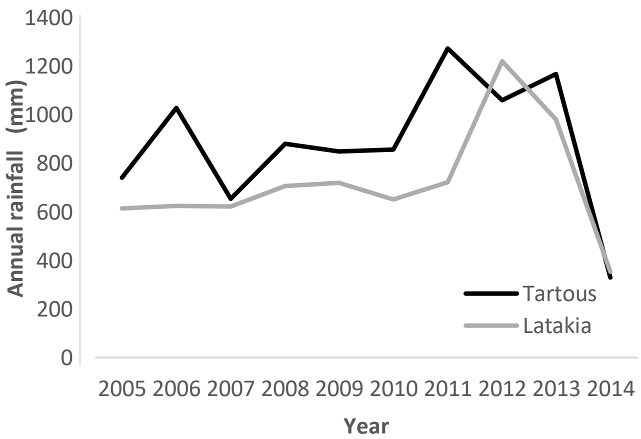


Figure 2-2: Rainfall in Tartous and Latakia During the past 10 years (Drought and Natural Disasters Fund Directorate.,2016)

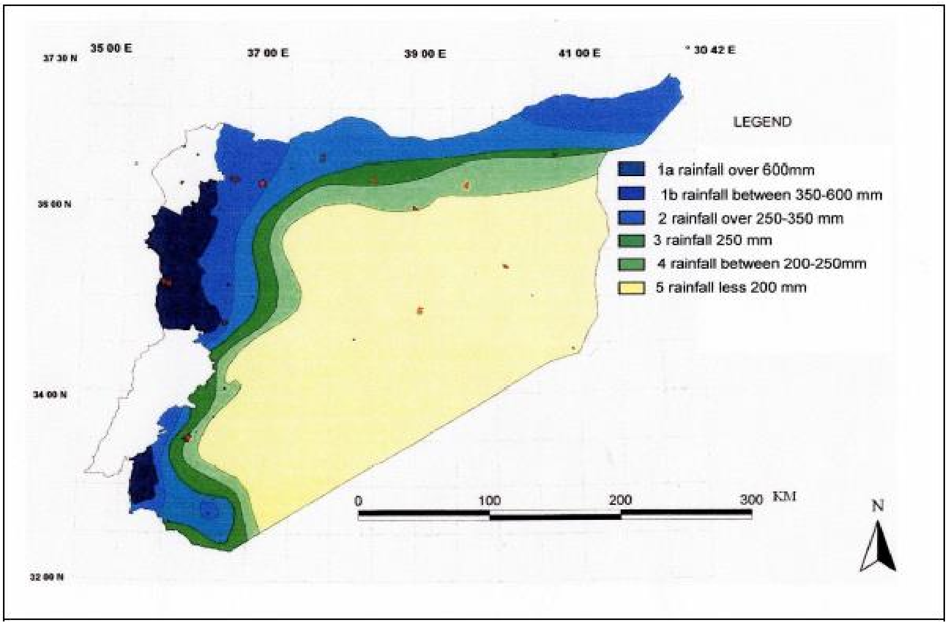


Figure 2-3: Generalized map of the agro-ecological zones of Syria (Annual agricultural static's abstract, 2003).

When going from rainfall to temperature in the coastal region, it is easily noticed that the hottest month is August and the coldest month is January (Drought and Natural Disasters Fund Directorate, 2016). The mean annual temperature ranges between 14 and 16 ºC at the top of coastal mountains chain. The mean annual temperature is affected by the altitude, and decreases gradually as altitude increases: "Banias 20°C (7 m), Safita 17.8°C (350 m), Mashta Al-Holw 15.4°C (500 m) Qadmous 14.3°C (750 m) and Slenfah 12.6°C (1100 m) " (Annual agricultural static's abstract, 2003). The mean temperature during the past 10 years was 19.8 for Tartous and 19.7 for Latakia (Figure 2-4) (Drought and Natural Disasters Fund Directorate, 2016).

Snow falls over the region where the altitude exceeds 1100 m above sea level, and the part with an altitude of 800-1100 m above sea level are subject to both rain and snow.

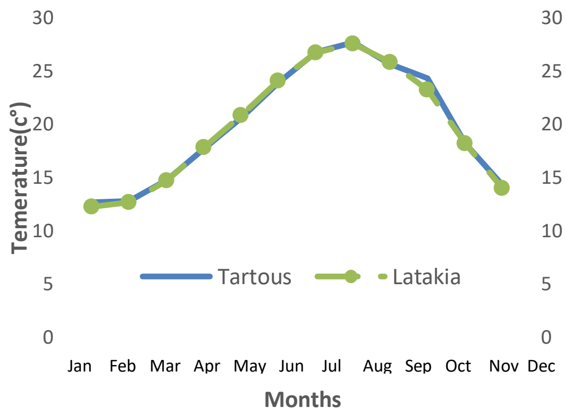


Figure 2-4: The mean temperature during the past 10 years for Latakia and Tartous (Drought and Natural Disasters Fund Directorate, 2016).

According to the topographical map of Syria (Figure 2-5), the elevation in the coastal region ranges between 0 – 1600 m. The coastal mountains are parallel to the coast with an altitude ranging from 1100 – 1600 m; elevation from 0 to 200 m is observed in coastal plains, which mainly are along the Mediterranean coast. The other elevations are dispersed between the coastal mountains and the coastal plains.

With taking all these variations above into account, 61 plots were established for the first time in 2008 by the Department of forestry of the Syrian Ministry of Agriculture in the coastal region, where most *Pinus brutia* forests of the country exist (Figure 2-5).

These plots were selected in this study so as to capture the whole range of variation across sites, stand ages and stand density. These plots were re-measured between March - May 2016. All plots were of circular shape, except for five plots which were rectangular 12, 19, 25, 44, and 49. The plots area varied from 69.99 m^2 to 1963.49 m^2; this variation has stemmed from the stand density, so that about 50 –75 trees were measured in most plots. All trees in each plot were numbered in strictly clock-wise direction to allow for easy recognition in future measurements.

The study used 51 plots to represent the analysis data (grey circles) and 10 plots to represent the validation data (red circles) (Figure 2-5).

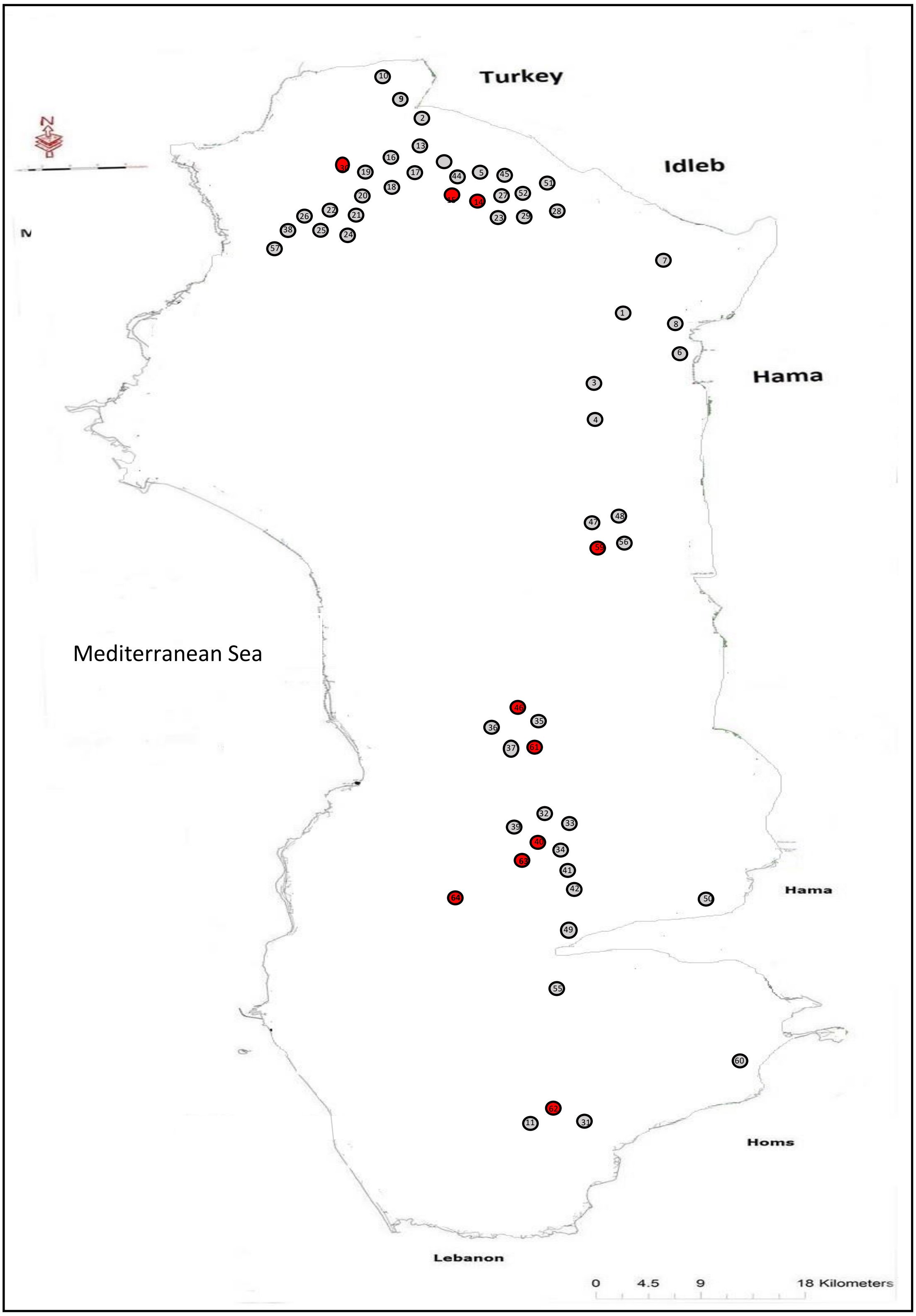


Figure 2-5: Distribution of the plots in the coastal region; the grey circles represent the plots which measured for the modeling process and the red ones are the plots which were measured for the validation process

2.2 General research framework

This thesis combines inventory data of forest measurements, empirical growth, and yield modeling and computer simulation techniques in the realization of study objectives (Figure 2-6).

The first step is collecting the data from the field, and then the creation and subsequent evaluation of inventory data to be used for modelling. For this purpose, the database consists of two parts: modeling (to construct the individual-tree growth model) and validation data (to evaluate the individual-tree growth model) (Section 2.3). Then, analyzing the data was to fit a plot-wise equation for tree height (Height curves), crown diameter (Crown diameter curves) and crown length (Crown length curves) (Section 2.4). This step is necessary to model missing data values, before moving to calculate tree and stand variables. By implementing this step, the data preparation will be complete for further tasks. The next step was studying the factors that affect individual-tree growth: competition and site productivity represented by the site index.

The competition will be analyzed by using a set of distance-dependent and independent competition indices (Section 2.5.1). The best one of distance-independent competition indices will be selected for further modelling.

Site index, which is a measure of potential site productivity, will be developed by testing eight biological growth equations (Section 2.5.2). The candidate equations are divided into two equal groups: 1) First group includes four equations based on the differential equations, and 2) the other group is based on the well-known height-age equations.

The fourth research step concerns the modelling of individual-tree growth, which consists of two processes: the growth and mortality (Section 2.6).

The growth includes four equations:

- The diameter at breast height increment
- Tree height increment: Linearized and potential-modifier height increment
- Crown ratio
- Generalized height-diameter relationship

The common statistical approaches will be used to describe theses equations in a compatible and appropriate way at each step.

The fifth research task is to implement the simulation of the developed individual-tree growth model in NETLOGO program (Section 2.7).

The last task will be evaluating the simulation model by applying the validation data, and by implementing the sensitivity analysis (Section 2.8).

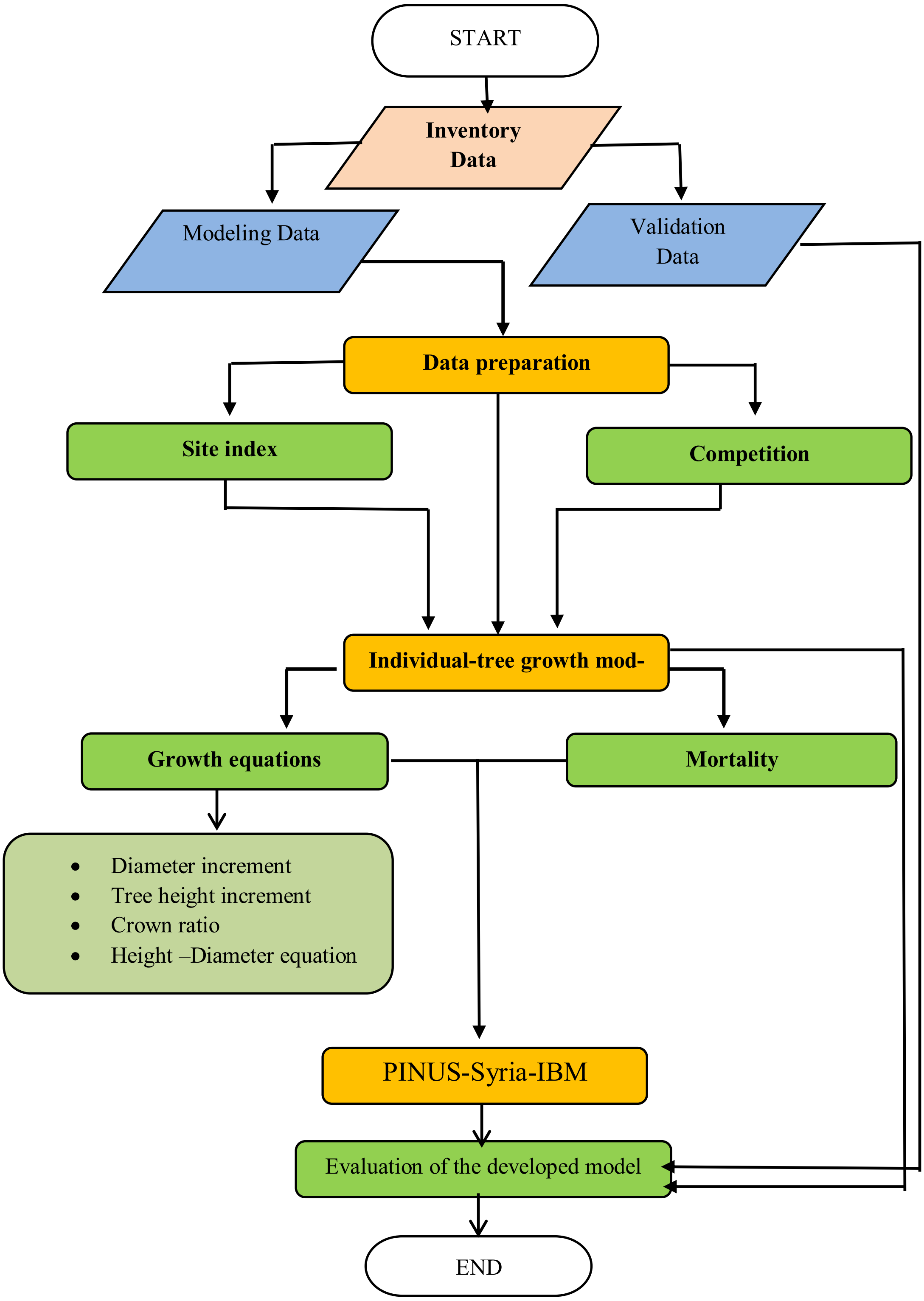


Figure 2-6: Overall framework showing the steps of research starting from the data inventory until the validation of growth and yield model. The terminal shape is used for start and end; The parallelogram is used for inventory data; The rectangle is used for the processes.

2.3 Data collection

2.3.1 Tree level variables

The study measured the data for the first time in 2008. The procedure for remeasurements was carried out for the second time in 2016 and it included two steps:

For each tree

- Status of tree (live or dead)
- Diameter at breast height ($d_{1.3}$), which was measured by using circumference tape.

For each plot

The study measured the tree height (h), height to crown base and crown diameter (CD) only for sample trees within each plot. It counted the trees in clock-wise direction and selected each 6th or 7th tree in the plot (depending on the tree density of the plot) as a sample tree. Each plot had from 10 to 11 sample trees, i.e. 663 sample trees for all plots (Modelling and validation). This sampling procedure followed a common approach in forestry, which is called systematic sampling.

During the period between two inventories 2008 and 2016, some sample trees had died, perhaps because of competition or old age where no evidence for other reasons was recorded, for example cutting, lightening catastrophic wildfires, insect outbreaks, etc. In this case, the study selected the next standing tree on the list as the sample tree.

The study measured the tree height (h) and height-to-crown base by using Haglöf Electronic Clinometer (Figure 2-7 A). Total tree height is defined to be the perpendicular distance between the ground level and the level of the top of a tree. The base of the live crown is defined as the point of insertion of the lowest live branch in at least three of the four horizontal quadrants defined around the stem of the tree (Hasenauer and Monserud, 1996).

The study measured crown diameter (CD) by recording the two crown diameter by tape measure only for sample trees; one being the horizontal diameter of the axis of the crown which passes through the center of the tree and the second being perpendicular to the first (Figure 2-7 B). The arithmetic mean crown diameter was calculated from these two field measurements to the nearest 0.01 centimeter and averaged.

It is worthy to mention that the study measured the diameter at breast height and tree heights for both inventories while crown measurements were measured only for second inventory.

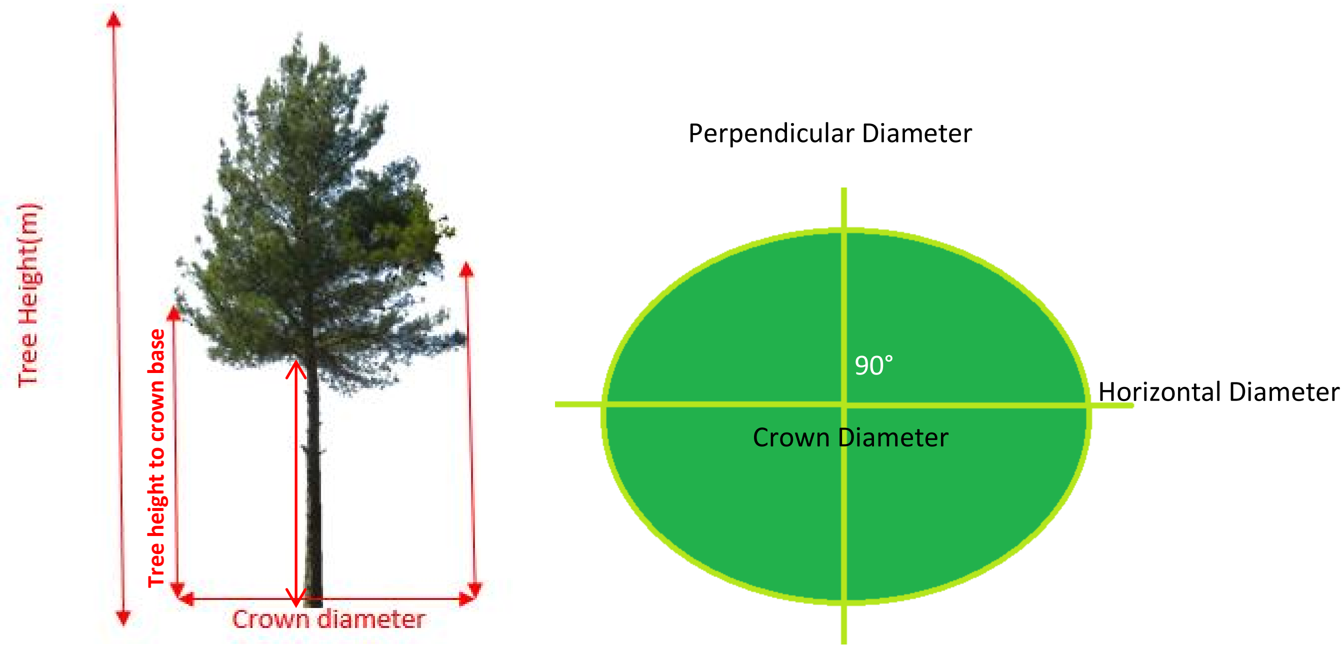


Figure 2-7: A: tree height is defined as the vertical distance from ground level to the highest green point on the tree; B: measuring the crown diameter, which is calculated as average of horizontal and perpendicular diameter

2.3.2 Stand level variables

In 2008 inventory, the study recorded the stand age by following two steps:

(1) By the Syrian ministry of agriculture records; (2) After the plots were selected, the study measured the ages of five dominant trees in each plot by using Haglöf increment borer, where the teamwork took the samples at stump height of the tree trunk and counted the rings in the core sample, as the study calculated the stand age for the last inventory 2016 by adding eight years (Figure 2-8).

Figure 2-8: Cumulative Frequency of stands age measured in 2008 for brutia pine in study area

The teamwork in the field recorded the additional following variables in each plot: altitude, slope, aspect, parent rock type (each type was coded), and soil depth (five measurements in different parts of the plot, one in the plot center and four around it) (Table 2-1).

Table 2-1: Characteristics of plots used in the modeling (shown first 6 plots) (See appendix 1 for all plots)and validation plots

Plot	Size m^2	Age in years 2008	Elevation m	Aspect degree	Slope %	Soil depth cm
1	706.8	54	375	330	45	44.4
2	452.3	66	548	330	30	23.4
3	1963.4	41	454	180	11	26.8
4	907.9	40	475	180	11	26.2
5	907.9	39	485	210	5	30
6	804.2	25	934.2	225	10	44.2
Validation plots						
14	201	45	561	120	15	34.6
15	314.1	40	582	60	18	38.6
30	804.2	93	643	330	10	21.8
40	380.3	34	851	160	9	44.6
46	380.3	33	47	275	3	14.8
59	706.5	102	195.9	170	35	23.8
61	452.8	98	801	245	25	37.8
62	69.9	37	758	170	21	48
63	452.8	39	743	60	15	31.6
64	452.8	36	487	200	30	29.2

Where: Size: Size of plot, Age: stand age

2.4 Data preparation

2.4.1 Height, crown diameter and crown length curves

- **Height curves**

In all plots, the study took the measurement of tree height (h) only for sample trees (Section 2.3.1). The study used the measured heights and diameters at breast height of sample trees to estimate the height of other un-measured trees in the plot.

For this purpose, the formula proposed by Michailow equation was applied (Michailow, 1943)

$$h = 1.3 + e^{\frac{a_0}{d_{1.3}} + a_1} \tag{1}$$

h = Tree height in m

$d_{1.3}$ = Tree diameter at the breast height in cm

a_0 , a_1 = Regression coefficients

e = Euler's number

As Van Laar and Akça (2007) and Yuancai and Parresol (2001) have suggested, the fitted curves should satisfy specific criteria. These criteria include (1) monotonic increment, which means that height increases as diameter increases; (2) inflection point: the point where the curve changes its direction; and (3) asymptote which means that when the diameter goes to infinity. Additionally, height curves must be plausible, steadily angling upward to the right of the Y-axis and becoming flatter; the study investigated this issue in detail.

Sometimes, due to measurement errors, curves do cross each other. To solve this problem, and in order to smooth height curves, the tree height-diameter ratio was found and all outliers were determined and eliminated from data of some plots.

- **Crown diameter curves**

In order to calculate the crown competition factor (CCF), which is used in this study (Section 2.3.1), the missing crown diameter values were determined. As height, the measurement of crown diameter (CD) was only taken for sample trees (Section 2.3.1). In each plot, sample trees were used to calculate the crown diameter of other trees, which were not measured by using nonlinear regression equations.

- **Crown length curves**

Crown length (cl) is calculated as a difference between tree height and height to crown base. The formula presented in Equation 2 completes the crown length values for the un-measured trees.

$$cl = a_0 + a_1 \cdot \ln(h) \tag{2}$$

Then, crown ratio is calculated as:

$$\frac{\mathrm{cl}}{\mathrm{h}} \tag{3}$$

cl = crown length (m)

h = tree height (m)

2.4.2 Calculation of tree variables

- Tree height for the un-measured trees (h)

After fitting Michailow equation for each plot in both inventories based on measured heights and diameters, height for each tree was calculated as shown in Equation 1.

- Tree basal area (ba)

The basal area of a tree is defined as the cross-sectional area (usually in m^2) of a single tree at breast height (Figure 2-9).

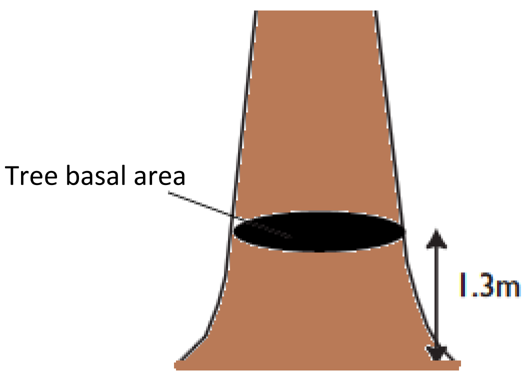


Figure 2-9: Tree basal area

Basal area is useful for making stand comparisons and a guide or indicator of thinning timing and intensity. It was calculated as follows (Husch et al, 2003 ; Pretzsch, 2009):

$$ba = \pi \cdot \left(\frac{d_{1.3}}{2}/100\right)^2 \qquad (4)$$

ba = tree basal area(m^2)

$d_{1.3}$ = Diameter at breast height (cm)

π = mathematical constant (Pi)

- Form factor ($f_{1.3}$)

Following an application of the Michailow equation and tree height calculation, the tree form factor was calculated, as required to calculate tree volume.

Form factor in this study was calculated using the following equation developed by Ali and Shater (2014)

$$f_{1.3} = 489.71 / (114.05 + d_{1.3}) + 4.31 / (d_{1.3}^2) - 3.9 - d_{1.3} + 1.023 \times d_{1.3} + 0.138 / (\ln (d_{1.3} \times (h^2))) \qquad (5)$$

$f_{1.3}$ = Form factor at breast height

$d_{1.3}$ = Tree diameter at breast height (cm)

h = Tree Height (m)

- Tree volume (vi)

It was calculated by using the following equation (Husch et al, 2003 ; Pretzsch, 2009):

$$\text{vi} = \frac{\pi \times {d_{1.3}}^2 \times h \times f_{1.3}}{40000} \qquad (6)$$

vi = Tree stem volume (m^3)

h = Tree Height (m)

$f_{1.3}$ = Form factor, h: Tree Height (m)

- Tree periodic mean annual diameter increment ($Id_{1.3}$): It was obtained by the difference between two successive diameters at breast height measurements (2008 and 2016) (Figure 2-10).

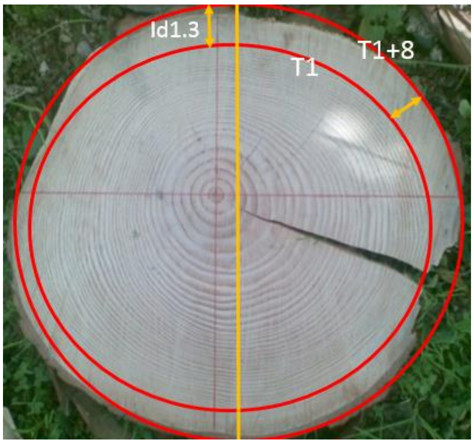


Figure 2-10: Measuring the diameter increment

$$Id_{1.3} = \frac{d_{1.3(t)} - d_{1.3(t-p)}}{p} \qquad (7)$$

$Id_{1.3}$	=	Periodic mean annual tree diameter increment (cm)
$d_{1.3}$(t)	=	Tree diameter at breast height in current inventory (cm)
$d_{1.3}$ (t-p)	=	Tree diameter at breast height in previous inventory (cm)
p	=	The length of period between inventories (years)

- Periodic mean annual tree height increment (Ih)

It was obtained by the difference between two successive height measurements (2008 and 2016) (Figure 2-11).

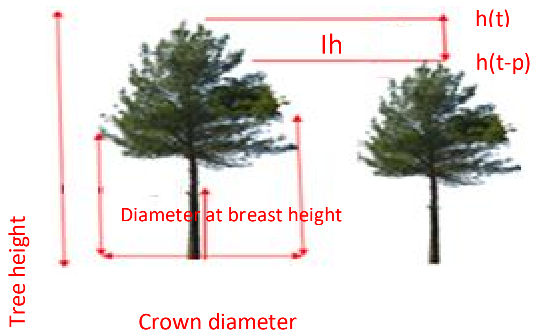


Figure 2-11: Measuring tree height increment between two inventories, the period (p) in this study 8 years, h = tree height; t = age

$$Ih = \frac{h(t) - h(t-p)}{p} \qquad (8)$$

Ih	=	Periodic mean annual tree height increment (m)
h (t)	=	Tree height in current inventory (m)
h (t-p)	=	Tree height in previous inventory (m)
p	=	The length of period between inventories (years)

2.4.3 Calculation of stand level variables

In most analyses of forest inventory data, measurements are usually summarized and expressed on per unit area basis. The unit used in this study is hectare. For this purpose, the ratio between one hectare (10000 m^2) and the actual plot size was calculated to generate a conversion factor.

$$CF = \frac{10000}{A} \tag{9}$$

A = Plot size (m^2)

CF = Conversion factor

The thesis calculated all stand level variables (basal area, volume, etc.) per hectare (Table 2.2).

In each plot where dead trees were recorded, the following variables were calculated:

The number of dead trees (removed) per hectare (N_{dead}), mean height of dead trees in each stand (H_{dead}), quadratic mean diameter of dead trees in each stand (Dq_{dead}), stand basal area of dead trees in each stand (BA_{dead}) and stand volume of dead trees in each stand (V_{dead}) (Pretzsch, 2009; Linkevičius, 2014).

The same equations, used for calculating N, H, Dq, BA, V (Tabl 2-2) were applied to calculate these variables for dead trees (removed).

Table 2-2: Calculated stand variables in the study

Stand Variable	Unit	Description	Equation	Reference
Number of trees per hectare (N)	Tree.ha^{-1}	It is an appropriate term to describe stand density in stands	$N = CF \cdot n$	(Husch et al, 2003 ; Pretzsch, 2009)
Stand basal area (BA)	m^2.ha^{-1}	The stand basal area is cross-sectional area of all stems in a stand measured at breast height	$BA = CF \cdot \frac{\pi \sum_{i=1}^{N} d_{1.3i}{}^2}{4}$	
Stand volume (V)	m^3.ha^{-1}	It is sum of all trees volumes in a stand and measured with cubic meter per hectare	$V = \frac{\sum_i^N v_i}{A}$	
Quadratic mean diameter (Dq)	cm	It is the measure of average tree diameter conventionally used in forestry, rather than arithmetic mean diameter.	$D_q = \sqrt{\frac{\sum_i^N d_{1.3i}{}^2}{N}}$	
Number of top trees (n_{100})	Tree		$n_{100} = A \cdot 100$	
Top basal area per hectare (G_{100})	m^2.ha^{-1}	The basal area of the 100 thickest trees per hectare.	$G_{100} = \frac{\pi}{4 \cdot 10000 \cdot n_{100}} \cdot \sum_{i=1}^{i=n100} d_{1.3}{}^2$	
Stand top diameter (D_{100})	cm	The diameter of the 100 thickest trees per hectare.	$D_{100} = \sqrt[2]{\frac{4}{\pi} \cdot G_{100}} \cdot 100$	
Mean stand height(H)	m	It is useful target variable for the early analysis and evaluation of silvicultural trials	$H = 1.3 + e^{(\frac{a_0}{Dq} + a_1)}$	(Michailow, 1943)
Top stand height(H_{100})	m	Top height is less affected to thinning. it is defines as mean height of the biggest trees per hectare	$H_{100} = 1.3 + e^{(\frac{a_0}{D100} + a_1)}$	

N	=	Number of trees per hectare	V	=	Stand volume (m^3. ha^{-1})
vi	=	Tree stem volume (m^3)	n	=	Number of trees per plot
A	=	Plot size in m^2	CF	=	Conversion factor
BA	=	Stand basal area in (m^2. ha^{-1})	Dq	=	Quadratic mean diameter (cm)
D_{100}	=	Top stand diameter (cm)	$d_{1.3}$	=	Diameter at breast height (cm)

G_{100} = Top basal area per hectare ($m^2.ha^{-1}$) π = Mathematical constant (Pi)
n_{100} = Top trees per hectare H_{100} = Top stand height(m)
H = Mean stand height (m)

Finally, the study described the total stand, which was calculated as the sum of growing and dead trees, using gross volume yield (GY), periodic annual volume increment (CAI) and the mean annual volume increment (MAI) (Table 2-3).

Table 2-3: Variables of total stand(remaining and removed trees)

Variable	Unit	Equation	Reference
Gross yield (GY)	m^3/ha	$GY = V(t) + V_{dead}$	(Pretzsch, 2009; Linkevičius, 2014)
Periodic annual volume increment (CAI)	m^3/ha/year	$\text{CAI} = \frac{V_{(t)} - V_{(t-p)} + V_{(dead)}}{P}$	
Mean annual volume increment(MAI)	m^3/ha/year	$\text{MAI}=\frac{Gross\ Volume}{Stand\ age}$	

GY = Gross volume yield in the current inventory ($m^3.ha^{-1}$)
V_{dead} = Stand volume of dead trees in each stand ($m^3\ ha^{-1}$)
V (t) = Volume of the growing stand in current inventory ($m^3\ ha^{-1}$)
$V_{(t-p)}$ = Volume of the growing stand in previous inventory ($m^3\ ha^{-1}$)
p = The time between inventories in years; MAI: mean annual volume increment,
CAI = Periodic annual volume increment ($m^3.ha^{-1}$)

2.5 Studying the factors that affect individual-tree growth

2.5.1 Competition Analysis

The research studied the impact of competition on basal area increment and height increment by using distance–independent and distance-dependent competition indices.

Distance-independent competition indices included all trees in all plots while the distance-dependent competition did not.

For studying the distance-dependent competition, two main steps were carried out as follows:

- **Identifying the competitors**

The study used the Fixed Radius Method (Hegyi, 1974; Mohammed and Röhle, 2011) by drawing a circle around the local tree j with a fixed radius and count those neighbors i = 1. . . n as competitors (Figure 2-12). Fixed radius in this study is half-height of the local tree, $d_{1.3}$ and height of local trees were measured (Appendix 2).

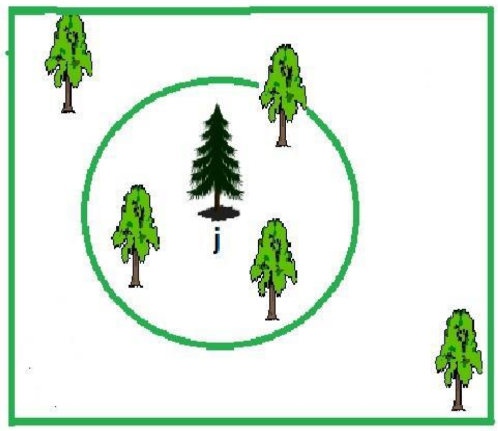


Figure 2-12: The studying of competition by fixed radius method

- **Tree mapping**

Position of each competing tree was measured by the distance and the azimuth from the local tree. The study measured the distance with tape and the azimuth with compass (Appendix 3). From this data, tree coordinates x-coord and y-coord were established in a way that allows to draw the positions of competitor trees in each plot by employing the following equations::

$$y\text{-}coord = dist \times cos\theta \qquad (10)$$

$$x\text{-}coord = dist \times sin\theta \qquad (11)$$

dist: distance from the center of plot to target tree in m; θ=azimuth of the tree

Then, several widely used distance-dependent competition indices and the distance independent competition indices were calculated and compared based on their relationship with an individual-tree growth, in particular, diameter increment and height increment. The group of distance-independent competition indices included the following indices: Hegyi 1974 which was developed in Canada for pine stands. It uses diameter at breast height. Crown Competition Factor (CCF) of Krajicek et al. (1961). Asymmetric or one-sided competition can be represented by including only trees larger than the subject tree when computing the index. Basal area of trees larger than the subject tree (BAL), the index developed by Wykoff et al (1982) basal area of trees larger than the subject tree (BAL index) and modified BAL index which is the basal area of trees larger than the subject tree divided by diameter at breast height represent this type, and the ratio of BAL and basal area of the stand (BAL/BA) (Jutras et al., 2003; Weiskittel, 2011).

The study introduced the BAL index by Wykoff et al. (1982). It is commonly used as distance-independent competition measure in individual-tree growth models (Wykoff, 1990; Teck and Hilt, 1991; Quicke et al., 1994; Monserud and Sterba, 1996). BAL is an effective measure that simultaneously considers the relative dominance of a tree and stand density. It is referred to as overtopping basal area, suggesting the nature of a kind of competition index, and directly related to the available light, since with increasing BAL, there is less light available for smaller trees. BAL describes a tree's competition status more accurately than other distance independent competition indices (Wykoff, 1990). BAL for the largest tree is 0 and for all smallest tree equals the stand basal area minus the basal area of the subject tree. The index developed by Schröder and Gadow 1999 $(1 - \left[\frac{BAL_i}{BA}\right]/RS)$, stand density index (SDI) developed by Reineke (1933) that describes the relative density in even-aged stands, and it is proxy for the availability of space for water and soil nutrients within stand (Lee, 1971; Peet and Christensen, 1987), and the ratio of the height of subject tree to the dominant height of the sample plot (h/H_{100}) (Avila and Burkhart, 1992; Zhang et al., 1997) and stand basal area (BA) (MA and Lei, 2015) (Table 2.4).

Table 2-4: The tested distance-independent competition indices

Index and Source	Equation
Hegyi (1974)	$\sum_{j=1}^{n} \frac{d_{1.3j}}{d_{1.3i}}$
Crown Competition Factor (CCF) cited in Krajicek et al. (1961)	$\sum_{j=1}^{n} (\pi \cdot \frac{CD_j^2}{4})/A$
BAL Wykoff et al (1982)	$\sum_{1}^{n} \frac{\pi \cdot d_{1.3\,maxJ}{}^2}{4}$
Schröder and Gadow (1999)	$(1 - \left[\frac{BAL_i}{BA}\right]/RS)$
Reineke(1933) (SDI)	$10^{logN+1.69 \times \log dg - 1.691}$
Cited in Hamilton,1986	$BAL/d_{1.3i}$
Cited in (Jutras et al., 2003)	BAL/BA
MA and Li (2015)	BA

$d_{1.3}$	=	Diameter at breast height	A	=	Plot size (m^2)
CD	=	Crown diameter (m)	RS	=	Relative spacing index of plot
BA	=	Basal area of the plot (m^2 /ha)	i	=	Subject tree
Dq	=	Quadratic mean diameter (cm)	SDI	=	Stand density index
BAL	=	Basal area of trees larger than the subject tree (m^2 /ha)			
N	=	Number of Trees per ha	j=competitor		

In terms of distance-dependent competition indices, several indices were tested (Table2-5). Heygie (1974) index is relatively simple to compute the size-distance ratio index using diameter at breast height and between-tree distance. The study modified the Heygi index 2 by Lee and Von Gadow (1997) where the same calculation can be made using tree basal area rather than diameter at breast height. Braath index is size-ratio competition index derived from the hypothesis that the competitive effect of a neighbor tree increases with increasing size and proximity (Tome and Burkhart, 1989). Martin and Ek (1984)'index is size-ratio index uses the diameter at breast height for both the neighbor and the cored trees. Rouvinen and Kuuluvainen (1997) indices are also size-ratio indices but employ sums of subtended angles. They developed four indices. First one is the sum of horizontal angles originating from the cored tree center and spanning the diameter at breast height of each neighbor tree. The second one is the sum of the horizontal angles multiplied by the ratios of the diameters at breast height of the neighbor and the cored trees. The third one sums vertical angles taken from the cored tree's base to the slope-adjusted top of each neighbor tree. Similar to the second one, the fourth one incorporates the ratios of heights between the cored tree and its neighbors.

Table 2-5:The tested distance-dependent competition indices

Index and Source	Equation
Heygi (1974)	$\sum_{\substack{j=1 \\ j \text{ competitor of } i}}^{n} \frac{d_{1.3j}/d_{1.3i}}{dist_{ij}+1}$
Heygi (1974) and cited in Piper (2008)	$\sum_{\substack{j=1 \\ j \text{ competitor of } i}}^{n} \frac{ba_i/ba_j}{dist_{ij}+1}$
Martin adn Ek (1984)	$\sum_{\substack{j=1 \\ j \text{ competitor of } i}}^{n} \frac{d_j}{d_i} \cdot \exp((16 \cdot dist_{ij})/(d_i + d_j))$
Braath (1980)	$\sum_{i=1}^{n} h_i/(\mathrm{h} \times dist_{ij})$
Rouvinen and Kuuluvainen (1997)	$\sum_{i=1}^{n} \arctan(d_{1.3i}/dist_{ij})$
Rouvinen and Kuuluvainen (1997)	$\sum_{i=1}^{n} (d_{1.3i}/d_{1.3})\arctan(d_{1.3i}/dist_{ij})$
Rouvinen and Kuuluvainen (1997)	$\sum_{i=1}^{n} \arctan(h_i/dist_{ij})$
Rouvinen and Kuuluvainen (1997)	$\sum_{i=1}^{n} (h_i/h)arctan(h_i/dist_{ij})$

BAL = Cumulative basal area of larger trees m^2 j = Competitor
ba = Tree basal area m^2 i = Subject tree
$d_{1.3}$ = Diameter at breast height cm h = Tree height m
distij = Horizontal distance from the ith neighbor tree to the cored tree (m)

Then to refer the strength of competition on basal area and height increment, some steps were carried out:

1) The study aaplied the competition indices in each plot.

2) The study constructed the relationship between basal area increment and $d_{1.3}$ of the central trees.

3) The study calculated the ratio between the actual basal area increment and predicted basal area increment. This ratio is called the relative basal area increment.

4) The correlation between all tested competition indices and relative basal area was calculated.

5) The study conducted regression analysis between relative basal area increment and competition indices. So, the indices with the best performance are the best indices.

The study applied the same procedure for height increment.

Analysing the competition was carried out with R 3.4.0 (R Development Core Team, 2017).

2.5.2 Developing the site index

2.5.2.1 Fitting the site index equation

The study calculated top height in each plot as the height corresponding to the top diameter according to the height curve (Michailow, 1943) as shown in Table 1 above. If H_{100} (t) is the mean height of the dominant trees at stand has age (t), where dominant (top) tree is mean height of the 100 highest trees per ha (Assmann, 1970), the site index is then defined as dominant height at a given age.

The most important desirable characteristics of site index equations are: (1) a logical behavior (height should be zero at age zero and equal to site index at reference age), (2) a sound theoretical basis, (3) polymorphism, (4) asymptote (5) existence of an inflection point and (6) base-age invariance (Bailey and Clutter, 1974; Elfving and Kiviste, 1997; Goelz and Burk, 1992). These requirements may not be achieved in some cases.

The difference equation method was used to model the dominant height growth of *Pinus brutia* forests (Borders et al, 1988). By definition, difference equations mean the discrete-time analogue type of differential equations. The use of difference equations is more appropriate when the data comes from long-term observation or stem-related data (Amaro et al., 1998).

The difference equation method is based on the fact that observations of the same plot or dominant tree should belong to the same site index curve. The study developed a difference algebraic form of height-age relation (or differential equation), where H_{100} (t_2) is expressed as a equation of the re-measurement age (t_2), the initial age (t_1) and the height at the initial measurementH_{100} (t_1).

A total of 10 algebraic difference equations from those most commonly used in forest research were selected for evaluation (Table 2-6). An algebraic difference approach has been used since it shows better properties and performance than other approaches (Cieszewski, 2002).

The equations were classified into two groups depending on the approach used to derive them: (1) Equations from differential equations: Amateis and Burkhart (1985), , McDill-Amateis equations (McDill and Amateis, 1992), Sloboda equation (1971) (Von Gadow and Hui, 1999; Kändler and Cullmann, 2016 and Hein, 2003), (2) Equations from height-age equations: Korf (1939) (Kitikidou et al, 2011), Schumacher equation (Schumacher, 1939), Hosffeld equation (Bailey and Clutter,1974), Hossfeld I(Kiviste et al.,2002), Strand equation (Strand,1964), Korf I equation and King-Prodam equation (Sharma,2013).

The study estimated the parameters using the Levenberg-Marquardt algorithm (Moré, 1977) in a nonlinear least square regression analysis. Then, the study fitted the difference equations using the non-linear least squares technique. After that, it was possible to estimate the site index and constructing site index curves.

2.5.2.2 Selection of reference age for site index

The implementation of the site index equation requires determining the reference age, which will result in reliable predictions of height at other ages (Stankova and Diéguez-Aranda, 2012). The reference age should be close to the rotation age (Goelz and Burk1992). The reference age could be selected as young as possible, in order to help in earlier decision making of the silvicultural treatments to be applied to the stand (Diéguez-Aranda et al 2005). In order to address this consideration, different reference ages and their corresponding observed heights were used to estimate heights at other ages for each tree. The predictions were compared with the observed heights, and finding the age which had the lowest relative error. The relative error in predictions (RE %) proposed by Diéguez-Aranda et al (2005) was calculated as follows:

$$RE = \frac{\sqrt{\sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2/(q-k)}}{\bar{Y}} \cdot 100 \tag{12}$$

Where: Y_i = Observed value; k = the number of parameters; $i = 1, \ldots, n$

RE % = relative error coefficient; q = Number of observations

$\hat{Y}$ = Fitted value; $\bar{Y}$ = Average value of observations

Table 2-6: Algebraic difference equations used in the study

Name	Height-age equation	Algebraic difference approach model and reference
Korf (1939)	$\mathrm{H}_{100} = b_0 \cdot \exp(-b_1/t^{b_2})$ Solved by b_1	$\mathrm{H}_{100}(t_2) = b_0 \cdot \frac{\mathrm{H}_{100}(t_1)}{b_0}^{(t_1/t_2)^{b_2}}$
Schumacher (1939)	$\mathrm{H}_{100} = b_0 + b_1(\frac{1}{t^{b_2}})$	$\mathrm{H}_{100}(t_2) = b_0 \cdot \exp(t_1/t_2 \cdot \ln(\mathrm{H}_{100}(t_1)/b_2))$
Hossfeld	$H_{100} = \frac{b_0}{1 + b_1 \cdot t^{-b_2}}$	$H_{100}(t_2) = b_0 + \frac{\frac{H_{100}(t_1) - b_0}{1 - b_1 \cdot H_{100}(t_1) \cdot t_1{}^{-b_2}}}{1 + \frac{t_1{}^{-b_2} \cdot b_1 \cdot (H_{100}(t_1) - b_0)}{1 - b_1 \cdot H_{100}(t_1) \cdot t_1{}^{-b_2}}}$
Korf I	$\mathrm{H}_{100} = b_0 \cdot \exp(-b_1/t^{b_2})$ Solved by b_2	$H_{100}(t_2) = b_0 \cdot \exp(\frac{-b_1}{t_2^{\ln(-\frac{b_1}{\ln\left(\frac{H_{100}(t_1)}{b_0}\right)}/\ln(t_1)}})$
King-Prodan	$H_{100} = \frac{t^{b_0}}{b_1 + b_2 \cdot t^{b_0}}$ solved by b_2	$H_{100}(t_2) = \frac{t_2{}^{b_0}}{b_1 + b_2 \cdot (\frac{\frac{t_1{}^{b_0}}{H_{100}(t_1)} - b_1}{b_2 + t_1{}^{b_0}}) + (\frac{\frac{t_1{}^{b_0}}{H_{100}(t_1)} - b_1}{b_2 + t_1{}^{b_0}}) \cdot t_2{}^{b_0}}$
Hossfeld I (Kiviste et al.,2002)	$H_{100} = \frac{t^2}{b_0 + b_1 \cdot t + b_2 \cdot t^2}$ solved by b_1	$H_{100}(t_2) = \frac{t_2{}^2}{b_0 + t_2 \cdot (\frac{t_1}{H_{100}(t_1)} - \frac{b_0}{t_1} + b_2 \cdot (t_2 - t_1))}$
Strand (1964)	$H_{100} = (\frac{t}{b_0 + b_1 \cdot t})^{b_2}$	$H_{100}(t_2) = (\frac{t_2}{(t_1 \cdot (H_{100}(t_1)^{-\frac{1}{b_2}} - b_0)/(1 + b_1 \cdot t_1)) + t_1 \cdot (b_0 + b_1 \cdot (t_1 \cdot (H_{100}(t_1)^{-\frac{1}{b_2}} - b_0)/(1 + b_1 \cdot t_1)))})^{b_2}$
Name	**Differential equation**	Algebraic difference approach model and reference
Amateis and Burkhart (1985)	$\frac{d\ln(\mathrm{H}_{100})}{d(\frac{1}{t})} = b_0 \cdot \ln(\mathrm{H}_{100}) + b_1 \cdot \ln(\mathrm{H}_{100}) \cdot t$	$\mathrm{H}_{100}(t_2) = \exp(\ln(\mathrm{H}_{100}(t_1)) \cdot \left({}^{t_1}/_{t_2}\right)^{b_1} \cdot \exp\left(b_0 \cdot \left({}^{1}/_{t_2} - {}^{1}/_{t_1}\right)\right))$
Sloboda (1971)	$\frac{d\mathrm{H}_{100}}{dt} = b_0 \times \frac{\mathrm{H}_{100}}{t^{b_1}} \cdot \ln(\frac{b_2}{\mathrm{H}_{100}})$	$\mathrm{H}_{100}(t_2) = b_2 \cdot (\frac{\mathrm{H}_{100}(t_1)}{b_2})^{e^{-\frac{b_0}{1-b1} \times (t_2^{(1-b_1)} - t_1^{(1-b_1)}}}$
McDill and Amateis (1992)	$\frac{d\mathrm{H}_{100}}{dt} = (1 - \frac{\mathrm{H}_{100}}{b_0}) \cdot b_1 \cdot \frac{\mathrm{H}_{100}}{t})$	$\mathrm{H}_{100}(t_2) = b_0/(1 - \left(1 - \frac{b_0}{\mathrm{H}_{100}(t_1)}\right) \cdot ({}^{t_1}/_{t_2})^{b_1})$

$\mathrm{H}_{100}(t_1)$ and $\mathrm{H}_{100}(t_2)$ = dominant height (m) at age t_1 and t_2 (years) respectively; ln =natural logarithm b_0, b_1, b_2 = parameters to be estimated

2.6 Individual-tree growth model

After preparation the data and analyzing the factors that affect the growth, the study paved the way to develop the individual-trre growth model which consists of growth(diameter increment, height increment, crown ratio and generalized height-diameter relationship) and mortality equations.

2.6.1 Development of diameter increment equation

The study modeled the individual-tree growth based on diameter increment. The predicted dependent variable was the diameter increment. This was obtained as a difference between two successive diameter measurements 2008 and 2016 divided by eight years.

The purpose was to develop the following equation for the future annual diameter increment

$$Id_{1.3} = f\ (tree\ size;\ site;\ competition) \tag{13}$$

$Id_{1.3}$: future annual diameter increment (cm).

The study tested a set of variables representing tree size, competition and site:

I. Tree size

The thesis tested squared diameter at breast height, inverse of diameter at breast height, natural logarithm of diameter at breast height, squared root of diameter at breast height, inverse of tree height, natural logarithm of tree height and squared tree height.

II. Site effects

The research included the site characteristics in this equation to give some site specificity (Stage, 1976; Wykoff, 1990; Monserud and Sterba, 1996). Elevation, soil depth, aspect times slope (geo-climatic variation (OGV), site index and their transformations were tested for site effects variables.

The tree age has generally been considered an important variable for individual-tree growth model, but in even-aged forests, the effect of the site quality on tree growth is generally accounted for by the site index (Lee, 1996; Schröder 2000), where site index is derived from the stand age and dominant height (Schröder 2000).

The other geo-climatic variation (OGV) were also tested because they generally have indirectly effect by influencing moisture, temperature, light, and other chemical and physical agents of the site, and provide more flexibility and biological interpretability (Weiskittel et al, 2011).

III. Competition effects

The study analyzed the effect of the competition on diameter increment by using distance independent competition indices, and using the the best indices in the competition analysis in the variables selection process.

Then, the linearized diameter growth sub-model was as follows

$$\ln(Id_{1.3}) =: \beta_0 + \beta_1 \cdot Tree\ size + \beta_2 \cdot \text{site} + \beta_3\ OGV + \beta_4 \cdot competition\ index + \ \varepsilon \qquad (14)$$

OGV: The other geo-climatic variation; $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4$,are regression coefficients,

The thesis used Snowdon correction factor in the equation to remove bias from back-transformed predictions and was calculated as sum of predicted values divided by sum of real values (Snowdon 1991).

The study carried out the variable selection process by applying stepwise regression analysis which was implemented in SPSS 22 Release (Aug13, 2013) with different combination of variables that represent the tree size and site and competition. In this process non-significant variables were removed. Further, to evaluate the developed equation, there are a set of assumptions for multiple linear regressions that have to be satisfied:

1. A Linear Relationship between the outcome variable and the independent variables.
2. No Multicollinearity: This assumption assumes that the independent variables are not strongly correlated with each other.

Multicollinearity is checked against 3 key criteria:

- Correlation matrix: When computing the matrix of Pearson's Bivariate Correlation among all independent variables, the correlation coefficients need to be smaller than 0.8.
- Tolerance: The tolerance measures the influence of one independent variable on all other independent variables; the tolerance is calculated with an initial linear regression analysis. Tolerance is defined as $T = 1 - R^2$ With $T < 0.2$ there might be multicollinearity in the data and with $T < 0.01$ there certainly is.
- Variance Inflation Factor (VIF): The variance inflation factor of the linear regression is defined as VIF = 1/T. Similarly, with VIF > 10 there is an indication for multicollinearity to be present (Myers, 1990; Hair et al., 2013).

3. The homoscedasticity: the variance for the error term is the same for all observations.
4. The error term is normally distributed.
5. The expected value of the error term is 0.
6. The error term is uncorrelated across observations.

2.6.2 Development of height increment equation

2.6.2.1 Development of linearized height increment equation

The predicted dependent variable was the height increment. This was obtained as a difference between two successive height measurements 2008 and 2016 divided by eight years.

A height increment equation is a function of different variables representing tree size, competition and site conditions (Monserud and Hasenauer, 1997; Uzoh and Oliver, 2006; MA and Li., 2015). The variables are the same to that used in modeling the diameter increment.

Multiple linear regression analysis was used to develop a linearized height increment equation. Because of desirable properties with the error structure (e.g., homogeneous variance), a logarithmic model for height increment was chosen (Stage, 1976; Uzoh and Oliver, 2006):

$$Ln\,(Ih) = f\,(tree\ size, site, competition) \tag{15}$$

Ih: future annual height increment (m).

The variable selection process was carried out in similar way to that had been mentioned in 2.6.1, and the equation was evaluated by linear regression analysis assumptions which were explained also in 2.6.1.

2.6.2.2 Development potential modifier height increment

The potential- modifier approach is more commonly used for predicting height increment in even-aged stands due to available dominant height equations (Weiskittel et al., 2011). The potential height increment in this study was obtained by the dominant tree height increment, which is reduced by competition indices (modifier) to get the individual-tree height increment.

The research achieved modelling of the potential- modifier height increment (Ih) by using Nagel (1999) equation.

Nagel (1999) equation consists of two parts, the first is the potential stand top height increment (IH_{pot}), and the second is the modifier, which is presented by the ratio between stand top height (dominant height H_{100}) and tree height in each plot ($\frac{H_{100}}{h}$).

$$Ih = h \times (\frac{IH_{pot}}{h_{100}}) + a_0 \cdot \left(\frac{H_{100}}{h}\right)^{a_1} + \varepsilon \tag{17}$$

Ih = Tree height increment
IH_{pot} = Potential stand top height increment
h = Tree height in m,
H_{100} = Stand top height (dominant height) (m)
a_0, a_1 = coefficients

In the even-aged stands like the case of this study, the potential modifier method assumes that the resulting potential dominant height increment is the same for all trees in each plot as all trees have the same age. To calculate the potential stand top height increment(IH_{pot}), the age dependent approach calculates the dominant height for the start and end of a growth period using dominant-height increment equation. By deriving developed site index, dominant height for each inventory was calculated by employing the site index and stand age as independent variables. Then, the difference between the dominant height for each inventory is the potential dominant height increment, which was used later to estimate the potential height increment.

$$IH_{pot} = H_{100}(t_2) - H_{100}(t_1) \quad (18)$$

IH_{pot} = The potential top height increment
H_{100} (t_2) = dominant height at age t_2
H_{100} (t_1) = dominant height at age t_1

To determine the modifier, the potential modifier method assumes also that trees below the dominant height are shorter solely because of competition (Hann and Ritchie., 1988), then, in order to predict the height increment for each tree in the plot, the predicted potential dominant height increment was adjusted by using a modifier. The work used the ratio between stand top height (dominant height H_{100}) and tree height in each plot $\left(\frac{H_{100}}{h}\right)$ as a modifier. This modifier was suggested by Nagel et al. (2002).

Further, the potential modifier height increment equation should satisfy regression assumptions by checking the two tests:

1) Multicollinearity of independent variables which was evaluated by producing Correlation matrix of independent variables.

2) The homoscedasticity: the variance for the error term is the same for all observations.

Additionally, to compare equations (potential modifier height increment and realized height increment) adjusted R-square was used. Adjusted R-square shows the proportion of the total variance that is explained by the model. It is calculated asshows:

$$R^2_{adj} = 1 - \frac{(1-R^2)\cdot(n-1)}{q-k-1} \quad (19)$$

R^2_{adj} = Adjusted R-squared
R^2 = R-squared
k = Number of variables in the equation
q = Number of observations

2.6.3 Development of individual-tree crown ratio

Crown ratio (CR), is the ratio of live crown length to the total height of the tree. The thesis computed the crown length by subtracting the height to crown base from the total height in the sample trees, then crown length values were completed by finding the relationship between crown length in each plot and tree height as explained in section (2.3.1).

The tree crown ratio equation is function of tree size, competition measures, and site factors (Hasenauer and Monserud, 1996).

The tested models in this study to develop the crown ratio are: Logistic, Chapman-Richard and Exponential models (Table 2-7)

Table 2-7: Testing tree crown ratio equations

Model	Model form	Reference
$Cr = (1 + \exp(\beta \times X))^{-1}$	Logistic	Hasenauer and Monserud, 1996
$Cr = (1 - \exp(\beta \times X))^{-1}$	Logistic	Popoola and Adesoye, 2012
$Cr = \exp(\beta \times X)$	Exponential	Leites et al., 2009
$Cr = (1 + \exp(-\beta \times X))^{-\frac{1}{2}}$	Richards	Popoola and Adesoye, 2012

Where

β: Intercept, X : Independent variables

Crown ratio values range from 0 (no crown, dead or defoliated) to 1 (crown extends over the entire tree bole).

To select a proper set of variables for the linear combination, the work considered the following variable groups for tree size, competition measures, and site factors.

The first group includes squared diameter at breast height, inverse of diameter at breast height, natural logarithm of diameter at breast height, squared root of diameter at breast height, inverse of tree height, natural logarithm of tree height and squared tree height.

The second group includes elevation, soil depth, aspect times slope (geo-climatic variation OGV), site index and their transformations.

The third group includes the distance independent competition indices which were tested to represent the competition variables.

The multiple linear regression equation for the independent variables was given as follows:

$$\beta \times X = \beta_0 + \beta_1 \times X_1 + \beta_2 \times X_2 + \beta_3 \times X_3 + \beta_n \times X_n \qquad (20)$$

Where

β_0 : intercept, $\beta_1 \ldots \beta_n$: parameters, X_1 to X_n : the independent variables

The study evaluated equation 20 by linear regression analysis defined in (section 2.6.1).

The research fitted equation to the data obtained in the study; then inserted into equation listed in Table 2-8 for estimating the parameters. The work used the parameter estimates from the linear least squares fit as starting parameters.

The study evaluated nonlinear equation by applying a nonlinear regression analysis (See section 2.6.2).

2.6.4 Generalized height- diameter equation

The study tested four equationss to model height-diameter relationship (Table 2-8). These tested equations used dominant height and dominant diameter at breast height as stand variables. The data used to build the generalized height- diameter equation came from 1326 sample trees from two inventories; all sample trees in the sample plots had their diameter at breast height and height.The research used 1115 sample trees for modeling while 212 sample trees were used for validation. The study fitted the candidate equations by using nonlinear regression analysis.

Table 2-8: Candidate equations to model the general height-diameter relationship for *Pinus brutia*.Ten

Author	Equation
Harrison et al. (1986)	$h = H_{100} \times (1 + b_0 \times e^{b_1 \times H_{100}})(1 - e^{\frac{b_2 \times d_{1.3}}{H_{100}}})$
Hui and Gadow (1993)	$h = 1.3 + b_0 + b_1 \times {H_{100}}^{b_1} \times {d_{1.3}}^{b_2 \times {H_{100}}^{b_3}}$
Mirkovich (1958)	$h = 1.3 + (b_0 + b_1 \times H_{100} - b_2 \times d_{1.3}) \times e^{\frac{-b_3}{d_{1.3}}}$
Stoffels and Van Soest modified (1953)	$h = 1.3 + (H_{100} \times (\frac{d_{1.3}}{D_{100}})^{b_0})$

Where:

h= total height (m) $d_{1.3}$ = diameter at breast height (cm);

H_{100}= dominant height (m) D_{100}= dominant diameter (cm)

b_0, b_1, b_2, b_3 = parameters e= Euler's constant

2.6.5 Development of individual-tree mortality equation

The work modeled the possibility of a tree dying in the next year by using logistic function (Equation 16), which is widely applied for tree mortality, tree mortality ranges between 0 and 1. The data used for mortality modelling records for 72 dead and 3004 live trees from 51 plots.

$$P_i = \frac{1}{1+e^{-(b_0+b_1 \times X_1+b_2 \times X_2+\cdots .b_n \times X_n)}} \tag{21}$$

Pi = The probability of tree mortality

b_0–b_n = Parameters to be estimated

x_1–x_n = Explanatory variables

The candidate variables for the mortality equation were numerous and diverse. As Pedersen (2007) pointed out, "*test statistics and a basic understanding of how forest ecosystems function and how factors contributing to mortality are expressed, play an important role in selecting the appropriate predictor variables*". Numerous studies have revealed many variables that are important for mortality predictions. To develop the natural mortality models, the research applied the tree size variables, competition variables and stand level variables.

The tree size variables were: tree diameter at breast height ($d_{1.3}$) and its transformations (natural logarithm of $d_{1.3}$, $d_{1.3}^{-1}$, $d_{1.3}^{2}$), tree basal area (ba), tree height (h). Additionally, one derivative variable was checked, h/ $d_{1.3}$.

The competition variables tested to select the best index for predicting the individual-tree mortality equation included the following indices: basal area of trees larger than the subject tree divided by stand basal area, stand density index, diameter at breast height divided by stand age, basal area of trees larger than the subject tree divided by diameter at breast height, ratio of the tree height and stand top height, squared diameter at breast height divided by stand basal area, basal area of trees larger than the subject tree times squared diameter at breast height, basal area of trees larger than the subject tree, diameter at breast height divided by stand age.

Stand level variables used for the analysis were: stand age, mean stand height (H), quadratic mean diameter (Dg), top height (H_{100}), site index (SI) and basal area of stand per hectare (BA).

When analyzing each variable, The work conducted a univariate analysis and variables with a significance level lower than 0.25 were used in multivariable analysis (Hosmer and Lemeshow, 2000).

The second step, the research verified the importance of each variable included in the equation by applying Wald statistics and comparison of each estimated coefficient with the coefficient from the equation that contains only this variable. Variables that do not meet these criteria were removed and new equation was fit.

Third and last step, the study checked correlations among the variables used in the equation.

Also, the equation was evaluated by the means of logistic regression analysis:

1) Checking the statistical significance of the model and its estimated parameters. There should be no high inter-correlations (multicollinearity) among the predictors. This can be assessed by a correlation matrix among the predictors. Tabachnick and Fidell (2012) suggest that as long correlation coefficients among independent variables are less than 0.90 the assumption is met.
2) The Pearson chi-square is calculated as follows:

$$X^2 = -2\ln(L_0) + 2\ln(L_M) \quad (22)$$

X^2 = Value of Pearson’s chi square statistics

L_0 = Value of the maximum likelihood function of logistic regression model with no predictors

L_M = Value of the maximum likelihood function of analyzed model with specified coefficients

Large chi-squared values provided evidence of lack of fit. When the chi-squared values we calculated are less than the critical chi-squared values with significant level p = 0.05, it means there is no significant difference between the probability of observed and predicted dead trees.

3) Estimating the following parameters: log likelihood function values, the Nagelkerkle and McFadden's coefficients of determination and areas under the ROC curves.

The Nagelkerkle R^2 and the McFadden R^2 are recommended (Allison, 2014), which were presented in this study (Allison, 2014).

McFadden's R^2 is defined as fllows:

$$R^2_{McF} = 1 - \ln(L_M)/\ln(L_0) \tag{23}$$

The Nagelkerkle R^2 is :

$$R^2_N = \frac{1-(L_0/L_M)^{\frac{2}{q}}}{1-(L_0)^{\frac{2}{q}}} \tag{24}$$

R^2_{McF} = McFadden's coefficients of determination ; q = Number of observations

R^2_N = Nagelkerkle's coefficients of determination

L_0 = Value of the maximum likelihood function of logistic regression model with no predictors

L_M = Value of the maximum likelihood function of analyzed model with specified coefficients

The log-likelihood function is defined to be the natural logarithm of the function.

$$l(\theta) = \log L(\theta) = \sum_{i=1}^{q} \log f(\tfrac{X_i}{\theta}) \tag{25}$$

L = Value of the maximum likelihood function q = Number of observations

θ = An unknown parameter X_i = Continuous random variable

The log-likelihood function is used throughout various subfields of mathematics, both pure and applied, and has particular importance in fields such as likelihood theory.

The larger the Log likelihood function value the worse adapted is the model.

The area under the receiver operating characteristic (ROC) curve was calculated for the mortality model. It is a threshold independent measure of model discrimination, where a value of 0.5 suggests no discrimination, 0.7–0.8 suggests acceptable discrimination, and 0.8–0.9 suggests excellent discrimination (Hosmer and Lemeshow, 2000).

The predicted and observed mortality were then compared by visually studying deviations over the explicatory variables included in the model. A threshold can be used to assign mortality. If the estimated probability of mortality exceeds the threshold then the tree is considered dead. The research tested three cut-points: the first was the overall mortality rate (Monserud and Sterba, 1999), the second was the intersection point of sensitivity and specificity (Adame et al, 2010) and the third was a random number which can also be considered by running the random calculation 10 times. The percentage of live and dead trees is the average classification rates (Bravo-Oviedo et al., 2006). In other words, the study implemented an individual-tree mortality equation either stochastically by using a random number or deterministically by using overall mortality rate and the intersection point of sensitivity and specificity. For the comparison of the stochastic and deterministic approaches, the simulations were run on a 100-year period using one-year growth steps by running the random calculation 10 times. The average of four different response variables (Quadratic mean diameter, stand basal area, stand volume and number of trees per hectare) of stochastic approach were compared with the four different response variables of deterministic approach, and then, the study used Mann Whitney U Test (Wilcoxon Rank Sum Test) for testing the null hypothesis that the differences between stochastic and deterministic simulations are negligible.

2.7 Simulation of individual-tree growth model

After developing the equations, the study will use NETLOGO to implement the simulations of the developed individual-tree growth model. The description of the PINUS-Syria-IBM (Individual Based-Model) presented follows the ODD Protocol (Overview, Design concept, Detail) (Grimm et al., 2010).

2.7.1 The purpose

PINUS-Syria IBM model is conceived to gain knowledge about the growth of even-aged *Pinus brutia* stands in the coastal region of Syria, which is considered an indispensable tool for applying sustainable forest management. The model simulates the growth and mortality of *Pinus brutia* influenced by distance-independent competition over time under different site conditions (site index, elevation, slope, aspect, soil depth). It can be used to determine the optimal rotation age (intersection of mean and current annual volume increment) where the wood production is maximized in absence of thinning. The model also is designed to better understand the effect of different thinning scenarios on growth.

2.7.2 Entities stand variables and scales

There are two types of entities, namely the patches and trees. The individual trees are described by a set of state variables governing the location of the tree and the dimension of the tree stem (Table 2-9).

Table 2-9: State variables, initialization, range values and behaviour in the individual-based model. Range values are drawn from the inventory data and literatutre

Variable	Unit	Explanation	Initialization	Range	Behavior
X	[m]	X-position	Random	0-100	Constant
Y	[m]	Y-position	Random	0-100	Constant
$d_{1.3}$	[cm]	Diameter at breast height	5 cm	5-140 (Gezer, 1986)	Variable
h	[m]	Tree height	Calculated	1.3-42(Gezer, 1986)	Variable
$f_{1.3}$	-	Form Factor	Calculated	0.1-0.99 (Data)	Variable
vt	[m^3]	Tree volume	Calculated	0-1 (Data)	Variable
ba	[cm^2]	Tree basal area	Calculated	0.001-0.8(Data)	Variable
BAL	[cm^2]	Basal area of trees larger than the subject tree	Calculated	0.001-0.8(Data)	Variable
Pt	-	probability of individual tree mortality	Calculated	0-1	Variable
cr		Individual tree crown ratio	Calculated	0-1	Variable

The size of simulated area is a 100 × 100 grid of patches (1 ha) surrounded by 10 patches on all sides for total simulated area (1.44 ha). Patches are 1 × 1 (m) in size. Patches have six primary state variable (Table 2-10):

Table 2-10: State variables of the patches, initialization, values and behaviour in the individual-based model. Range values are drawn from the inventory data

Variable	Unit	Explanation	Initialization	Value	Reference	Behaviour
SI	[m]	Site Index	Scenario dependent	[5 – 30] with increment 1	Own-data	Constant
ASP	[Radian]	Aspect	Scenario dependent	[0 – 360] with increment 10	Own-data	Constant
SLO	[Percent]	Slope	Scenario dependent	[0 – 100] with increment 10	Own-data	Constant
ELE	[m]	Elevation	Scenario dependent	[100–1000]with increment100	Own-data	Constant
Dep	[m]	Soil depth	Scenario dependent	[10 – 150] with increment 10	Own-data	Constant

One-time step represents one year and simulations run for 150 years.

2.7.3 Process overview and scheduling

The PINUS-Syria-IBM is a distance-independent individual-tree growth model. During one-time step, the model describes three main processes: Growth, mortality and thinning treatment. Growth consists of three sub-routines namely diameter at breast height increment, tree height increment, crown ratio.

The flowchart (Figure 2-13) shows the sequence of the execution of the processes in a one-time step. Implementing these processes starts with updating the state variables of all trees (e.g. tree basal area, form factor, tree crown ratio and tree volume). These variables determine the competition indices (compete) of the individuals that are calculated of the single tree level. The processes, described in detail below (Section 6 and Section 7), are scheduled in the following sequence:

1. Growth(grow): it is calculated for each individual tree

   I. Diameter at breast height increment (id)

   II. Tree height increment (ih)

   III. Crown ratio (cr)
2. The individual-tree Mortality (check-mortality): it is calculated for each individual tree
3. Thinning treatments (conduct-thinning): it is implemented at stand level.

Finally, the stand variables (calc-global-vars) get updated: e.g. quadratic mean diameter, stand basal area, stands volume, means and current volume increment.

2.7.4 Design concepts

1. Basic principles

The PINUS-Syria-IBM describes individual trees of pure even-aged brutia pine stands. It uses a distance-independent approach for calculating the competition indices. This is similar to PROGNAUS developed by Monserud et al (1997) which continues to be refined and developed today (Ledermann, 2006), and is in contrast to other stand growth models which consider the specific spatial configuration.

The main basic assumptions of PINUS-Syria-IBM:

- The competition which influences resources, have been defined according to the most common approach: symmetric (Two-sided competition) / Asymmetric (One-sided competition). Two-sided competition occurs where resource uptake among competitors is independent of the relative sizes, and one-sided competition occurs where the largest trees obtain all the contested resources (Schwinning and Weiner, 1998). Although there is not a general relationship between the degree of size symmetry or asymmetry and the particular growth-limiting resources, many studies (Weiner et al., 1990) pointed out to an association between size-symmetric competition and competition for below-ground resources on the one hand, and between size-asymmetric competition and above-ground competition for light on the other.
- Site characteristics (Site index, elevation, soil depth, etc.) play the main role in driving tree growth.
- Competition and site index are the main factors on the mortality
- Larger trees are subject to Senescence that increases tree mortality further.

2. Emergence

A size deminsions of tree emerge from trees interactions. For example, tree diameter at breast height, tree height, crown ratio and stand density index.

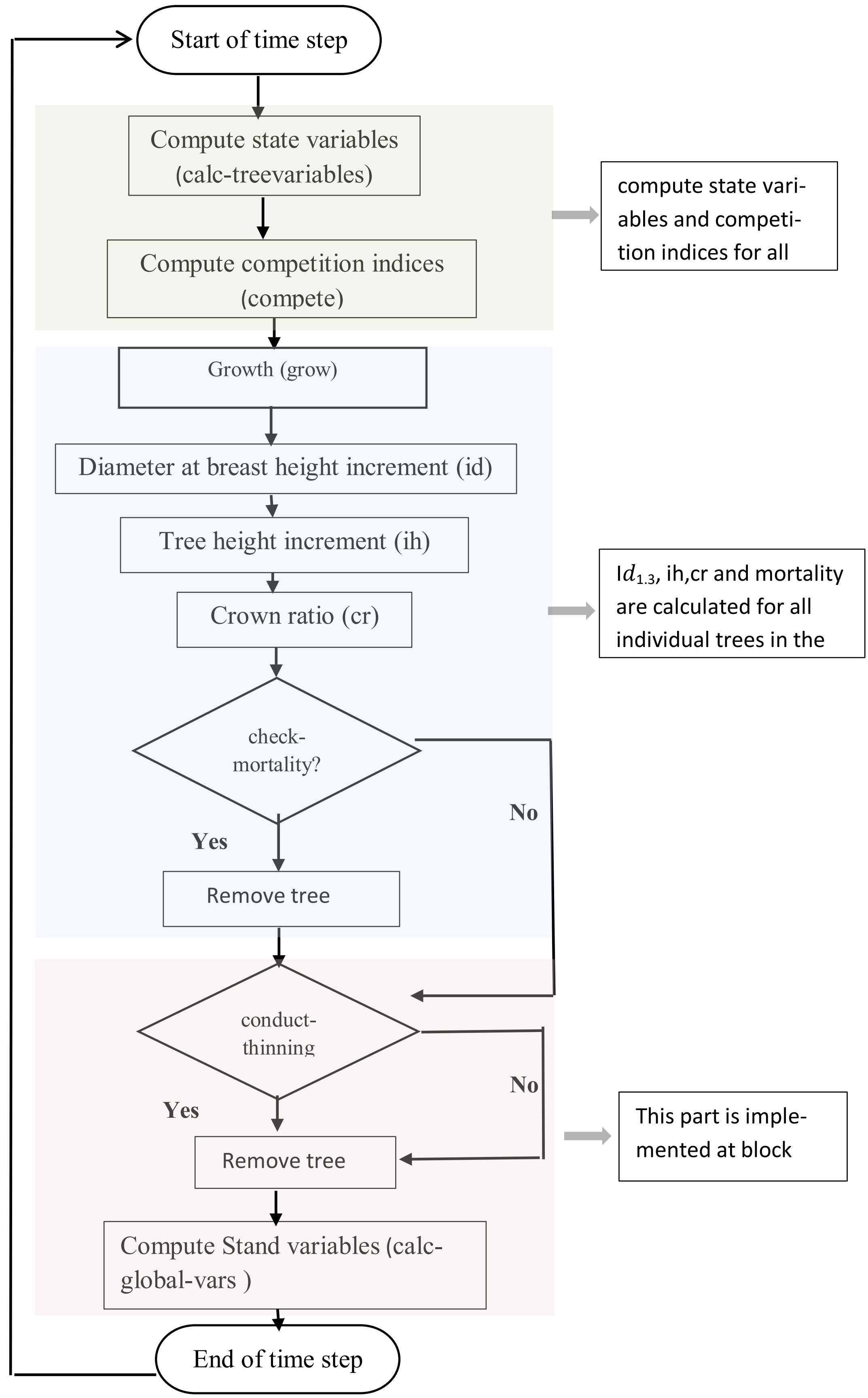


Figure 2-13:The proposed flowchart of the model processes in its execution order. The flowchart provides the sub-models (diameter at breast height increment, tree height increment and mortality) and calculations of competition indices, tree and stand variables

3. Interaction

Individual trees interact with each other through competition for resources. The competition effect alters individual-tree growth and its survival. This is described by two competition approaches (See sub-section 2.5.1): symmetric and asymmetric competition.

PINUS-Syria IBM represents both the symmetric competition and asymmetric competition. Crown competition factor and stand density index are examples for the symmetric competition, BAL and modified BAL are examples for the asymmetric competition. The selected indices todevelop the growth and mortality equations are explained in section 3-4.

4. Observation

Measures related to state variables: diameter at breast height, tree height, tree basal area, tree volume, form factor.

Variables describing the growth process of the individual trees: Diameter increment, height increment, crown ratio, probability of mortality and volume increment.

Variables at stand level: stand density, stand volume, stand basal area, stand current and mean annual volume increment which determines the optimal rotation age, stand mean height, quadratic mean diameter, stand crown ratio.

These measures are implemented every time step.

5. Sensing

Brutia pine trees “sense” all other trees in the plot in case of symmetric competition or all larger trees in case of asymmetric competition.

6. Stochasticity

The stochastic component are the random spatial distribution of the individuals at model initialization and mortality.

Objectives, learning, and predictions are not relevant.

7.Initialization

At the start of the simulation, individual trees are randomly distributed according to the chosen initial density. A tpical value of the initial density is 2000 trees distributed over the simulated area of (1) hectare and the buffer but can be varied according to the experimental design. The trees are randomly distributed. The initialization of the plot is done with

inventory data from trees are randomly distributed. The initialization of the plot is done with inventory data from the study site. Since no trees smaller than 5 cm were not measured in the stand, each simulated stand starts with an initial diameter at breast height 5 cm. The initial height is calculated by using a generalized height-diameter equation.

The site characteristics are assumed constant to be homogeneous for the whole plot across time in the simulation. The values of each site variable are derived from inventory data (Table 2-11). PINUS-Syria IBM provides the possibility to use other input data. The parameters of growth and mortality equations are assigned according to the individual-tree model as explained in section 6.

2.7.5 Sub-models

PINUS-Syria IBM model consists of three processes: the growth, mortality and thinning treatment. The growth includes three sub-routines calculating the:

- The diameter at breast height increment
- Tree height increment to evaluate the simulated height of trees, and the
- Crown ratio

The growth and mortality equations were explained methodologically in the previous section 2.6 and the developed equations are shown in the results chapter.

Tree and stand variables calculated for each time step simulation were explained in sub-sections 2.4.2 and 2.4.3.

- Thinning procedures

Regarding thinning treatments, the type of thinning from below is implemented because it is common in Middle East for even-aged stands. Thinning from below is a noncommercial thinning which was applied by cutting on a diameter basis, removing the smallest sizes (smallest diameters), leaving large trees (Marquis and Ernst, 1991).

Each treatment will be carried out with different densities (Table 2-12):

These treatments are applied in all site indices in brutia pine stands for once or twice (Table 2-11).

Table 2-11:Thinning treatments applied in the simulation model in different sites: Types of thinning, intensity, number of thinning

Site index	Types of thinning	Intensity of thinning	Number of thinning
10		**0 %** (No thinning)	One
15		10% (Light thinning)	
20	Thinning from below	20% (Moderate thinning)	
25		35% (Heavy thinning)	Two
30		45% (Very heavy thinning)	

2.8 Methods used for model evaluation

2.8.1 Sensitivity analysis

The research tested the relative importance of the parameters within the simulation model using global sensitivity analysis (Ginot et al., 2006). The study varied several input parameters over broad parameter ranges. The work performed analysis using Latin Hypercube Sampling (LHS), which is implemented in R (Carnell,2009). The research defined the range and distribution of each input parameters (Table 2-12). 300 sets of input parameters were generated for different combinations, then explicitly accounting for the partial correlation between the parameters to calculate the influence of the input factors on the model output.

Table 2-12:Input factors of *Pinus brutia* stands for the sensitivity analysis

	Site index	Elevation	Soil depth	Slope	Aspect
Range	10-30	100-1600	10-150	10-100	30-350
The used varying values	10-15-20-25-30	100-400-800-1200-1600	10-40-80-120-150	10-35-60-85-100	30-100-170-240-350

Simulations were carried out for 3125 parameter combinations with 10 repetitions each, and model outputs were stored after 70 years.

The simulated size of 1 ha was initialized with 2000 trees, and no further recruitment occurred during the simulation. The model outputs include stand volume (V), Quadratic mean diameter (Dq), mean stand height(H), mean annual volume increment(MAI), periodic annual volume increment (CAI), stand density index (SDI), mean diameter increment (mid), mean height increment (mih), mean crown ratio(mcr), Stand basal area (BA), mean basal area of trees larger than the subject tree (mbal) and mean probability of individual tree mortality (mpt).

2.8.2 Validation procedure

Unfortunately, the ideal is rarely available,so in this study after developing the site index, the appropriate decision was to take the different density and site index into account when selecting the validation plots, and that may provide a convincing test in the light of the data available (Vanclay and Skovsgaard, 1997). The work implemented the validation procedure but only for the diameter and height increment sub-models by using independent data, which came from 10 validation plots representing different site indices measured for first time in 2008 and were re-measured in 2016.

The work placed the independent data into individual-tree level simulation program and made simulations of trees growth.

The study evaluated simulation results using two steps: (1) simulated values were plotted against measured values, and sub-models residuals were plotted against simulated values.
(2) The methods presented in Table 2-13 as were estimated in the empirical study to determine the accuracy of sub-models predictions - were estimated to compare simulated and measured values for the developed sub-models.
Stand level variables like stand volum are very informative and easily calculated from tree level variables (Table 2-2) and were compared with stand variables measured in 2016.

Table 2-13:Methods of evaluation of individual-tree growth model

Performance criteria	Formula	Ideal
Model bias	$\frac{1}{q}\cdot\sum_{i=1}^{q}(\hat{Y}_i - Y_i)$	Zero
Relative bias	$\frac{\bar{e}\cdot 100}{\bar{Y}}$	Zero
Root mean square error	$\sqrt{\frac{\sum(Y_i-\hat{Y}_i)^2}{q-1}}$	Zero
Relative Root mean square error	$100\cdot\sqrt{\frac{\sum(Y_i-\hat{Y}_i)^2/(n-1)}{\sum\hat{Y}_i/n}}$	Zero
Model Precision	$S_e=\sqrt{\frac{\sum_{i=1}^{n}(\hat{Y}_i-\bar{e}-Y_i)^2}{q-1}}$	Zero
Relative Model Precision	$S_e\%=\frac{S_e\times 100}{\bar{Y}}$	Zero
Model Accuracy	$m_x=\sqrt{{S_e}^2+\bar{e}^2}$	Zero
Relative Model Accuracy	$m_x\%=\frac{m_x\times 100}{\bar{Y}}$	Zero

Y_i = Observed value k = Number of variables in the equation
$\bar{Y}$ = Average value of observations $\bar{e}$ = Model Bias
$\hat{Y}$ = Fitted value q = Number of observations
i = $1,\ldots,n$ (Soares et al., 1995, Weisberg, 2005; Pretzsch, 2009)

The study also validated the mortality equation by analyzing the characterization of the sub-model error. The probability of mortality for each tree was predicted. The predicted and observed mortality were then compared by visually studying deviations over the explicatory variables included in the model.
Described validation procedure will help to clarify if developed sub-models produce reliable predictions on the basis of independent data.Validation process is helpful procedure to assess if developed sub-models give reliable predictions.

3 RESULTS

3.1 Results of initial data processing

The following sections deal with a detailed description of the yield characteristics.

3.1.1 The results of height curve fitting

The first and most important step for modeling the tree height increment and to calculate stand variables was estimating the missing values of trees height which were not measured for each plot in both inventories. For this purpose, the study used Michailow (1943) equation.

According to the results of height curve fitting for both inventories (Appendices 4, 5, 6 and 7), the relationships between diameter at breast height and tree height are clearly plausible and not linear. Plausible curves mean that height curves produced by both inventories steadily shift to the right side of abscissa (X) axis and the upper side of the ordinate (Y) axis and do not intersect each other; these curves precisely follow the growth patterns of trees. This behaviour agrees with Yuancai and Parresol (2001) and Van Laar and Akça (2007) criteria (Section 2.4.1).

The coefficients of determination of the Micahilow (1943) equation ranges from 0.17 to 0.98.

The tree heights are strongly related to site productivity, and they are influenced by stand density so the values of height are considerably different from plot to plot in our study. The graphs in Figure 3-1 illustrate the difference of high curves among the plots which were taken as an example. The values of coefficient of determination in the low density stands are slightly smaller than those of high density stands. The height curves of plots belonging to good site quality are generally higher than those of plots on poorer site qualities.

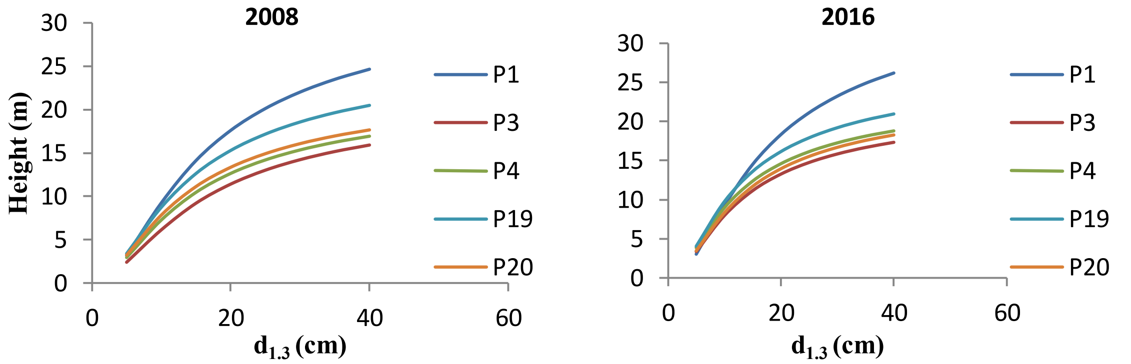


Figure 3-1: height curves of different plots for first (left) and second (right) inventory

By estimating the individual trees height in all plots in both inventories, the base for calculating the stand variables and developing the individual-tree height increment was prepared.

3.1.2 Calculation of stand variables

The calculations results of stand variables at the first and the second measurement as well as the dead trees between two measurements for each plot came mainly from re-parametrized Michailow equations which allow estimating stand mean height and stand top height (Appendices 8, 9, 10 and 11). By means of these calculations, it could easily calculate the most common stand variables (Husch et al., 2003; West, 2004; Van Laar and Akça, 2007) like stand basal area, stand volume, and number of trees per hectare for both inventories 2008 and 2016, and then the establishment of the relationships between variables (Table 3-1).

Table 3-1: Summary of yield characteristics (Quadratic mean diameter, mean stand height, stand basal area, stand volume, top stand diameter, top stand height and number of trees per hectare) for both inventories

	D_q cm		H m		BA $m^2. ha^{-1}$		V $m^3. ha^{-1}$		D_{100} cm		H_{100} m		N Tree. ha^{-1}	
	2008	2016	2008	2016	2008	2016	2008	2016	2008	2016	2008	2016	2008	2016
Min	10.0	11.8	5.9	9.2	6.1	15.4	13.5	37.8	15.7	17.6	9.4	10.0	224.0	219.0
Max	40.9	43.2	23.7	24.7	67.4	77.4	323.7	390.1	51.9	52.4	25.8	26.8	3144.0	3065.0
Mean	23.9	26.6	14.7	16.6	38.8	46.3	146.2	189.4	33.5	36.1	16.9	18.5	1027.5	1001.2
SD	7.9	7.9	4.4	4.4	14.0	14.6	74.5	89.8	9.1	8.8	4.5	4.7	678.6	659.8

BA = Stand basal area in ($m^2. ha^{-1}$)   Dq = Quadratic mean diameter (cm)

D_{100} = Top stand diameter (cm) H_{100} = Top stand height(m)

H = Mean stand height (m)   N = Number of trees per hectare

V = Stand volume ($m^3. ha^{-1}$)

These calculations at stand level not only give enough idea about the stand, but they also allow comparing different sites with each other. Considering the appendices 1 and 8, the calculations results show that stand variables considerably differ from plot to plot because of effect the density and the site productivity. The calculations also show that quadratic mean diameters are proportional to number trees per hectare, where the diameter increases as number of trees decreases, the number of trees very high in the stands with small trees and low in the stands with big trees, this relationship is so important in understanding the mortality process and how the density affects the growth. Diameter clearly affects the basal area and standing volume, where they increases with increasing the diameter, similar behavior was recorded for the relationship between standing volume and the tree height (Figure 3-2), but in the appendices, the reader can notice that some plots have similar values of diameter or height but different values of volume and basal area, this clearly indicates that diameter or height is not the only variable controlling the growth.

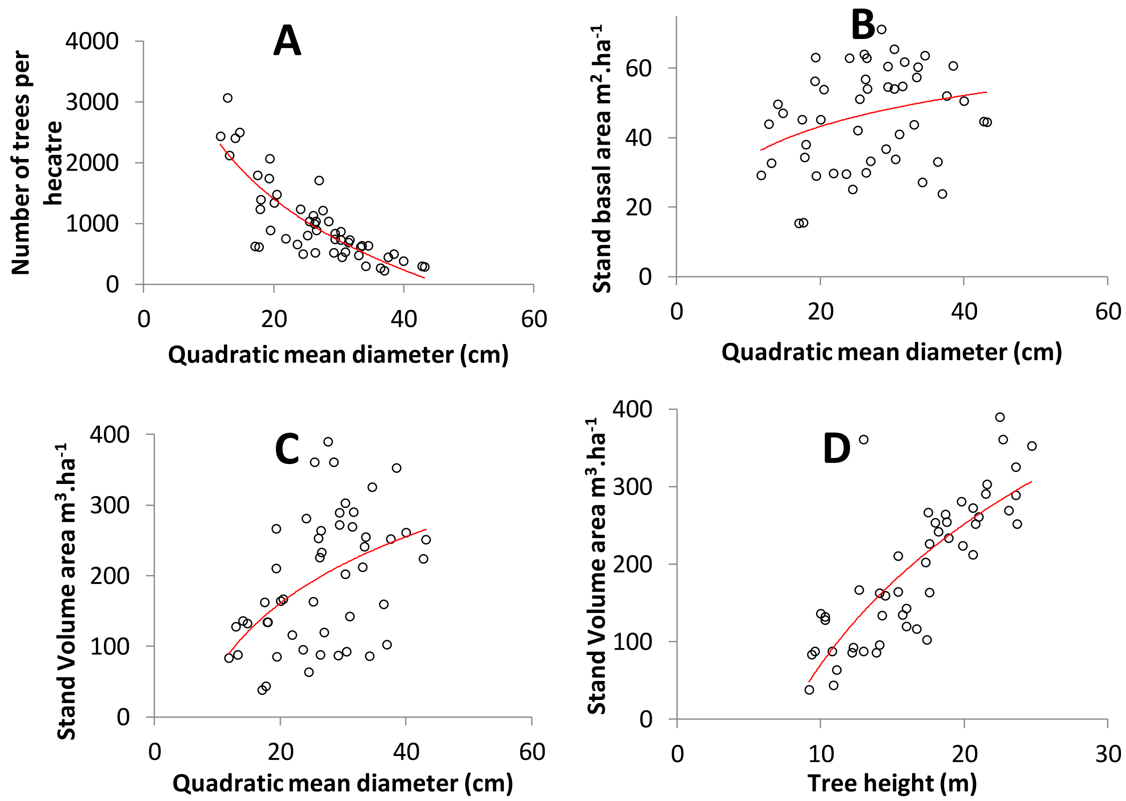


Figure 3-2: Relationships between most common stand variables for the plots which measured for modeling process; A: relationship between number of trees per hectare and quadratic mean diameter; B: relationship between stand basal area and quadratic mean diameter; C:relationship between stand volume and quadratic mean diameter; D: relationship between tree height and standing volume

72 removed trees (dead trees) from 39 modeling plots and 29 trees from validation plots were recorded; so, in each plot where dead trees were recorded, the following variables were calculated: number of removed trees per hectare, mean removed diameter at breast height, mean removed tree height, removed stand basal area and removed stand volume (Table 3-2). This step is necessary to model the individual-tree mortality.

Table 3-2: The main variables for the removed stands for the *Pinus brutia* forests

	$D_{q\ dead}$ cm	H_{dead} m	BA_{dead} $m^2.\ ha^{-1}$	N_{dead} Tree. ha^{-1}	V_{dead} m^3ha^{-1}
Min	5.2	2.8	0.0	5.1	0.1
Max	35.0	22.0	4.7	110.5	12.2
Mean	16.0	11.8	0.8	34.1	2.6
SD	6.9	5.2	1.0	29.7	3.0

N_{dead} = The number of dead trees dead per hectare, H_{dead} = Mean height of dead trees in each stand

Dq_{dead} = quadratic mean diameter of dead trees in each stand, V_{dead} = Stand volume of dead trees in each stand

BA_{dead} =Stand basal area of dead trees in each stand

3.1.3 Crown diameter curves

. To predict the crown diameter in 2016 inventory in each plot, a non-linear regression equation between tree crown diameter and diameter at breast height was used (Appendix 12 and

Appendix 13). When looking deeply at appendices 1,8 and 12; the study infers that the relations are different among plots, the difference are due to competition and site characteristics. The statistical analysis of the simple regression models was based on coefficients of determination (R^2), the equation's significance, standard errors and the coefficients' significance. The R^2 value ranges between 0.96 and 0.31. The values in high density stands are relatively better compared with those in low density stands.

By implementing this step, it is possible to calculate the crown competition factor as one of the tested competition indices.

3.1.4 Crown length curves

As explained in section 2.4.1 in methodology chapter, crown length was measured only for sample trees in the second inventory, so a logarithmic model between crown length and height relationship was used in each plot (Appendix 14 and Appendix 15).

The statistical analysis of the simple regression models was based on: coefficients of determination (R^2), the equation's significance, standard errors and the coefficients' significance. The relationships in this study explain between 44 % and 99 % of crown length variations. All regression models were highly significant. The R^2 values are relatively better in the high density stands and in the young aged-stands.

Calculating the crown length is considered the base for developing individual crown ratio equation.

By finding the relationships between crown diameter and diameter at breast height, relationship between crown length and tree height, the preparations of data for analyzing the competition, developing the site index and then in the developing the individual-tree growth model, were completed.

In the next section, the study will move to analyze the competition and determine the candidate competition indices to develop the equations included in the individual-tree growth model.

3.2 Competition indices

The first step to analyze the competition was estimating the relative basal area increment. The relationship between basal area increment and $d_{1.3}$ of the local trees was found; the non-linear regression explained 52 % of the basal area increment variation. The ratio between the actual basal area increment and predicted basal area increment is used to calculate the relative basal area increment. The same manner was applied for height increment, R^2 was 27 %.

3.2.1 Spearman correlation test

The next step in analyzing the competition was implementing a Spearman correlation test between various competition indices and both basal area increment and height increment.
Whether with height increment or basal area increment, the results showed that correlations with the distance-independent indices are stronger than with correlations distance-dependent indices.
In regard to basal area increment, the correlation test indicate that all distance-independent competition indices show a clear and negative significant correlation while the correlation with distance-dependent competition indices showed a clear and significant correlation with the exception of the Martin and Ek index and Rouvinnen 2 index which are statistically insignificant. In regard to height increment, results of the correlation test indicate that all distance-independent competition indices show a clear and negative significant correlation. Only BAL/BA index was statistically insignificant, whereas the correlation with distance-dependent competition indices was a clear and significant negative (Figure 3-3).

3.2.2 Determination of appropriate competition indices

The last step was selecting the candidate competition indices for modeling the diameter and height increment. The criterion for selecting the appropriate competition index that better relates to tree relative diameter and height increment was based on the coefficient of determination (R^2). The higher the value the better index expresses the relationship.
Values of R^2 vary according to tree dimension and competition index (Table 3-3). A table shows similar values of R^2 in each group, e.g., with the exception of two indices, R^2 values of the relationships between distance-independent indices and relative height increment range between 0.31 and 0.18. The difference is not so large. These results are expected because of the similarities in the indices' formulations and because of associations among the input variables (e.g., $d_{1.3}$, height) used to assess the size of competitors.

Table 3-3: Relationships between competition indices and relative basal area increment and relative height increment

Index	Distance-independent indices					
	Relative basal area increment			Relative height increment		
	R^2	Intercept	Parameter estimate a_1	R^2	Intercept	Parameter estimate a_1
CCF	0.37	1.0046	-0.948	0.19	0.9585	-0.313
Reineke	0.40	7.563	-0.961	0.31	3.5293	-0.378
BAL	0.40	4.2529	-0.836	0.20	2.1566	-0.31
Schröder	0.11	1.1988	-0.275	0.18	1.0401	-0.155
BA	0.35	0.6633	-0.283	0.28	2.3506	-0.358
BAL/d1.3	0.20	1.3604	-0.418	0.21	1.1054	-0.19
Heygie	0.003	1.3526	-0.057*	0.055	1.4025	-0.102*
BAL/BA	0.10	1.068	-1.52	0.01	0.988	-0.27*
Index	Distance-dependent indices					
	Relative basal area increment			Relative height increment		
	R^2	Intercept	Parameter estimate a_1	R^2	Intercept	Parameter estimate a_1
Heygie1	0.17	1.613	-0.373	0.049	1.102	-0.87*
Heygi2	0.14	1.520	-0.271	0.012	1.039	-0.35*
Martin	0.007	1.356	-0.047*	0.155	1.473	-0.099
Braath	0.14	1.649	-0.352	0.19	1.193	-0.137
Rouvinnen1	0.18	2.706	-0.479	0.139	1.587	-0.181
Rouvinnen 2	0.07	2.148	-0.244	0.081	1.459	-0.112
Rouvinnen 3	0.12	2.288	-0.367	0.158	1.562	-0.181
Rouvinnen 4	0.132	2.352	-0.384	0.201	1.647	-0.206

* = parameter not significant in parenthesis: standard error of the estimate; a_0 and a_1 = coefficients; R^2 = coefficient of determination.

More interesting is similarities to a large extent regarding R^2 between certain pairings of distance-dependent and distance-independent indices in case of relative height increment, that could be attributed to using the same input variables.

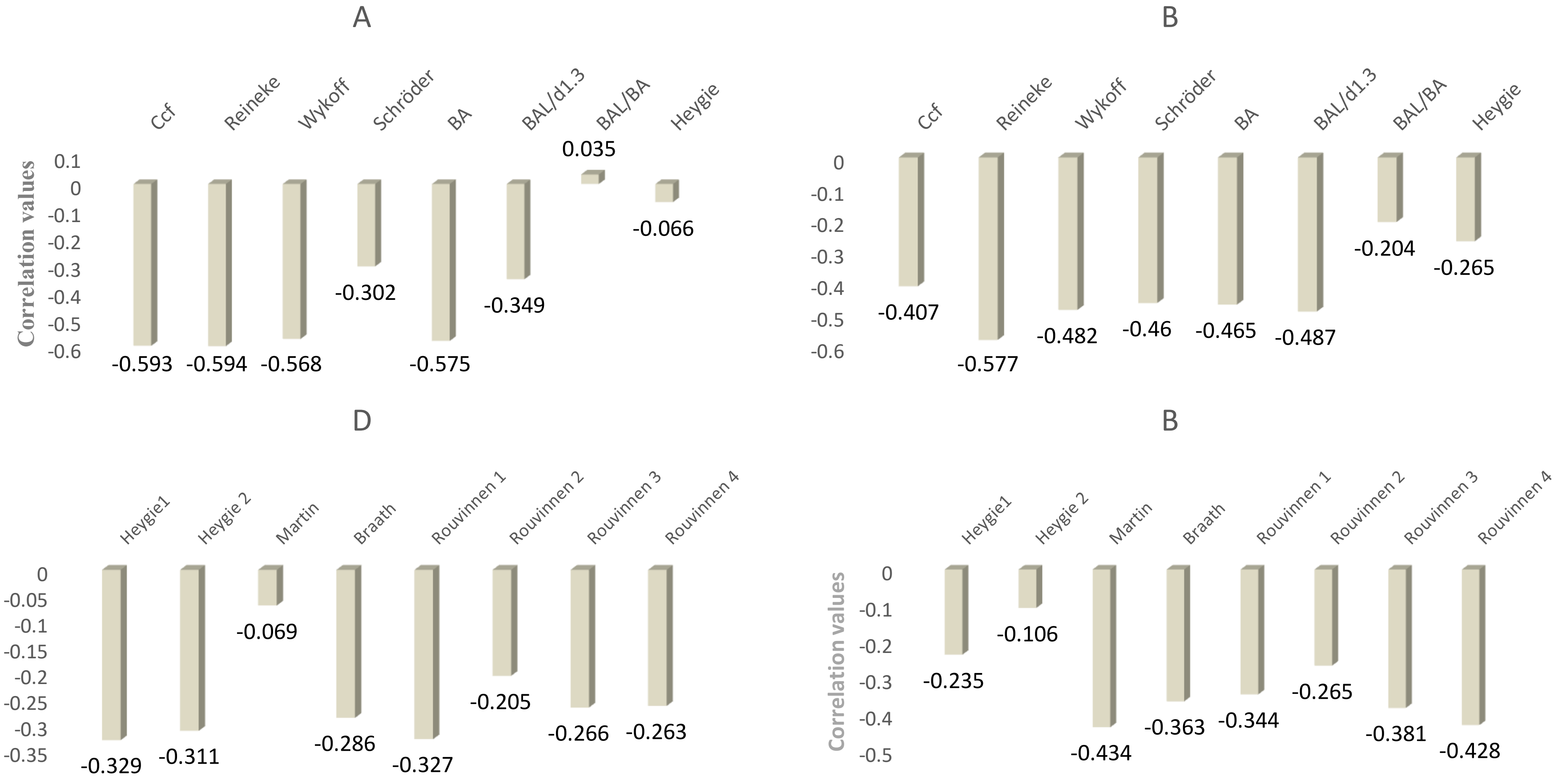


Figure 3-3: Correlation between competition indices and both basal area and height increment; A: Correlation between distance-independent competition indices and basal area increment; B: Correlation between distance-independent competition indices and height increment ;C: Correlation between distance-dependent competition indices and basal area increment ; D: Correlation between distance-dependent competition indices and height incremen

The value of the relative basal area decreases as competition index increases and the line of the best fit points down to the right, indicating a negative relationship between competition index and relative basal area increment (Figure 3-4), similarly observed for the relationship between relative height increment and competition indices.

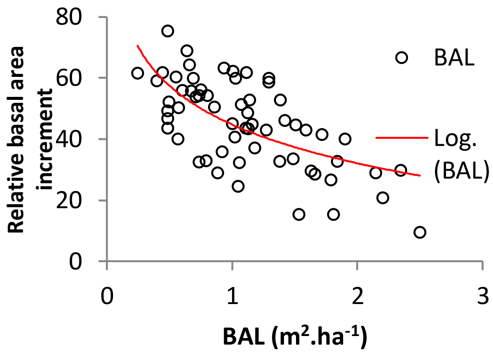


Figure 3-4: Relationship between BAL index and relative basal area increment The figure shows only the significant correlation between CIs and tree dimensions

The distance-independent competition indices which gave the best results in this analysis are the candidate for further analysis to model the diameter and height increment equation.

Before closing this part, it is important to highlight the relationship between productivity and competition which is the oft-observed point but still unclear. The results of this study suggest that measured productivity responds directly to competition whether distance-dependent or independent indices. Although not all the competition indices tested seem to give the same response to site productivity, but at all indices, it is noted that the higher the site index, the higher the competition on resources (Figure 3-5).

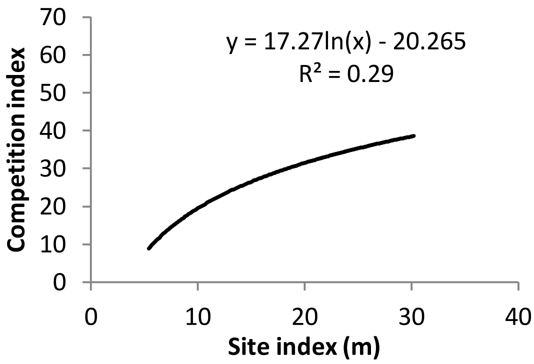


Figure 3-5: The relationship between site index and competition index in the modeling data

3.3 Site index

According to the descriptions in methodology chapter, ten equations could be adapted to the value pairs from age t and upper level H_{100}. The estimated parameters for each equation are listed in Table 3-4. All the parameters were found to be significant at 5% level.

Table 3-4: Estimated parameters and coefficient of determination of tested site index equations

Model	Parameter			R^2
	b_0	b_1	b_2	
Korf (1939)	59.53		0.558	0.955
Schumacher (1939)	45.314		47.407	0.965
Hossfeld	-65975.7	0.002	1.236	0.966
Korf I	47.576	12.666		0.967
King-Prodan	1.59	-28.321	1213.806	0.97
Hossfeld I (Kiviste et al.,2002)	8.712		0.024	0.967
Strand (1964)	0.01	0.00042	0.999	0.969
Amateis and Burkhart (1985)	-1.354	-0.292		0.77
Sloboda (1971)	1.446	0.804	2075.73	0.99
McDill and Amateis (1992)	38.51	1.289		0.966

The analysis of the fit statistics revealed that the Amateis and Burkhart (1985) equation performed relatively poorly for fitting and validation when compared with other equations. It explained only 77 % of the total dominant height variations. Other equations gave similar results in terms of statistical tests with a slight superiority of Sloboda equation, which gave the highest accuracy and precision for fitting and validation data (Table 3-5).

Table 3-5: Results of different statistical tests made to candidate equations for the plots

Model	Bias	Relative bias	Precision	Relative precision	Accuracy	Relative accuracy
Modeling Data						
Korf (1939)	0.105	0.573	0.757	4.138	0.765	4.178
Schumacher (1939)	0.058	0.318	0.767	4.191	0.769	4.203
Hossfeld	0.041	0.222	0.762	4.164	0.763	4.170
Korf I	0.033	0.182	0.720	3.932	0.720	3.936
King-Prodan	0.0136	0.0741	0.6507	3.5553	0.6509	3.5561
Hossfeld I (Kiviste et al.,2002)	0.030	0.163	0.718	3.925	0.719	3.928
Strand (1964)	-0.07	-0.40	0.68	3.71	0.68	3.73
Amateis and Burkhart (1985)	-1.67	-9.15	4.48	24.49	4.79	26.14
Sloboda (1971)	0.038	0.205	0.633	3.457	0.634	3.463
McDill and Amateis (1992)	0.106	0.581	0.736	4.023	0.744	4.064
Test data						
Korf (1939)	0.030	0.164	0.947	5.172	0.947	5.174
Schumacher (1939)	0.011	0.057	0.704	3.848	0.704	3.849
Hossfeld	0.011	0.061	0.832	4.544	0.832	4.545
Korf I	-0.031	-0.172	0.783	4.276	0.783	4.279
King-Prodan	-0.032	-0.175	0.664	3.630	0.665	3.634
Hossfeld I (Kiviste et al.,2002)	-0.027	-0.145	0.789	4.313	0.790	4.316
Strand (1964)	-0.100	-0.547	0.803	4.386	0.809	4.420
Amateis and Burkhart (1985)	-1.71	-9.36	5.28	28.85	5.55	30.33
Sloboda (1971)	-0.017	-0.091	0.609	3.328	0.609	3.329
McDill and Amateis (1992)	0.032	0.176	0.890	4.864	0.891	4.867

The relative errors (RE) by age were computed to determine the most appropriate reference age and the results showed that the age 48 (years) results are in lowest error value of predictions, so the reference age was approximated to 50 (years) (Figure 3-6).

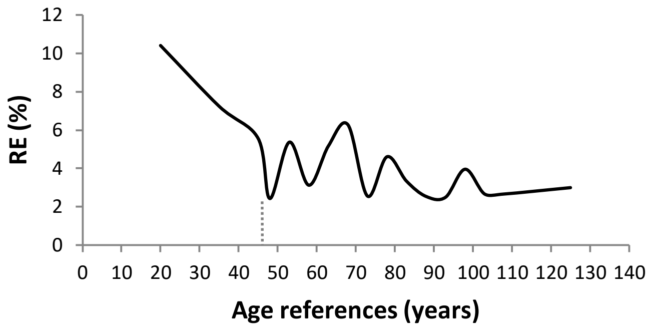


Figure 3-6: Relative error in dominant height predictions related to choice of reference age for model for Sloboda equation

Since the statistical analysis alone is not sufficient, the graphical tests were taken into account and for this purpose, the parameters were used to generate site index curves in order to know how well the data is distributed with the developed equations. Five classes were determined based on reference age 50: 10, 15, 20, 25 and 30 m.

The equations represented well the dominant height development for plots over age (Figure 3-7) and (Appendix 16). The shapes of the curves from these equations seem to be biologically reasonable. The site index values in Sloboda for all plots at 50 years ranged between 5.4 m and 30.2 m. The height is zero at age zero and equal to site index at reference age. They are polymorphic curves, there is an inflection point and base-age invariance.

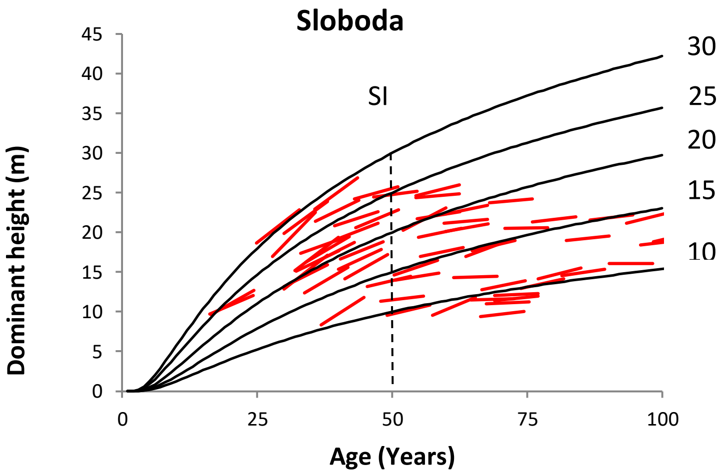
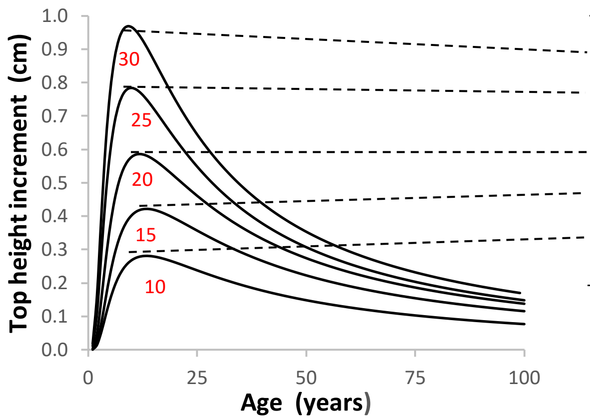


Figure 3-7: Distribution of dominant height development (2008-2016) with the developed site index equations which categorized into five site classes (10, 15, 20, 25, and 30)

By applying Sloboda equation, Figure 3-8 shows a culmination of increment height between 9 years in site Class 30 and 14 years in site Class 10. It follows the common pattern (culmination of increment top height and then decline as age increases) for the top height increment in forestry.



SI 50 [m]	Age [years]	Annual top height Increment [m]
30	9	0.968
25	10	0.784
20	12	0.586
15	13	0.422
10	14	0.281

Figure 3-8: Site index system (SLOBODA equation) for Pinus brutia stands with corresponding development of dominant height growth

The error distributions are presented for the data used in fitting the equations and the bias does not correlate with stand top height and stand age. Figure 3-9 presented Sloboda equation as an example to explain this point. Sloboda equation met the nonlinear assumptions; and is statistically considered quite adequate.

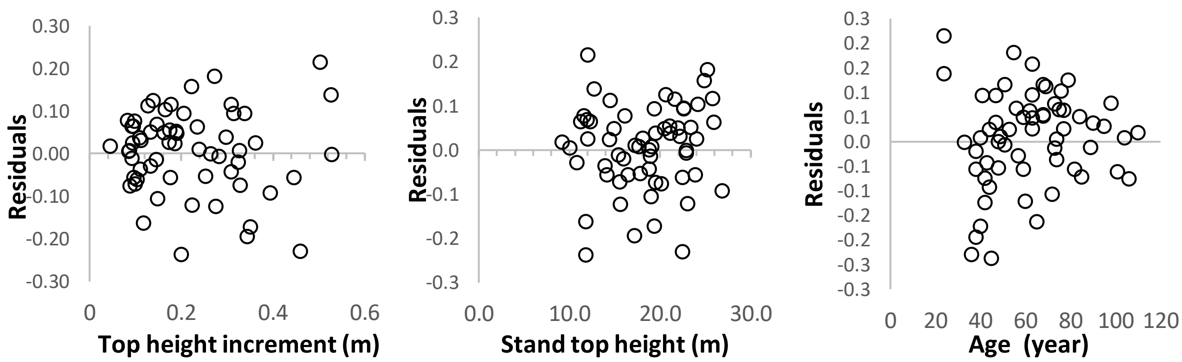


Figure 3-9: The relationship between residuals of fitted equation (Sloboda equation) and each of top height increment stand top height and stand age

Based on the above findings, Sloboda equation was confirmed as most appropriate for site index characterization of *Pinus brutia* stands in Syria, which is considered an indispensable factor to develop the individual-tree growth model.

After processing the data, analyzing the competition and developing the site index, the road is paved for developing the individual-tree growth model.

3.4 Individual-tree growth model

When selecting the equations of diameter increment, height increment, crown ratio, generalized height-diameter relationship and mortality, the assumptions for multiple linear, nonlinear and logistic regressions were satisfied, e.g. any relationship that violates accepted biological principles was rejected even if it results in efficient predictions for a particular data set, the goodness of fit was executed as well as the statistical significance of the parameters and unbiased distribution of residuals.

3.4.1 Diameter increment equation

The predictor variables determined in chapter 2 were tested using the empirical single tree increment data, and the results of fitting different equations were compared to select the best equation. Finally, the following form turned out to be best:

$$\ln(Id_{1.3}) =: \boldsymbol{\beta_0} + \boldsymbol{\beta_1} \cdot \ln(\boldsymbol{d_{1.3}}) + \boldsymbol{\beta_2} \cdot \boldsymbol{d_{1.3}}^2 + \boldsymbol{\beta_3} \cdot \ln(\boldsymbol{SI}) + \boldsymbol{\beta_4} \ln(\boldsymbol{SL} \cdot \cos(\boldsymbol{ASP})) + \boldsymbol{\beta_5} \cdot \boldsymbol{SDI} + \boldsymbol{\beta_6} \cdot \boldsymbol{BAL} + \boldsymbol{\varepsilon} \quad (26)$$

Where: SL is the slope angle in percent, ASP is the aspect in radians, ln ($d_{1.3}$) is the value of the natural logarithm of $d_{1.3}$ (cm); ${d_{1.3}}^2$ is the value of the square of $d_{1.3}$ (cm); BAL: basal area of trees larger than the subject tree; SDI: Stand density index, $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6$ are regression coefficients; ε = error of the estimate

All parameter estimates of the diameter growth equation are logical and significant at the 0.001 level and the highest value of the standard error of coefficients was 0.076 (Table 3-6). The equation showed good performance for explaining the variations in diameter increment, where the coefficient of determination (R^2) was 0.58 and that means the equation can explain 58% of the variation of diameter increment for *Pinus brutia* in the coastal region in Syria.

Table 3-6: Estimates of the parameters, significance and stand error of each parameters of *Pinus brutia* diameter increment equation

Equation	Unstandardized Coefficients		Unstandardized Coefficients	t	P.value
	B	Std.Error	Beta		
Constant	-2.971	0.076	-	-39.261	0.000
Ln($d_{1.3}$)	0.211	0.029	0.187	11.259	0.000
(${d_{1.3}}^2$)	-0.0001	0.000	-0.126	-7.368	0.000
SDI	-0.001	0.000	-0.658	-44.551	0.000
BAL	-0.013	0.000	-0.122	-8.294	0.000
Slo.Cos(ASP)	0.019	0.002	0.103	8.097	0.000
Ln(SI)	0.865	0.019	0. 676	45.56	0.000

Where: SDI is stand density index (N/ha), and BALis the basal area in larger trees (m^2 /ha), SL is the slope angle in percent, ASP is the aspect in radians, ln(dbh) is the value of the natural logarithm of $d_{1.3}$ (cm); ${d_{1.3}}^2$ is the value of the square of $d_{1.3}$ (cm), $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6$ are regression coefficients

The positive parameters for variable natural logarithm of diameter at breast height and negative parameter for squared diameter at breast height (Both represent the tree size) confirm the presumed relationship between tree growth and tree diameter, that is, for a given set of stand conditions trees grow at low level when young, increase to maximum point and then decline thereafter. Competition is represented by stand density index and basal area larger than the subject tree (BAL) index which are distance-independent competition indces. Stand density index is a relative measure of stand density the converts a stand's current density into a density at a reference size. It is an effective index of competition in pure, even-aged stands (Uzoh and Oliver, 2008; Weiskittel et al, 2011) and represents two-sided (symmetric). Another competition index is BAL. BAL index is the total basal area per hectare in trees that are larger than the subject tree. It represents an expression of the relative social rank of the subject tree in terms of basal area. It represents the one-sided competition (asymmetric competition). The sign of the parameters of BAL and stand density index, is all negative, it implies that the diameter increment is significantly and negatively related to BAL and stand density index for *Pinus brutia* stands. Site index, slope and aspect represent the site characteristics. The positive sign of the site index indicates that trees grow obviously more rapidly on the good site quality than on bad site quality. This is consistent with the definition of site productivity trees grow faster on the better sites, whereas the small value of positive sign of slope and aspect parameter show the a bit positive effect on tree diameter.

Table 3-7 shows the partial effect of each explanatory variable such as on the predicted diameter increment, holding the others constant at their sample mean.

Table 3-7: The partial coefficient of correlation which assesses the contribution of each variable on the dependent variable

Variable	Partial coefficient of Correlation
$\ln(d_{1.3})$	0.133
$(d_{1.3}{}^2)$	-0.095
SDI	-0.631
BAL	-0.150
Slo.Cos(ASP)	0.146
Ln(SI)	0.640

Where: SDI is stand density index (N/ha), and BAL/$d_{1.3}$ is the basal area in larger trees (m^2 /ha), SL is the slope angle in percent, SI is the site index(m), ASP is the aspect in radians, ln(dbh) is the value of the natural logarithm of $d_{1.3}$ (cm); $d_{1.3}{}^2$ is the value of the square of $d_{1.3}$ (cm), β_0, β_1, β_2, β_3, β_4, β_5 , β_6 are regression coefficients

The residual plots of the final individual-tree diameter increment equation for *Pinus brutia* are given in Figure 3-10. They proved that there were no obviously observable patterns on these residual plots.

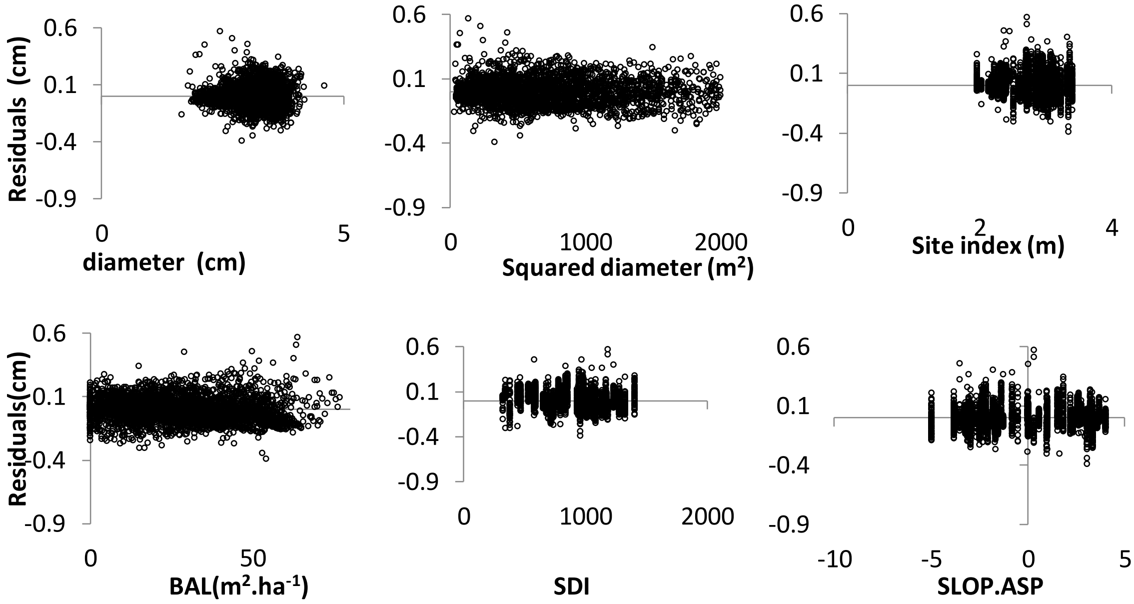


Figure 3-10: The relationship between residuals of diameter increment equation and variables used in constructing the equation (Natural logarithm of site index, squared diameter at breast height, aspect and slop, natural logarithm of diameter at breast height, basal are of trees larger than the subject tree divided by diameter at breast height, stand density index), this step as one of set of steps to make sure if regression assumptions are satisfied.

Due to the logarithmic transformation of the predicted variable, a Snowdon correction factor was calculated and applied for the equation to remove bias from back-transformed Predictions (Snowdon 1991). The correction factor in this study was equal to 0.85. A prediction of annual year future growth ($id_{1.3}$, corrected) is calculated as:

$$Id_{corrected} = 0.85 \cdot \exp(\ln(\mathrm{I}d_{1.3}))$$

(27)

Where: ln (Id) is the prediction of the logarithmic model (Equation 26).

The diameter increment equation was evaluated by root mean square error (RMSE) and relative root mean square error. These tests were 0.09 cm and 17% respectively.

In addition to the developed equation, one supplementary equation for diameter increment equation was fitted without geo-climatic variation (OGV) and evaluated exactly according to the previous steps explained above:

$$\ln(\mathrm{I}d_{1.3}) = -2.785 + 0.166 \cdot \ln(d_{1.3}) - 9.2 \times 10^{-5} \cdot d_{1.3}{}^2 + 0.860 \cdot \ln(SI) - 0.001 \cdot SDI - 0.013 \cdot BAL \quad (28)$$

All parameter estimates of the diameter growth equation are logical and significant at the 0.001 level. The equation showed good performance for explaining the variations in diameter increment, where the coefficient of determination (R^2) was 0.57 and that means the equation can explain only 0.01 of variation of diameter increment less than the diameter increment equation with OGV.

3.4.2 Development of height increment equations

3.4.2.1 Development of realized height increment equation

The following height increment equation is a function of tree size, site characteristics and competition (Lemmon and Schumacher, 1962; Beck, 1974; Wykoff et al., 1982):

$$\ln(Ih) =: \beta_0 + \beta_1 \cdot \ln(d_{1.3}) + \beta_2 \cdot h^2 + \beta_3 \cdot \ln(SI) + \beta_4 \cdot \ln(ELEV) + \beta_5 \cdot \ln(depth) + \beta_6 \cdot \frac{BAL}{d1}.3 + \varepsilon \quad (29)$$

Where: ln(ELEV) is the elevation in meters, ln (depth) is natural logarithm of soil depth in stand(cm), ln($d_{1.3}$) is the value of the natural logarithm of $d_{1.3}$ (cm); h^2 is the value of the square of h (m),BAL/$d_{1.3}$:basal area of trees larger than the subject tree divided by diameter at breast height , β_0, β_1, β_2, β_3, β_4, β_5 , β_6 are regression coefficients

All parameter estimates of the height growth equation are logical and significant at the 0.001 level (Table 3-8) and the highest value of the standard error of coefficients was 0.25. The equation showed reasonable performance for explaining the variations in diameter increment, where the coefficient of determination (R^2) was 0.36 and that means the equation can explain 58% of the variation of diameter increment for *Pinus brutia* in the coastal region in Syria.

Table 3-8: Estimates of the parameters, significance and stand error of each parameter of *Pinus brutia* height increment equation

Equation	Unstandardized Coefficients		Unstandardized Coefficients	t	P.value
	B	Std.Error	Beta		
Constant	-3.361	0.255		-13.162	0.000
Ln($d_{1.3}$)	-0.826	0.055	-0.445	-27.619	0.000
(h^2)	0.001	0.000	-0.219	-8.624	0.000
Ln(SI)	1.562	0.043	0.741	36.180	0.000
Ln(ELEV)	0.153	0.024	0.094	6.309	0.000
Ln(depth)	-0.080	0.032	-0.039	-2.469	0.000
BAL/$d_{1.3}$	-0.227	0.017	-0.329	-13.211	0.000

Where: BAL/ $d_{1.3}$ is the basal area of trees larger than the subject tree (m^2 /ha) divided by diameter at breast height (cm), SL is the slope angle in percent, ASP is the aspect in radians, ln(ELEV): the elevation in meters, ln(depth) is natural logarithm of soil depth in stand(cm), ln($d_{1.3}$): the value of the natural logarithm of $d_{1.3}$ (cm); h^2: the value of the square of $d_{1.3}$ (cm)

Tree size is represented by the natural logarithm of diameter at breast height and squared tree height (Monserude and Sterba, 1996; Uzoh and Oliver, 2006). Site index, elevation (m) and soil depth (cm) are included in the equation as representative of physiographic and topographic variables (Monserude and Sterba, 1996; Uzoh and Oliver, 2006). Site index, elevation and soil depth represent the site characteristics. The positive sign of the site index indicates that trees grow obviously more rapidly on the better sites than on poorer ones, while the elevation and soil depth have smaller effect on height growth.

Competition is represented by modified BAL index (BAL/$d_{1.3}$) (Hamilton, 1986). The negative sign of the parameters of BAL/$d_{1.3}$ indicates that the diameter increment decreases as BAL/$d_{1.3}$ increases.

To determine the contribution of each variable on the dependent variable which is in this study the height increment, the partial coefficient of correlation was applied. Table 3-9 indicated the site index was the strongest individual predictors than any other variable, followed by the natural logarithm of diameter at breast height.

Table 3-9:The partial coefficient of correlation which assesses the contribution of each variable on the dependent variable

Variable	Partial coefficient of Correlation
$Ln(d_{1.3})$	-0.266
(h^2)	-0.157
Ln(SI)	0.554
Ln(ELEV)	0.115
Ln(depth)	-0.045
$BAL/d_{1.3}$	-0.236

Where: $BAL/d_{1.3}$: the basal area of trees larger than the subject tree (m^2 /ha) divided by diameter at breast height, Ln(ELEV) : the elevation in meters, ln (depth) is natural logarithm of soil depth in stand (cm), ln ($d_{1.3}$): the value of the natural logarithm of $d_{1.3}$ (cm); h^2 : the value of the square of $d_{1.3}$ (cm)

At last, the residuals do not correlate with variables used in construction of linearized height increment equation as the following (Figure 3-11) showed:

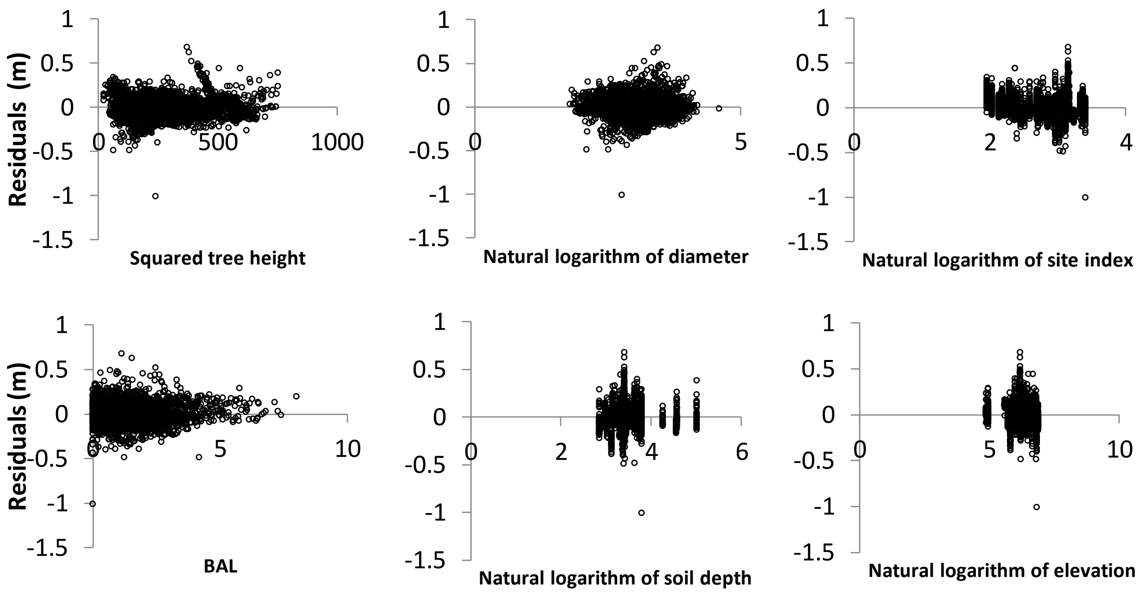


Figure 3-11: The relationship between residuals of height increment equation and set of variables used in constructing the equation (natural logarithm of depth, ratio of basal are of trees larger than the subject tree and diameter at breast height, elevation, squared tree height, natural logarithm of diameter at breast height, natural logarithm of site index).This step as one of set of steps to make sure if regression assumptions are satisfied.

Due to the logarithmic transformation of the predicted variable, a Snowdon correction factor was calculated for the equation to remove bias from back-transformed predictions (Snowdon 1991). The correction factor was equal to 0.917. A prediction of future annual height increment (Ih, corrected) is calculated as:

$$Ih_{corrected} = 0.917 \cdot \exp(\ln(\mathrm{Ih})) \quad (30)$$

Where: ln (Ih) is the prediction of the logarithmic model equation (29)

In addition to the developed equation, one supplementary equation for diameter increment equation was fitted without (geo-climatic variation (OGV)) and evaluated exactly according to the previous steps explained above:

$$\ln(Ih) = -2.907 - 0.766 \cdot \ln(d_{1.3}) - 0.001 \cdot h^2 + 1.580 \cdot \ln(SI) - 0.215 \cdot BAL/d_{1.3} + \varepsilon \quad (31)$$

Where: $\ln(d_{1.3})$ is the value of the natural logarithm of $d_{1.3}$ (cm); h^2 is the value of the square of h (m),$BAL/d_{1.3}$:basal area of trees larger than the subject tree divided by diameter at breast height

All parameter estimates of the diameter growth equation are logical and significant at the 0.001 level. The equation showed good performance for explaining the variations in diameter increment, where the coefficient of determination (R^2) was 0.35 and that means the equation can explain only 0.01 of variation of height increment less than the height increment equation with OGV.

3.4.2.2 Development of potential-modifier height increment

The potential top height increment was calculated as differences between two successive of top heights in two inventories.

Then, the reparametrized nonlinear height increment equation (Nagel, 1999) is as follows:

$$Ih = h \times (\frac{IH_{pot}}{h_{100}}) + 0.407 \cdot \left(\frac{H_{100}}{h}\right)^{1.709} \quad (32)$$

Where: Ih: tree height increment; IH_{pot}: potential stand top height increment; h: tree height in m, H_{100}: stand top height (dominant height) in m, a_0, a_1 : coefficients

Table 3-10 shows the main statistical parameters of this equation,and the equation shows no multicollinarity.

Table 3-10:The coefficient of variables for potential modifier height increment equation and correlation matrix between the independent variable used in modeling

Adjusted R^2	Coefficients		Correlation	
	Value	Std err	a_0	a_1
0.52	0.407	0.018	1	-0.747
	1.709	0.124	-0.747	1

Where: Std Err=standard error.

Figure 3-11 showed that the predicted height increment correlates well with the observed increment. R^2 is 0. 54.

The following Figure 3-12 visualizes the homogeneity of variance of equation’s residuals for modelled height increment and the tree height.

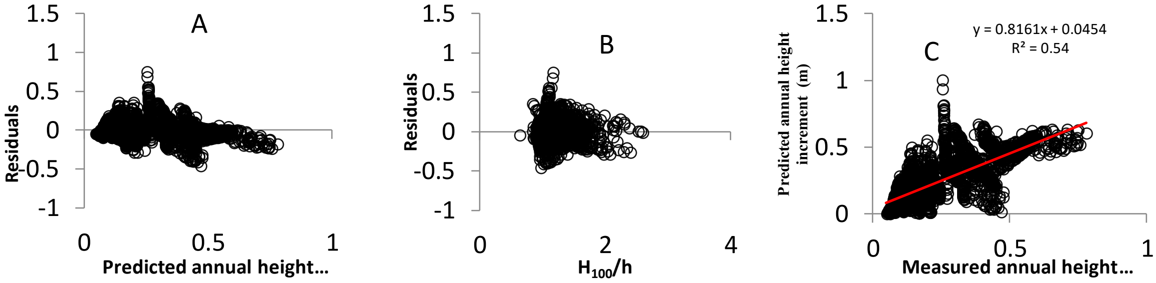


Figure 3-12: The relationship between residuals of height increment equation and modelled height increment (A) and ratio of stand top height and tree height (B); the relationship between predicted and measured height increment(c).

The linearized height increment equation was evaluated by calculating absolute and relative root mean square error (RMSE). These tests gave good results where the absolute and relative RMSE were 0.11 m, 23.1 % respectively; the same tests were applied on potential-modifier height increment equation. These tests gave good results where the absolute and relative RMSE were 0.11 m, 22.19% respectively.

Adjusted R-squared value of potential modifier height increment was 0.52 and adjusted R-squared value of realized height increment was 0.49, the RMSE for potential modifier height increment and linearized height increment were 22.19, 23.1 respectively.

To sum it up, the developed height increment equations satisfies the linear and nonlinear regression assumptions by using a set of tests. The potential modifier height increment gave relatively higher performance than realized modifier height increment based on Fitting statistics' results.

3.4.3 Crown ratio equation

The combinations of variables that showed a good performance in the all possible regression algorithm were tested in order to select the best nonlinear model, exponential, logistic, or Richards equation.

Also, correlation analysis was carried out to give an insight into the association between crown ratio and the growth variables. It was observed from the correlation matrix presented in Table 3-11 that crown ratio decreased with increasing tree size and competition.

Table 3-10: Correlation matrix for individual-tree crown ratio

		CR	SDI	BAL	lnSI	Squared $d_{1.3}$	$d_{1.3}$
Pearson Correlation	**CR**	1.000	-.671	-.322	-.782	-.147	-.297
	SDI	-.671	1.000	.475	.465	-.034	.008
	BAL	-.322	.475	1.000	.245	-.361	.065
	lnSI	-.782	.465	.245	1.000	.197	.279
	Squared $d_{1.3}$	-.147	-.034	-.361	.197	1.000	.576
	$d_{1.3}$	-.297	.008	.065	.279	.576	1.000

Table 3-12 presents the selected versions of the exponential, logistic and Richard equations. These equations used diameter at breast height and squared diameter at breast height to represent the tree size, stand density index and basal area of trees larger than the subject tree to represent the competition, site index to represent the site characteristics.

Table 3-11: Selected tree crown ratio equations

Model	Examined equations
Hasenauer and Monserud, 1996	$(1+\exp(-4{,}178 + 0{,}001 \times SDI - 0.002 \times BAL + 0.926 \times lnSI - 6{,}6 \times 10^{-5} \times {d_{1.3}}^2 + 0{,}011 \times d_{1,3})^{-1}$
Popoola and Adesoye, 2012	$(1+\exp(-(8.356 - 0{,}002 \times SDI + 0.004 \times BAL - 1.852 \times lnSI + 0.00013 \times {d_{1.3}}^2 - 0{,}022 \times d_{1,3}))^{-\frac{1}{2}}$
Leites et al., 2009	$\exp(0.782 - 0{,}00039 \times SDI + 0.00099 \times BAL - 0.312 \times lnSI + 3.08 \times 10^{-5} \times {d_{1.3}}^2 - 0{,}004 \times d_{1,3})^{-1}$

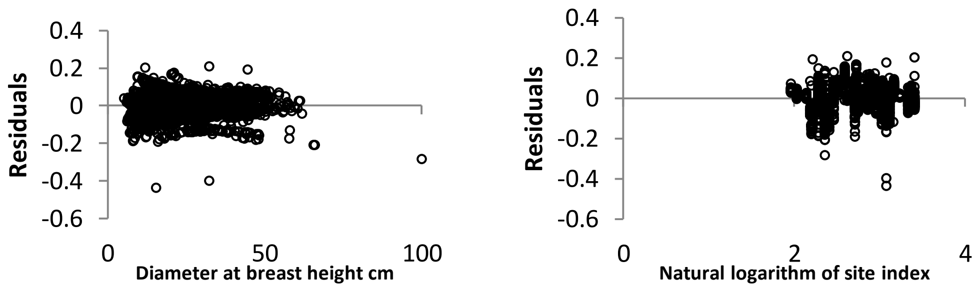
Where: SDI is stand density index, and BAL is the basal area in larger trees (m^2 /ha), $d_{1.3}$is the diameter at breast height (cm) . SI is the site index (m)

By evaluating the equations, Table 3-13 showed the exponential equation gave the best results (higher adjusted R^2 and lowest values of root mean square error and relative root mean square error).

Table 3-12: Predicted statistics for crown ratio equation using the modeling data

Model	R^2	RMSE	Relative RMSE
Hasenauer and Monserud, 1997	0.735	0.078	10.02
Popoola and Adesoye, 2012	0.735	0.23	35.4
Leites et al., 2009	0.764	0.068	8.6

In addition, the residuals do not correlate with variables used in construction of crown ratio equation (Figure 3- 13).



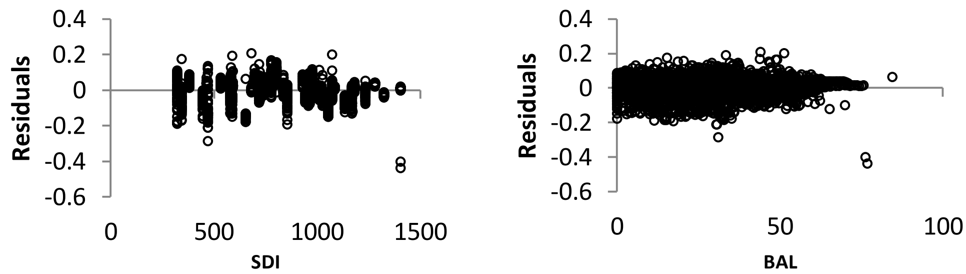


Figure 3-13:Relationship between residual and estimated CR using exponential equations.

Given the results of tests, the exponential equation gave best results among the tested equations and satisfied the nonlinear regression assumptions.

3.4.4 Generalized height-diameter relationship

The candidate height-diameter equations which have one to four parameters were re-parameterized, and all the equations were found to be the best fit for the data significantly at value = 0.05. The coefficient of determination (R^2) values for all the fitted equations were ranged from 0.50 to 0.81 (Table 3-14).

Table 3-13: Estimates of the parameters of generalized height-diameter equation of *Pnus brutia*

Equation	Estimated Parameters			
	b_0	b_1	b_2	b_3
Harrison et al. (1986)	441.06	0.037	3.98×10^{-5}	-
Hui and Gadow (1993)	0.323	0.397	0.387	0.480
Mirkovich (1958)	2.927	1.033	0.003	9.489
Stoffels and Van Soest modified by Tomé (1988)	0.559	-	-	-

The parameter estimates and the goodness-of-fit statistics of the different generalized height-diameter equations tested are shown in Table 3-15. The equation that performed best (lowest values of bias, relative bias, precision and accuracy and highest values of adjusted R^2) was the equation proposed by Mirkovich (1958).

Equation proposed by Hui and Gadow (1993) performed adequately accounted for approximately the same percentage of variance as an equation proposed by Mirkovich (1958).

Table 3-14: Selection statistics of the general height-diameter equation for brutia pine stands in the coastal region in Syria

Equation	R^2	Bias	Relative Bias	Precision	Relative Precision	Accuracy	Relative accuracy
Harrison et al. (1986)	0,506	0.74	4.73	3.98	25.4	6.18	39.56
Hui and Gadow (1993)	0.808	0.079	0.507	2.58	16.51	2.63	16.83
Mirkovich (1958)	0. 81	0.018	0.115	2.53	16.22	2.54	16.24
Stoffels and Van Soest modified by Tomé (1988)	0.76	0.7	4.47	2.82	18.03	5.29	33.86

In addition to the previous steps, the tested equations involved visual examinations of residuals against the predicted values. Figure 3-14 shows the residuals plotted against predictions of height for Mirkovich equation as an example. Graphical diagnostics of residuals for the height predictions indicated that the differences between predicted and actual values are approximately normally distributed in all equations.

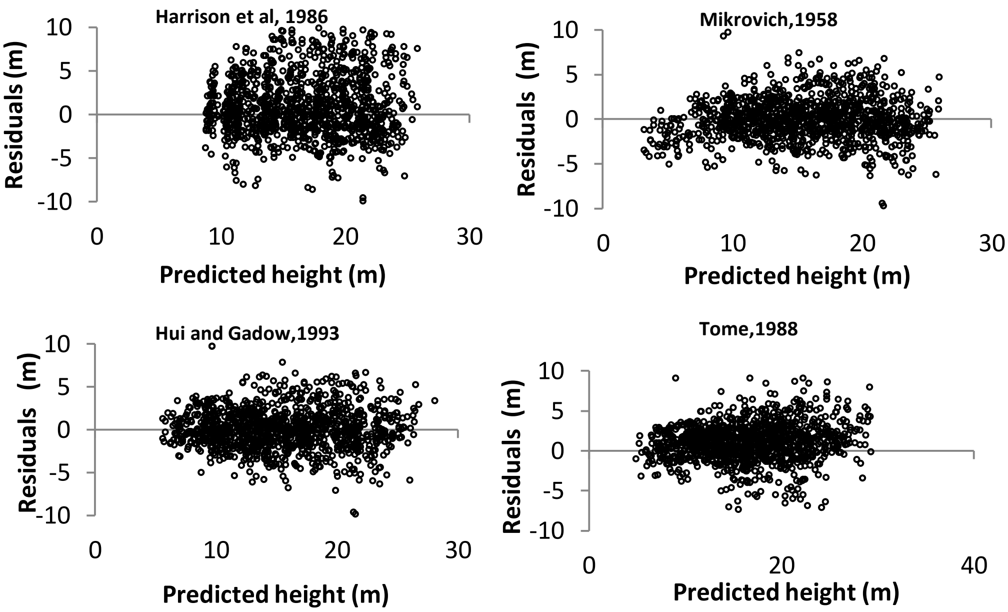


Figure 3-14:Analysis of residuals for the tested equations, for representing the height-diameter relationship using Mirkovich equation

Methods of evaluation were also applied in the second group of data (212 sample trees). So, based on the different performance evaluations, the equation proposed by Mirkovich (1958) provides more satisfactory results as compared to the other tested equations.

Table 3-15: Validation statistics of the generlaized height-diameter equations for *Pinus brutia* in the coastal region in Syria

Equation	Bias	Relative Bias	Precision	Relative Precision	Accuracy	Relative accuracy
Harrison et al. (1986)	0.5	3.3	2.9	19.5	4.4	29.2
Hui and Gadow (1993)	-0.5	-3.7	2.76	18.16	4.6	30.3
Mirkovich (1958)	-0.4	-3.1	2.7	18	4.2	27.8
Stoffels and Van Soest modified by Tomé (1988)	0.7	4.9	3.1	20.4	5.8	38.2

3.4.5 Mortality equation

After checking the candidate variables by univariate analysis, the variables of three groups (tree size, competition, and stand level) with a significance level lower than 0.25 were used in multivariable analysis.

The general mortality model was formulated as the following logistic equations:

$$P_i = \frac{1}{1+e^{-(b_0+b_1\times d_{1.3}+b_2\times BAL+b_3\times Dq+b_4\times SI)}} \tag{33}$$

Where Pi is the probability of tree mortality, b_0, b_1, b_2, b_3, b_4 are coefficients, $d_{1.3}$: diameter at breast height, BAL: basal area of trees larger than the subject tree, Dq: quadratic mean diameter, SI : site index(m).

Estimated coefficients and corresponding standard errors are presented in (Table 3-17). All parameters in the equations (diameter at breast height, basal area of trees larger than the subject tree, quadratic mean diameter and site index) were highly significant ($p < 0.001$). The standard errors of explanatory variables are close to zero. In Equation (33) Wald statistics showed that the highest predictive capacity in the equation was for the independent variable quadratic mean diameter (Dq), whereas the lowest predictive capacity in the equation was for the independent variable site index (SI). With continuous variables, the probability ratio describes the change of probability per one unit change of covariate. This means that the probability of mortality becomes 1.290 times higher than site index, quadratic mean diameter and basal area of trees larger than the subject tree with 1 cm increase in diameter at breast height.

Table 3-16: Evaluation of coefficient of developed individual-tree mortality equation

	Variables	**B**	**Std.Error**	**Wald**	**Sig.**	**Odds ratio(exp(B))**
Equation (33)	Intercept	-5.088	0.535		0.000	
	$d_{1.3}$	-0.255	0.028	90.404	0.000	1.290
	BAL	0.102	0.011	81.420	0.000	0.903
	Dq	0.122	0.025	91.302	0.000	0.885
	SI	0.035	0.024	23.697	0.002	0.965

Where: $d_{1.3}$: diameter at breast height, BAL: basal area of trees larger than the subject tree, SI; site index, Dq: quadratic mean diameter, Sig=significance

On the other hand, the effect of variables on the predicted probability of mortality was shown in Figure 3-15. For the effect of diameter at breast height on predicted mortality rates, the mortality rate curve can capture the U-shape. The mortality rate is highest in the smallest diameters, it rapidly decreases as diameter increases and then increases again for very large trees, as Figure 3-15 also illustrate the effect of stand basal area and basal area of larger trees on predicted mortality rates. Higher stand basal area or basal area in larger trees significantly increases mortality rates.

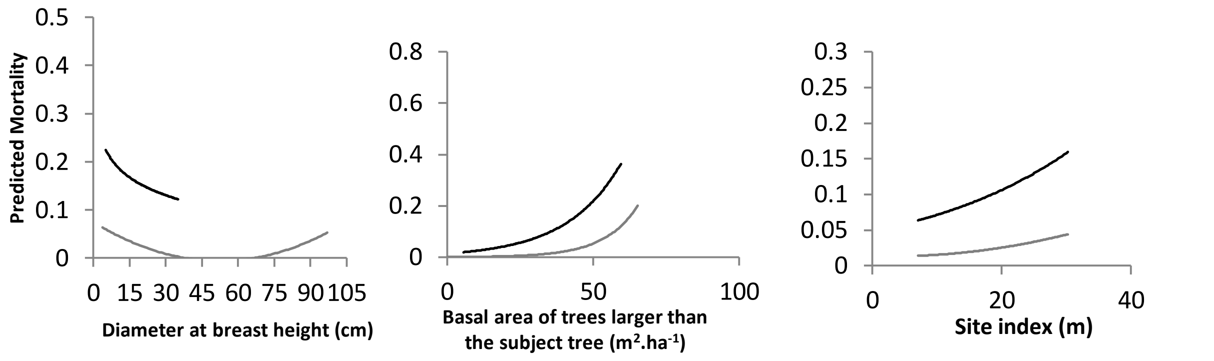


Figure 3-15:Predicted probability of individual-tree mortality of *Pinus brutia* as a function of tree diameter at breast height, and basal area of trees larger than the subject tree, and site index for observed dead (black) and live trees(grey) for modeling data.

The evaluation of the predictive capacity of developed mortalitz equation is presented in (Table 3-18).

Table 3-17: Statistical parameters of developed logistic equation

	-2log likelihood	NagelkerkeR^2	McFadden R^2	ROC area
Equation(33)	455.637	0.349	0.325	0.933

The relative area below a ROC curve is a measure of accuracy based on the sensitivity and the specificity of the test. The relative area below the ROC for Equation (33) was 0.933 which means that the accuracy of the individual-tree survival equation for *Pinus brutia* was very good according to Hosmer and Lemeshow (2000) (Figure 3-16).

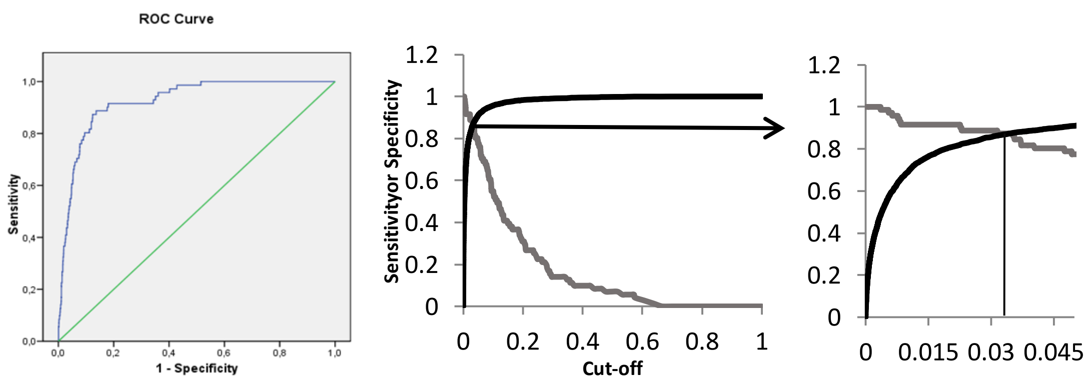


Figure 3-16:Visualization of ROC curves. Left Figure represent the equation (33), the blue line is a ROC curve, green line y = x curve (Indicates no discrimination), right Figure: sensitivity-specificity diagram

A threshold can be used to assign mortality. If the estimated probability of mortality exceeds the threshold, then the tree is considered dead. The cut-off value was assigned in three ways, the first: based on the Interception point of sensitivity and specificity (Adame et al, 2010; Thapa, 2014; Ma and Lei, 2015) which was 0.035 for equation (33) (Figure 3-16); the second: the average observed mortality rate which was 0.17 for equation (33). The first two thresholds are considered as deterministic method while the third which is the random number is considered as stochastic method. The results of using these threshold are shown in the following table (Table 3-19).

Table 3-18: Overall prediction rates for the developed mortality equation

	Mortality equation		
	Percentage correct		
Cutoff point	Alive%	Dead%	Total%
Average observed mortality rate	97.9	35.2	66.55
Sensitivity-specificity cut-off	85.6	85.6	85.6
Random number	86.2	35.2	60.7

To summarize, the developed mortality equation showed very high capacity to predict natural mortality of trees. Three cut-off points (the interception point of sensitivity and specificity, the average observed mortality rate and a random number) were used. The interception point of sensitivity and specificity scored better results than the average observed mortality rate and a random number.

3.5 Simulation of individual-tree growth model

Once the growth model has been calibrated, its forecasting accuracy must be assessed. The most important aspect of model evaluation is the comparison of prognosis and empirically observed growth, therefore in the first part in this section is the short-term forecasts on the independent 10 plots for a growth interval of eight years to test the goodness-of-fit of the calibrated model. To be efficient in management, a growth model must be realistic over several decades, so a long-term steady state predicted by the model was checked for quantitative plausibility. The third part of this section addresses the sensitivity analysis. This analysis allows determining how sensitive a model's outputs are to changes in parameter values. The fourth part is the applications of simulation model which suggests the optimal rotation age in the absence of thinning and allows exploring the impact of the thinning on growth.

3.5.1 Short-term prediction of a eight-year period

The description of independent data, which came from10 plots, is seen in the appendices 2, 4, 6, 8, 10, 12 respectively. The program simulated the development of the plots for 8 years (2008 - 2016). Diameter increment and linearized height increment equations were validated, and then transforming it to tree diameters at breast height ($d_{1.3}$) and tree height respectively.

In order to validate the equation: firstly, bias, relative bias, precision, relative precision, accuracy, and relative accuracy were calculated in order to estimate the precision of predictions of diameter increment, linearized height increment and potential-modifier height increment

(Table 3-20).

Table 3-20: The validation results of fitted diameter equation applied in independent plots

Plots	Bias	Relative Bias	Precision	Relative precision%	Accuracy	Relative Accuracy%
Diameter increment						
14	0.46	3.70	0.64	5.15	3.76	30.33
15	0.44	2.63	0.67	3.99	2.72	16.22
30	-0.97	-2.04	2.45	5.14	3.19	6.69
40	-0.08	-0.47	0.44	2.59	0.64	3.77
46	-0.31	-1.50	0.72	3.48	0.78	3.79
59	0.21	0.96	0.33	1.49	1.02	4.63
61	0.73	1.70	1.06	2.48	2.00	4.67
62	0.52	3.90	0.55	4.08	3.94	29.33
63	1.89	5.95	2.04	6.42	6.29	19.84
64	0.46	1.59	0.97	3.36	1.86	6.42
Linearized height increment						
14	1.03	10.23	1.13	11.22	1.53	15.19
15	0.05	0.39	0.45	3.23	0.45	3.26
30	-0.74	-4.00	1.09	5.88	1.32	7.11
40	1.34	12.07	1.50	13.46	2.01	18.08
46	0.70	4.80	0.87	5.98	1.11	7.67
59	-0.24	-3.10	0.28	3.53	0.37	4.70
61	-0.45	-2.52	0.53	3.01	0.69	3.92
62	0.56	7.91	0.62	8.86	0.83	11.88
63	0.44	2.41	0.46	2.56	0.64	3.52
64	-0.20	-1.05	1.11	5.71	1.13	5.80
Potential-modifier height increment						
14	0.19	1.88	0.36	3.53	0.40	4.00
15	-0.33	-2.36	0.49	3.53	0.59	4.25
30	-0.68	-3.65	0.99	5.35	1.20	6.48
40	-0.52	-4.66	0.57	5.16	0.77	6.95
46	0.08	0.53	0.51	3.50	0.51	3.53
59	0.04	0.46	0.12	1.49	0.12	1.56
61	-0.44	-2.48	0.81	4.59	0.92	5.21
62	-1.63	-23.16	1.68	23.91	2.34	33.28
63	0.35	1.90	0.66	3.66	0.75	4.13
64	-0.65	-3.32	0.77	3.97	1.01	5.17

Second: the difference between predicted and observed values of diameter increment, height increment in the ten plots were presented (Appendices 17, 18, 19). They showed that observed values are very close to those of predicted ones. So they indicated that the growth model provided reasonable predictions. Based on the developed individual-tree growth model, Table 3-21 below shows the results of the actual stand volume of the ten plots at first measurement as well as the predicted stand volume at the second measurement The range of difference percentage related to the observed values is from -0.4% to 14.3 %. The average difference percentage of ten plots is 4.45%.

Table 3-21: Estimated stand volume based on the developed diameter increment and linearized height increment equations

Plots	V ($m^3.ha^{-1}$) From field measurements	Validated from the developed equation	Differences	Relative error of estimation%
14	136.7	155.1	18.4	13.4
15	214.0	224.9	10.9	5.1
30	154.3	138.1	-16.2	-10.5
40	166.5	178.4	11.9	7.1
46	199.6	200.4	0.8	0.4
59	61.5	61.3	-0.2	-0.4
61	331.5	339.1	7.5	2.3
62	107.8	120.5	12.7	11.8
63	249.2	284.7	35.5	14.3
64	305.3	308.3	3.0	1.0

With moving to the validation of mortality equations which used independent data from 10 plots representing different indices, the probability of each tree was calculated. The evaluation process used also three cut off points. The overall predictions of mortality for validation data obtained using the average observed mortality rate, the intersection point of sensitivity. The results based on the interception point of sensitivity and specificity showed that the percentage of correctly predicted statuses 80.9 % for growing and 72.4 % for dead trees and 76.65 % overall followed by the average observed mortality rate cut-off, and then the random number cut-off (Table 3-22).

Table 3-22: Overall predictions rates for the developed mortality equation applied on validation data

	Equation 33		
	Percentage correct		
Cut-off point	Alive%	Dead%	Total %
Average observed mortality rate	97.6	27.5	62.6
Sensitivity-specificity cut-off	80.9	72.4	76.65
Random number	95.3	26.2	60.8

3.5.2 Model plausibility

The model behavior should also be consistent with biological knowledge and practical experience of stand growth over a long time in the absence of violent natural or human disturbance. The efficiency of a growth model over a single growth period of eight years is obviously not sufficient to guarantee applicability for management. To check the plausibility of the model, the study applied the model to simulate the development of a stand without harvest under different scenarios over 150 years.

RESULTS

The PINUS-Syria simulates the long-term behavior of diameter increment and height increment corresponding to the five site indices 10, 15, 20, 25, 30 under the effect of the independent predictors.

Figure 3-17 indicates that there are differences in the growth rates between site indices, the higher site index the higher growth. But the growth decreases as diameter at breast increases that could be explained that over time trees become larger and the stand basal area increased, decreasing the increment as showed in Figure 3-17 (A). The pressure on water and soil nutrients, which stand density index is considered as a proxy for them, caused higher competition which in turn leads to slower increment. Figure 3-17 (F) supports this result, where diameter increment decreases as the stand basal area increases under different densities. The lower density, the lower competition, and thus the higher diameter increment. In terms of BAL which can be regarded as descriptive size for the performance of the single tree, the result seems plausible where the diameter increment decreases as BAL increases.

Regarding the height increment, Figure 3-17 showed that the height increment culminates in early-aged before height increment starts decreasing overage. The relationship between the site index and tree height are so closely related, the higher the site index, the higher the height increment. The competition stimulates a little the height increment before the competition decreases and slows the height increment.

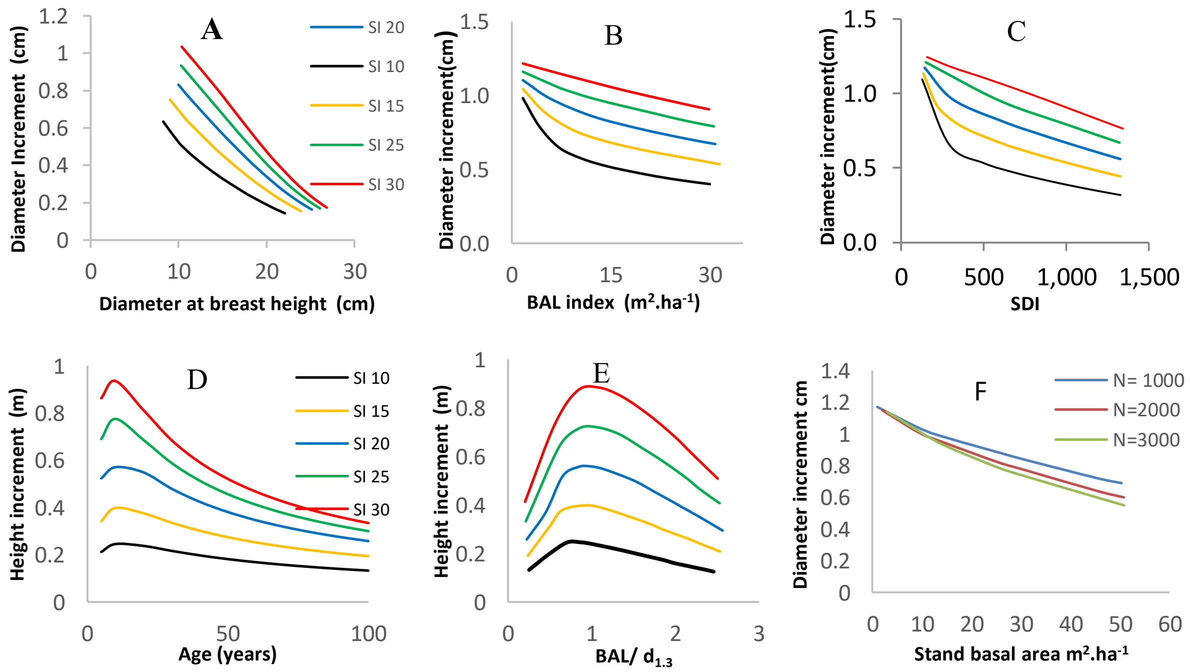


Figure 3-17:The effect of predictors on growth of *Pinus brutia* plot representing different site index values, different densities, where the conditions are: elevation = 500 m, soild depth = 60 cm; slope = 20 % and aspect =50 degree. A: Effect of tree diameter on diameter increment representing different site indices where the initial density is 1500 tree per ha; B: Effect of BAL on the diameter increment representing different site indices where

the initial density is 1500 tree per ha C: Effect of stand density index on diameter increment; D: Developing the height increment over time under different site index values representing different site indices where the initial density is 1500 tree per ha; E: Effect of BAL/ $d_{1.3}$ on the height increment representing different site indices where the initial density is 1500 tree per ha F: Effect of stand basal area on diameter increment under three different densities

The equation proposed by Mirkovich (1958) was used to estimate the diameter-height relationship for different site indices and different ages. The simulations of the site index effect on the height-diameter relationship were made using the age of 35 and values of dominant height estimated by Sloboda equation (1971) (Figure 3-18 A). In more productive sites, the height-diameter curves of *Pinus brutia* were steeper and presented larger asymptotes than in poor sites. The height estimates of *Pinus brutia* for different ages have been made using site index (20 m) and values of dominant height computed from Sloboda equation (1971) (Figure 3-18 Right). Although fixed intervals of 10 years were used to describe the effect of age on height-diameter relationship of *Pinus brutia*, there is a decrease in the distance between height-diameter curves with increasing age (Figure 3-18 B), i.e. the distance between height-diameter curve of age 15 and 25 is larger than the distance between height-diameter curve of age 45 and age 55. Probably that is attributed to the reduction in height and diameter growth in old ages, making the changes in the height-diameter curves become very small.

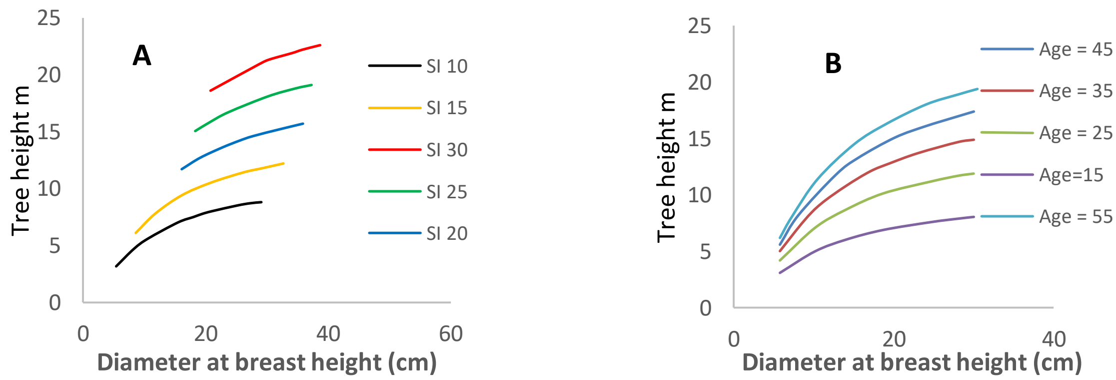


Figure 3-18:Effect of site index(A) and age (B) on the height-diameter relationship according to the developed generalized height-diameter equation for *Pinus brutia*.

With moving to simulating the effect of competition on crown ratio, the study found that effect is similar to the effect of competition on diameter and height increment. The crown ratio decreases as competition increases; and because there is a close relationship between site index and tree height, it is easily noted that better site index, the smaller crown ratio values as Figure 3-19 (A) showed. Also, the simulation process indicated that the higher values of the crown ratio are noticed in the smaller diameter values under different site indices Figure 3-

19(C) and under different densities Figure 3-19 (D) where the higher density led to less crown ratio values.

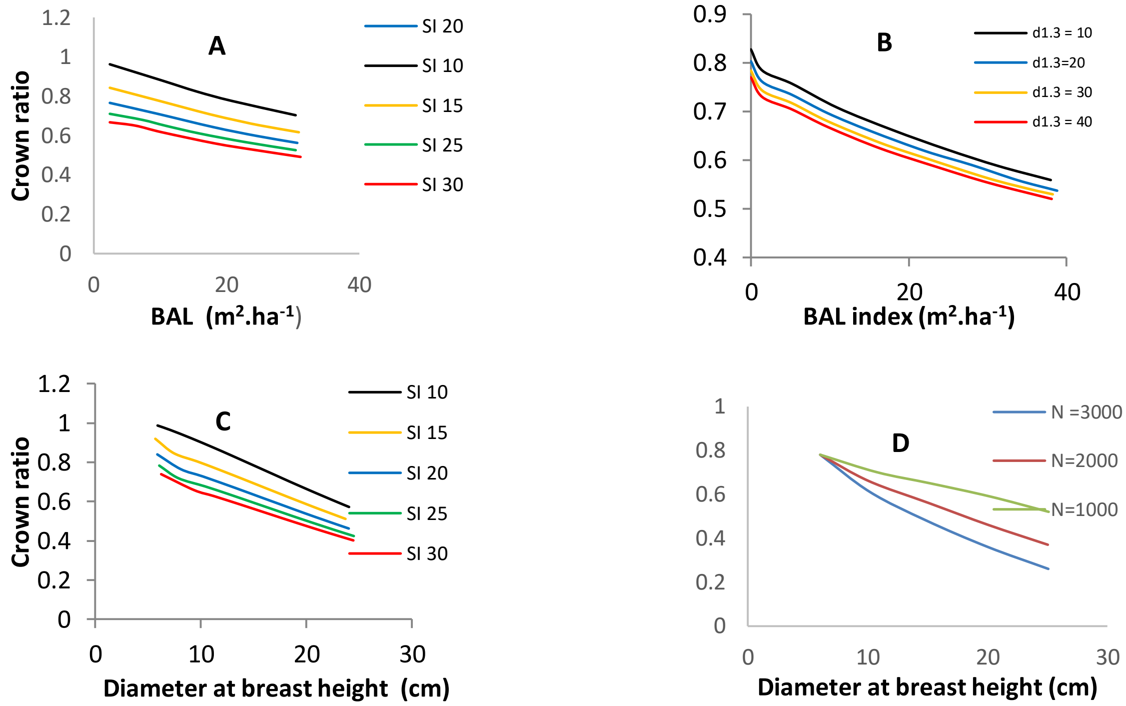


Figure 3-19:The effect of predictors on crown ratio of *Pinus brutia* plot representing different site index values, different densities, where the conditions are: elevation = 500 m, soild depth=60 cm; slope= 20 % and aspect =50 degree. A: Effect of competition on crown ratio in *P. brutia* plot representing different site index values: 10, 15,20, 25 and 30; B: Effect of competition on crown ratio under different values of diameter at breast height where the initial density is 1500 tree per ha;C:Effect of tree diameter on crown ratio representing different site index values: 10, 15, 20, 25 and 30 where the density is 1500 tree per ha; D: Effect of tree diameter on crown ratio under three different densities

The simulation runs were also analyzed for the development of the probability of mortality over time in the even-aged stands of *Pinus brutia* under different site indices: 10, 15, 20, 25, 30 (Figure 3-20). The simulation results showed that the better the site index, the higher the probability of mortality. These findings seem consistent with biological knowledge and practical experience of stand growth, where the competition on resources is higher in the better site index, thus high mortality rates occurs, within the same context, it is easy to understand why high mortality rates are seen in high density stands compared with the low density stands. With going to analyze the effect of tree diameter on the mortality rate, the study found that the probability of mortality increases with an increasing diameter at breast height in the small diameters up to a certain point, then the mortality decreases as diameter at breast height increases with pointing out that probability of mortality culminates sooner on higher density stands and declines more rapidly after reaching the point of culmination compared with those growing on fewer density stands.

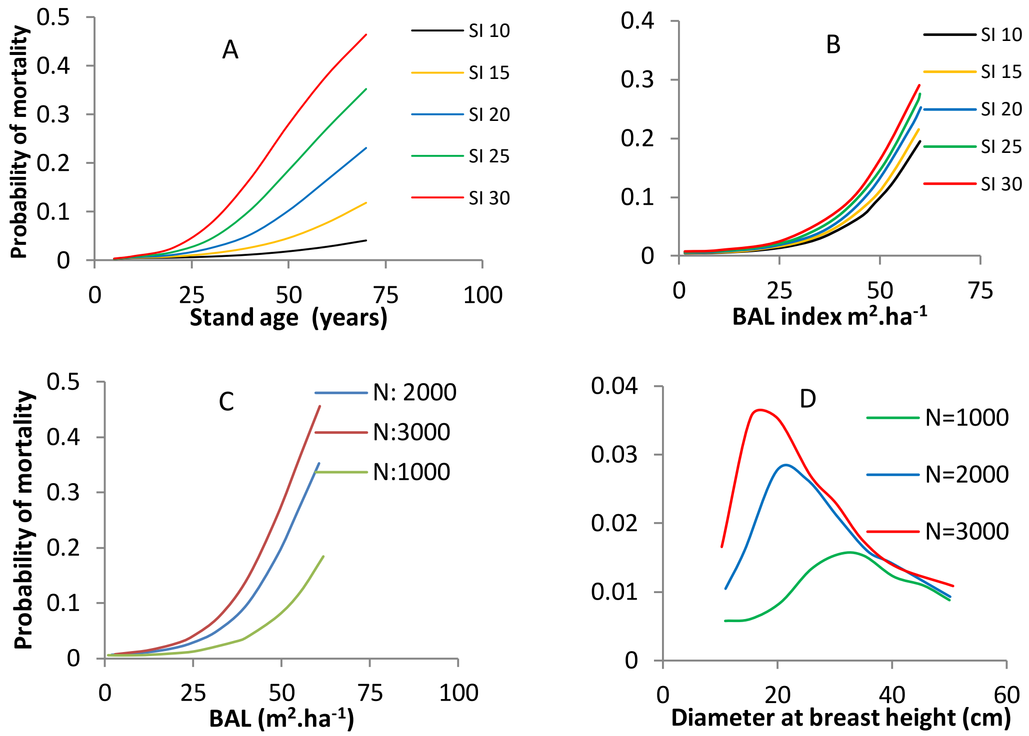


Figure 3-20:The effect of predictors on mortality of *Pinus brutia* plot representing different site index values, different densities, where the conditions are: elevation = 500 m, soild depth=60 cm; slope= 20 % and aspect =50 degree. A: Developing the probability of mortality over time under different site indices where stand density 1500 per hectare; B: The effect of competition on probability of mortality where stand density is 1500 tree per hectare under different site indices; C: The effect of competition on probability of mortality where stand density is 1500 tree per hectare under different densities; D: The effect of diameter at breast height on probability of mortality where stand density is 1500 tree per hectare under different densities.

Furthermore, the study compared four different response variables (Quadratic mean diameter, stand basal area, stand volume and number of trees per hectare) of stochastic and deterministic approaches. Because the outcomes of independent samples were not normally distributed, a nonparametric test was appropriate. The study used Mann Whitney U Test (Wilcoxon Rank Sum Test) for testing the equality of means in two independent samples representing stochastic and deterministic approaches respectively.

The following Figure 3-21 (A) showed the number of trees per hectare decreases as quadratic mean diameter increases. In this figure, we can notice that the behavior of mortality by using stochastic and deterministic approaches is different. In the stochastic approach, the trees start dying at early diameters while in the deterministic approach the mortality is showed starting from 22.4 cm. Deterministic versus averaged stochastic projection results showed practical differences in mean stand values for a number of trees, basal area, volume, or quadratic mean diameter (Figure 3-21).

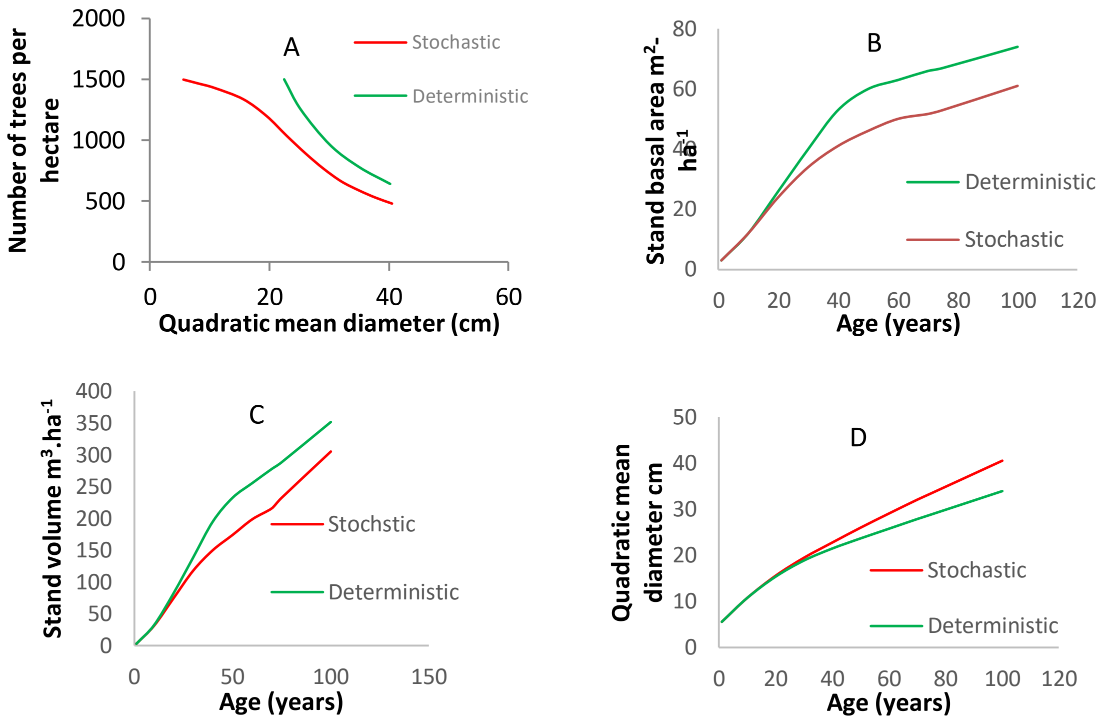


Figure 3-21:A:Mean 100-year stochastic and deterministic simulations of the number of trees per hectare, B) Basal area; C: Stand volumeand;D: quadratic mean diameter, the other conditions are: elevation = 500 m, soild depth=60 cm; slope= 20 % and aspect =50 degree

Considering these differences and the results of their associated t-tests, we are forced to reject the null hypothesis and to conclude that deterministic and stochastic simulations may yield different predictions.

3.5.3 Sensitivity analysis

The study tested the individual-tree growth model in a global sensitivity analysis by determining partial correlation coefficients for site characteristic parameter. 300 sets of input parameters were generated for different combinations.

Simulations were carried out for 3125 parameter combinations with 10 repetitions each, and model outputs were stored after 70 years.

The results of Figure 3-22 show on the left side the distribution of the analyzed output variables for all input variable combinations. The pie charts on the right side illustrate the partial correlation between the input parameters and the outcomes.

The diameter increment, height increment, crown ratio mortality are influenced to a varying degree by input parameters.

Among the parameters which were tested (site characteristics), the most influencing input parameter is the site index.

Soil depth affects positively on diameter increment while the Aspect has no clear effect. The mean height increment varied widely in the outcomes of sensitivity analysis, indicating a sensitive behavior. Height increment increase as site index increases, this leads to a positive effect on growth, while slope affects negatively on height increment. Elevation has a positive effect on the height increment and this result is considered a bit surprising and the study will try to explain the causes that stand behind this result in detail in the discussion chapter. Increasing the elevation leads to increase in the crown ratio, while crown ratio decreases as site index and soil depth increase.

In terms of the probability of mortality, the sensitivity analysis showed that increasing the soil depth leads to an increase in the probability of mortality because the site index and soil depth are so related and this result confirms with the biological knowledge of growth behavior, while the probability of mortality decreases as elevation increases. Aspect and slope have no clear effect.

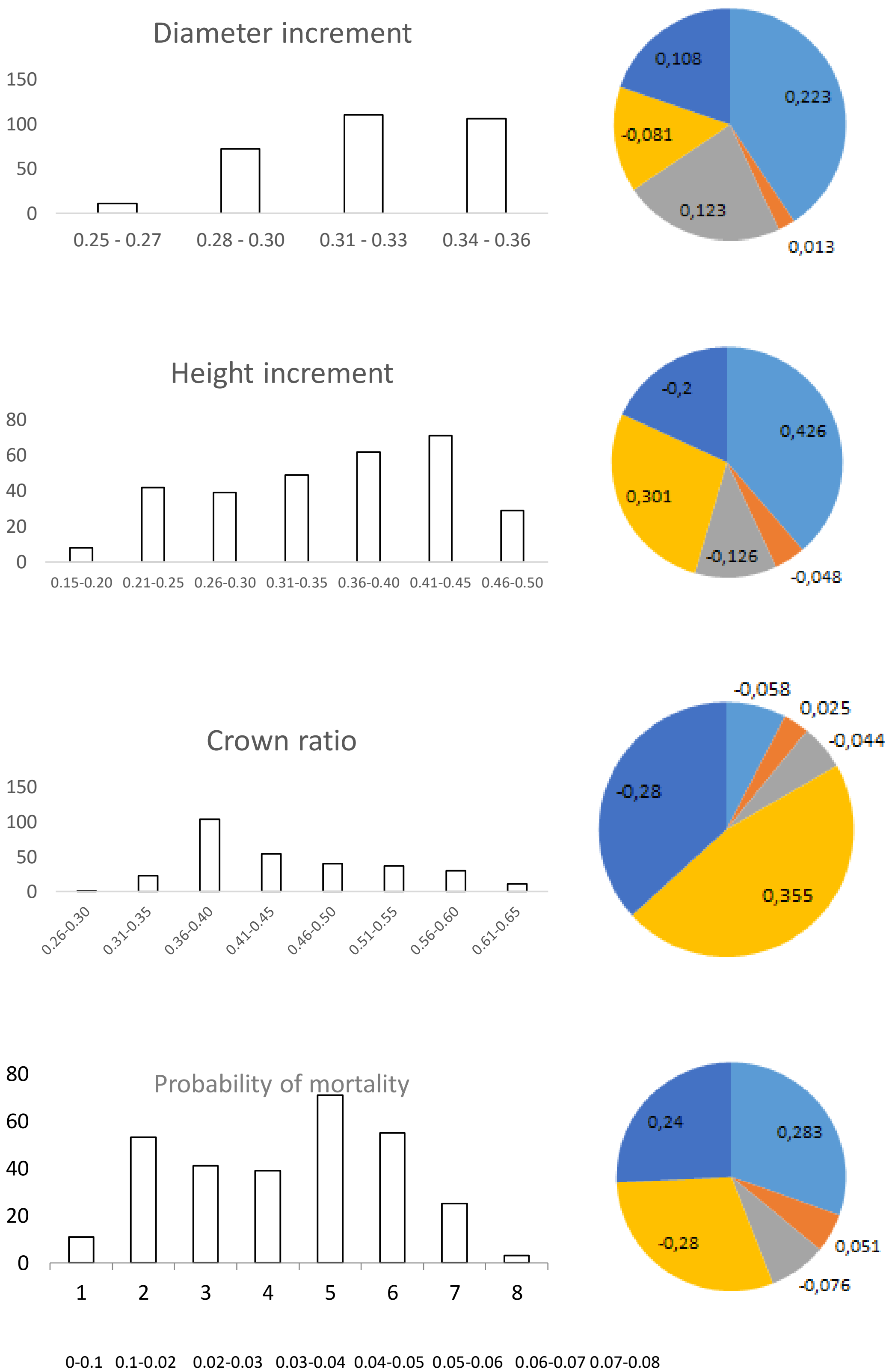


Figure 3-22:Sensitivity analysis where distribution of the analyzed output variables for all input variable combinations (left) and the pie charts on the right side illustrate the partial correlation between the input parameters and the outcomes (right).Input parameters are : site index: aspect: slope: elevation: soil depth:

3.5.4 Application of the PINUS-Syria Model

3.5.4.1 Optimal rotation age

Optimal rotation age where the wood production is maximized is determined as a result of intersection the mean volume increment and current volume increment.

The most significant parameter affecting rotation length is the site index. As expected, stands with poor site indexes have longer optimal rotation lengths than stands on better sites. The mean annual increment (MAI) with the optimal rotation length in the example presented in this study was 11.5 m^3 ha^{-1} on the best site and 2.9 m^3 ha^{-1} on the poorest site. The rotation length was 40 years for the best site and 112 years for the poorest site (Figure 3-23).

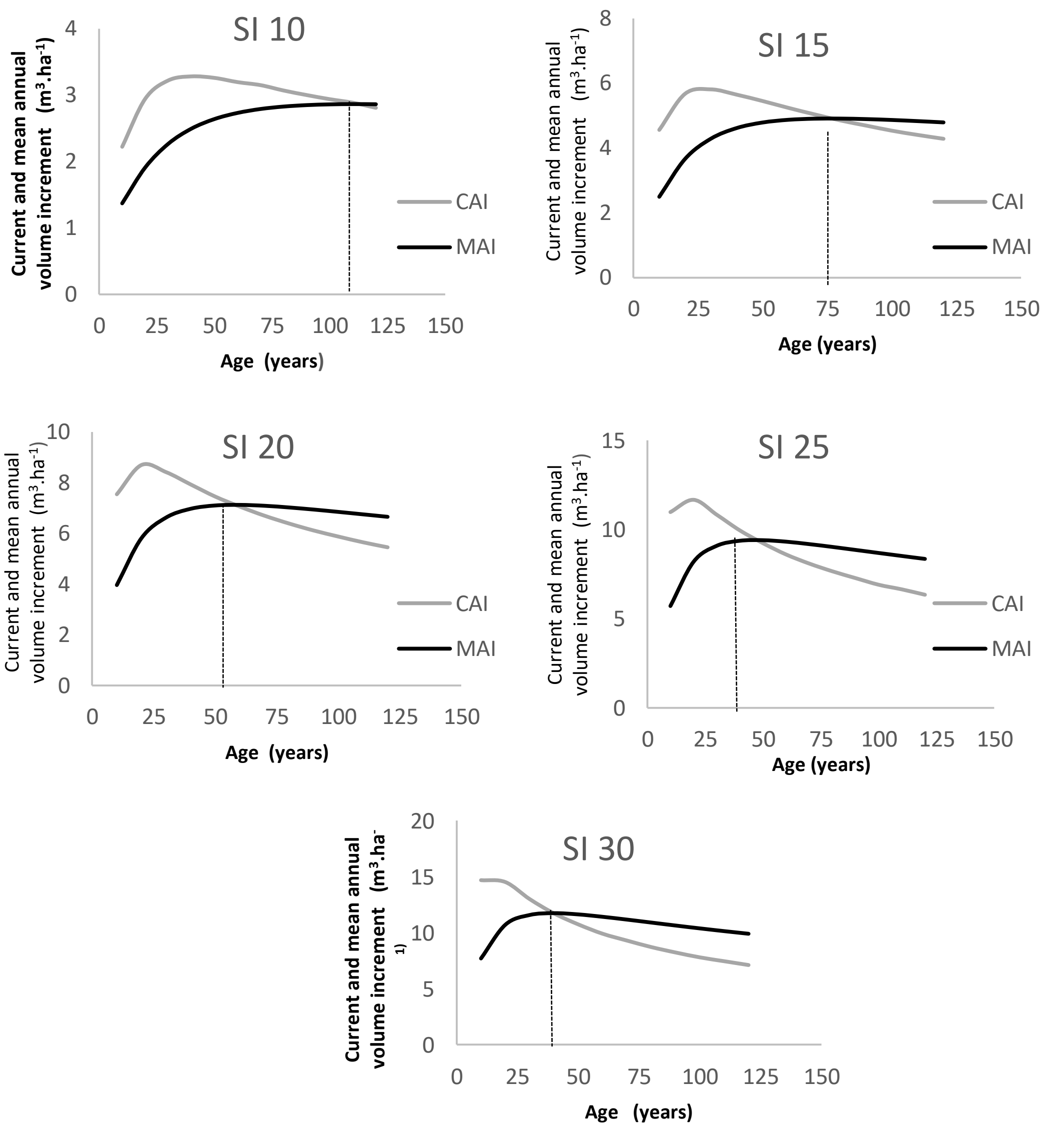


Figure 3-23:Mean annual increment (MAI) and current annual increment (CAI) curves of a P. brutia plot representing different site index values: 10, 15,20, 25 and 30 where the density is 1700 tree per ha, with elevation = 500 m, soild depth= 60 cm; slope= 20 % and aspect =50 degree

3.5.4.2 Thinning treatment

The model tested different forest management scenarios to suggest the appropriate intensity, time of executing the thinning treatment, and frequency of thinning of *Pinus brutia* stands.

For the appropriate intensity, the model simulates the stand development under five different forest management scenarios: (a) absence of thinning, (b) light thinning with 10% of basal area removed, (c) moderate thinning with 20% of basal area removed, (d) heavy thinning with 35% of basal area removed, and (e) very heavy thinning with 45% of basal area removed.

The following Table 3-23 presents an example to stand with 2000 trees. ha^{-1}, three different site indices 25, 20, 15 m. The growth was the highest for the scenario with very heavy thinning, the heavy thinning scenario comes second; and followed by the moderate thinning scenario, light thinning scenario, and finally the scenario with no thinning. Considering these results, it has been shown that diameter growth is so related to the intensity of thinning. The lower intensity, the higher growth which could be explained as an attempt to compensate for extreme basal area reductions, where the higher the more competitors were removed i.e. more growing space provided for each one of the selected potential trees. The same behavior is recorded for the height but it remains less affected by thinning compared with the diameter increment. Moderate and heavy thinnings in good and very good productivity sites reach within 10-40 years of the production period to the optimum age. It delivers a surplus of volume in relation to other thinning strategies. In poor sites where the site index is 10 m, there is no great economic benefit from the application of moderate, heavy thinning treatments.

Table 3-23: Simulation of the stand volume development, diameter at breast height, tree height in optimal schedcuals which maximize wood production under five different management scenarios(No thinning, light (with 10% of basal area removed), moderate (with 20% of basal area removed), heavy (with 35% of basal area removed) and very heavy thinning (with 45% of basal area removed)) which was carried out at 15 years for once in a very good site (SI=25 m) with initial density= 2000, elevation = 500 m, soild depth= 60 cm; slope= 20 % and aspect =50 degree

	SI 25				
	No thinning	**light**	**Moderate**	**Heavy**	**Very heavy**
Standing volume (m^3)	461.5	484.2	513.1	593.7	763.5
Diameter (cm)	23.5	25.2	27.3	31.8	37.2
Height (m)	24.2	25.2	26.2	28.2	30.8
Rotation age (years)	42	46	51	63	84
	SI 20				
	No thinning	**light**	**Moderate**	**Heavy**	**Very heavy**
Standing volume (m^3)	417.2	447.1	474.4	576.3	729.8
Diameter (cm)	23.5	25.4	27.5	32.4	37.6
Height (m)	21.9	22.9	23.8	26.2	28.5
Rotation age (years)	51	57	63	81	106
	SI 15				
	No thinning	**light**	**Moderate**	**Heavy**	**Very heavy**
Standing volume (m^3)	350.3	384.9	416.6	535.4	653.7
Diameter (cm)	23.1	25.2	27.5	33	37.7
Height (m)	18.7	19.8	20.8	23.4	25.5
Rotation age(years)	64	72	81	110	137

For the appropriate frequency of thinning, the model simulates the stand development under three different forest management scenarios: (a) absence of thinning, (b) one thinning, (c) two thinning (Figure 3-24). Two thinnings scenario result in the highest total volume production, up to 32 % more than unthinned stands at age 42 years; and 21 % more than one thinning scenario at age 53.

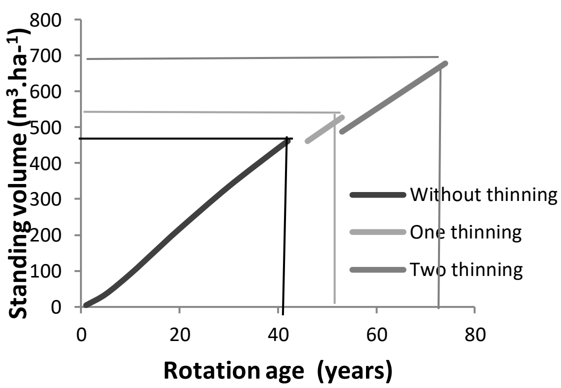


Figure 3-24:Simulation of the stand volume development in optimal schedules which maximize wood production under three different management scenarios (No thinning, one thinning at 20 years and two thinning at 15 and 20

years) in a very good site (SI=25 m), the other conditions are: initial density= 2000, elevation = 500 m, soild depth=60 cm; slope= 20 % and aspect =50 degree.

For the appropriate timing of thinning, the model simulates the stand development under five different forest management scenarios: the absence of thinning, stand at 10 years, stand at 15 years, stand at 20 years and stand at 30 years (Table 3-24). Tree responses in growth were significant and immediate after thinning. Despite an early age is preferably chosen to implement the thinning to eliminate weak and unhealthy trees to release the other trees from the competition, postponing the thinnings by 5-10 - 20 years, allows increasing the stand volume 1- 12.5 % compared with no thinning scenario.

Table 3-24: The impact of different timing of thinning on the rotation age and volume, the other conditions are: initial density= 2000, elevation= 500 m , soil depth= 60 cm, slope = 20 %, and aspect= 50 degree

	No thinning	**10**	**15**	**20**	**30**
Rotation age (years)	42	44	46	48	52
Volume ($m^3.ha^{-1}$)	461	465	482	498	527

4 DISCUSSION

This chapter elucidates on the meaning, importance, limitations, and implications of the results highlighted in the previous chapter. This chapter emphasizes the significance of data collection, size and representation, which form the basis for this work. Next, it discusses the nature of the individual tree's responses to competition, and the comparisons between distance-dependent and independent indices, as well as, this chapter permits discussion of some points related to the site curves. Then, the discussion chapter highlights separately on five primary model components including diameter increment, height increment, crown ratio, height-diameter relationship, and mortality. In this chapter, It is necessary to review the practical aspects of the developed model and the contribution which the thesis makes for Brutia pine stands and also shedding the light on the possible future prospects that support more and more efficient forest management in Syria.

4.1 Data collection, size and representation

Building the perfect forest growth model essentially requires perfect data, but waiting through decades for such perfect data and model, which do not exist anyway, corresponds to a lack of logic. Therefore, researchers are trying to compensate for this by obtaining and relying on representative, but high-quality data. This study has followed the same orientation when it utilized data from permanent plots of *Pinus brutia,* which were established and inventoried for the first time in 2008, and re-measured in 2016 as a step towards an improved yield assessment and growth modelling of *Pinus brutia* stands in Syria.

Combining two measurements (2008 and 2016), the number of plots and the data so obtained well represented the most common growing conditions plus a record of the dead trees in Syrian Brutia pine stands, which was deemed good enough to build viable growth models. As Buongiorno (1996) suggests, such data needed not be of so high accuracy, insofar they will produce a practical growth model that is not difficult to check thereafter if the model mimics tree growth reasonably well or not.

Using data from permanent plots for forest growth modeling is not the only obstacle which faces the researchers. When it comes to the practicality of field measurements, it is usually impossible to measure some variables for example, tree height and crown length for all trees in a whole forest, plot or stand, Hence, sampling techniques are efficiently used to provide a robust estimation (Freese, 1962; Goulding and Lawrence, 1992; Shiver and Borders, 1996). Accordingly, it is conventional in forestry to select candidate trees to model un-measured trees in each plot through a systematic sampling, for example. This is considered as the most frequently used sampling technique in forest inventory because it saves time and effort and the procedure is practically easy to apply on the field. This point is exemplified by the fact that it can easily explained to the field crew, and its potential to yield more precise results than simple random sampling when considering a similar number of sample points (Asrat and Tesfaye, 2013).

This study has used the circumference tape to measure the diameter at breast height since this measure results in a smaller dispersion. Kramer and Akca (2008) recommended using it in case of trial surface recording and for the purpose of incremental examination. With the measurement of the tree height, which is considered more difficult than measuring the diameter at breast height, we find that the probability of error is higher. Hence, this study used HCH Haglöf Clinometer with Height measuring function, but using this device did not completely prevent the error of measurements, which could come from the distance. A higher distance to the tree thus increases the possibility of error, which could occur from the inappropriate sighting of the treetop, especially in case of the high-density stands. Additionally, measurement from the wrong direction could lead to errors in tree height measurements.

Data collection in this study adequately accounted for all these mentioned factors. Among others, one advantage of building growth models in this study is that it helps in identifying knowledge gaps in the light of the inventory data used. The main limitation, however, is that the samples were unequally distributed regarding soil depth, elevation and slope, which could lead to results that possibly less reflect the influence of topographic factors. Future studies should assess in fine details the effect of the topographic factors on the growth and yield of *Pinus brutia* stands.

Consideration for accurately assessing the effect of soil depth on the growth of Brutia pine stands, for example, requires that plots should be distributed along various degrees of soil depth within plots characterized by the same other conditions that influence growth. It is equally important to note the point that there were no sample stands with age below 16 years; this gap should be covered in future studies as it could effectively avoid the unreasonable tree height estimates so obtained in the early age of the studied stands. Furthermore, the long-term experimental plots as mentioned in this study focus only on pure and even-aged stands, and do not consist of any mixed stands, which deserves some consideration in future studies.

The data size upon which individual-tree growth models were developed in this study is similar to many previous works on *Pinus* species. For example, Kitikidou et al (2012) used data from 20 experimental plots (established in 2010) in Chalkidiki (Northern Greece) to develop an individual-tree growth model, site index and mortality equations for *Pinus halepensis* MILL. Similarly, Körner (2015) used data from 30 plots as measured in 2008, 2009 and 2010 to model growth and yield of forest plantations in the Dominican Republic; In Spain in Galicia, the study used a network of 155 plots (Crecente-Campo et al 2010). In North-east Greece, researchers used data from 78 permanent sample plots, which were established in 2000 and re-measured in 2005, for Site quality and individual-tree growth modeling in pure and mixed *Pinus brutia* stands (Palahí et al 2008).

In terms of the validation process, a half and half split generally seems to be the most popular method in other disciplines as Snee (1977) observed, fewer proportion of data are usually required for validation of tree growth models, especially when considering forest plantations. Ma and Lei (2015) used 17 % of the data to validate individual-tree diameter growth and mortality model of natural Mongolian oak forests in northeast China. Misir et al (2007) also used 20% of the observations to validate an individual-tree mortality model for Crimean pine plantations in Turkey. Other studies have used less data for validation. For example, Linkivicius (2014) and Adame et al (2010) used about 10% of the available data for validating their models. This study used 10 plots, i.e. 19 % of data to validate an individual-tree growth model. The data used for validation in this study, which spreads over a range of stand conditions (site index, elevation, age, soil depth, aspect), is deemed sufficient as long as multiple silvicultural options were not being evaluated.

4.2 Individual tree's response to competition

In even-aged stands, trees are presumably growing under uniform site and conditions. Variations in tree growth are often determined by competition among neighboring trees, which is considered the main factor in this respect. Analysis of tree-tree competition is necessary to develop good models for diameter and height increments, as well to predict tree mortality. For this reason, a set of competition indices mentioned in the methodology chapter were tested in this study. It is interesting to note that this study forms the first attempt to analyze the competition indices in Syria, given that no earlier publication is available on this topic. Moreover, the use of both distance-dependent and independent site indices in the analysis especially give this attempt an additional importance. The study used a non-linear regression (logarithmic equation) model for describing the relationship between tree dimensions and competition indices, where many previous studies used this same equation (e.g., Piper, 2008; Mohammed and Röhle, 2011).

Competition changes over time, this is not only attributed to the size and growth of competing trees, but also to the mortality or removal of competitors. The impact of all distance-dependent and distance-independent competition indices was negative on tree basal area growth; i.e. the basal area increment decreases as the competition increases, and that agreed with the expectations and the common behavior of competition on growth (Contreras and Chung, 2011; Linkivicius, 2014). The Reineke index, which represents a two-sided competition has the most influence on the relative basal area increment. This index used the quadratic mean diameter and number of trees per hectare, hence, it is less influenced by age and site quality. These results conformed to findings of many publications that used this index in building their individual-tree diameter increment equations (e.g., Uzoh and Oliver, 2008; Berrill et al, 2013).

The BAL index and BAL-modified index represent the one-sided competition indices. They combine the individual tree's basal area percentiles with a measure of density and stand basal area. With this, the largest diameter/ height tree in a plot would have a competition index value of zero, while the smallest diameter/ height tree in the plot would have a competition index value near that of the plot's total basal area. As these indices decrease, the predicted increment increases (Wykoff, 1990; Hann and Larsen, 1991; Uzoh et al., 1998; Uzoh, 2001; Palahí et al, 2003; Palahí et al, 2008; Ma and Lei, 2015).

Using the relative diameter at breast height and the relative height made some distance-dependent indices perform well, e.g. Heygi1 index and four indices of Rouvinen and Kuuluvainen (1997). Similar results were found in the study carried out by Piper (2008) where Heygi1 index was used.

Based on our empirical or simulation study, the height growth is generally stimulated a bit by competition until certain point before it start decreasing with competition, and thus it is less affected by competition than diameter growth. These findings have a significant practical relevance. In the case of diameter increment maximization, all competitors around the local tree have to be eliminated. If the goal is to maximize the height increment, some competitors around the subject tree have to remain.

Regardless of the above, one main weakness of this study concerns the distance-dependent competition indices, where the fixed radius method was used. This method did not allow for the measurement of the positions all trees in sample plots, and it has been proved disadvantageous when it is utilized in long-term growth studies (Pretzsch, 2009). In future studies, it is recommended to select other methods for estimating distance-dependent competition. Exam-

ples of such methods include Influence zone overlap methods, Competition elimination angle methods, Angle count sampling methods, and Vertical search cone methods. It is predicted to provide deeper understanding of the dynamic of Pinus brutia stands and using it may improve the the PINUS-SYRIA predictions (Pretzsch, 2009). Testing these methods and comparing them with the current individual-tree growth model would be an
interesting step in selecting the best competition indices for modelling tree growth and mortality.

4.3 Site curves of *Pinus brutia* and forest yield

This study tested several site index equations for the *Pinus brutia* stands in the coastal region of Syria. Sloboda equation (1971) gave the best performance when used to produce site class curves. At 100 years, the site class curves developed in this study by Sloboda equation (1971) reached a little higher height than those developed by the study presented by Suliman (2013) in the Rabiaa Region in Syria, which used the Richard-Chapman equation (Figure 4-1 A).
By comparing the curvesobtained from this work with site index curves (Korf equation) for (*Pinus brutia* Ten.) developed by Kitikidou et al (2012) in central Cyprus, the study found that all stands in the coastal region in Syria for all site classes (except site index 10) show lower growth rates at younger and older ages (Figure 4-1 B).

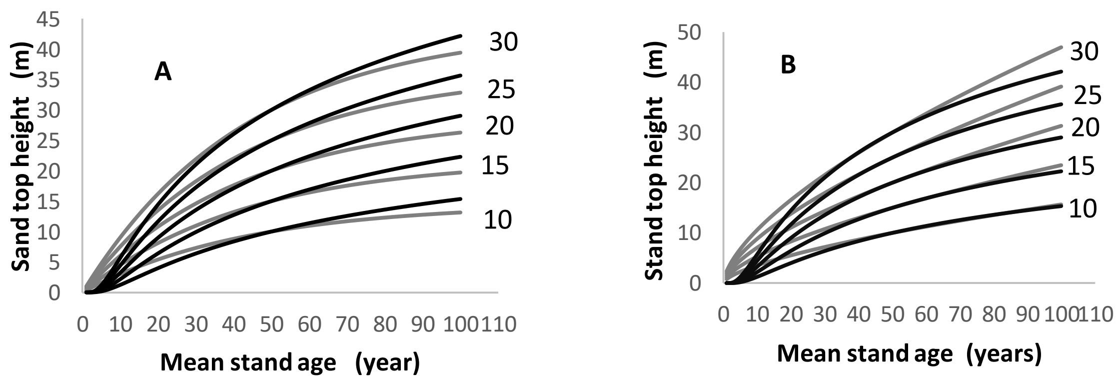


Figure 4-1: A: Comparison between the site class curves obtained by Suliman (2013)'s study (gray curves) and site class curves of this study (Black curves) for *Pinus brutia* when dominant heights 10, 15, 20, 25 and 30 are reached at age 50, B: Comparison between the site class curves in Central Cyprus (gray curves) (Kitikidou et al, 2012) and site class curves of this study (Black curves) for *Pinus brutia* when heights 10, 15, 20, 25 and 30 are reached at age 50

This study showed the culmination of increment height between the ages of 9 and 14 years. The result is similar to the study by Yu (1982) who used Sloboda equation, and attributed that "to empirical evidence". In accordance with the general experience, increment height culminates sooner on better sites, but declines more rapidly on the good sites after reaching the point of culmination (Kramer, 1988). This study precisely aligns with this explanation, as the maximum values of height increment were found in the young plots and the minimum values recorded in the old plots.

The reference age in this study was 50 years. Besides this age is common in literature for coniferous species, the relative error test was lowest at this value. According to Goelz and Burk (1992) the reference age should be close to the rotation age and should be as young as possible, in order to help in earlier decision making of the silvicultural treatments to be applied to the stand; in this study, the rotation age in the best productivity sites was close to 50 years and that supported more that age 50 years is so appropriate to be taken as reference age. Furthermore, most available research works from the Mediterranean region have applied this same value as reference age; for example, Nahal (1982), Suliman (2013), and Diéguez-Aranda et al. (2005) who equally found the best base age for *Pinus radiata*, *P. taeda* and *Betula pubescens* stands was 50 years.

This study tested the base age as an invariable property. This means that whatever the base age, height will equal site index when age equalsbase age. This property meets the desirable characteristics as cited by Bailey and Clutter (1974); Elfving and Kiviste (1997) and Goelz and Burk (1992).

Unlike the anamorphic curves, which assume a common shape for all site classes, the polymorphic curves used in this study show that height growth exhibits pronounced sigmoid shapes on higher-quality sites, and “flatter” shape on lower-quality sites.

One of the problematic points in forestry literature concerns the asymptotic parameter of *Pinus brutia* site index equation, which was so high and forced the dominant height to continue growing at rather old ages. Although the growth characteristic according to Wenk et al (1990) is contradictory, and the assertion of Shvets and Zeide (1996) that non-asymptotic curves are not acceptable for growth modeling, there is strong evidence that growth in volume per hectare in even-aged stands is not asymptotic, and the gross accumulated volume may not show any inflection points (Garcia 1997). Gadow (1987) also indicates that stand height increases until the decomposition phase. In the same context, Bontemps and Duplat (2012) indicated that top height growth in pure and even-aged stands can be accurately described by a non-asymptotic curve, with better performances than those of asymptotic curves. Körner (2015) used this kind of curves to model the individual-tree growth model for *Pinus caribaea* Morelet var. *hondurensis* in the Dominican Republic. According to Author, the model performed well. The site class curves developed for Scots Pine in Spain by Abejon and Ferreiro

(1986) show that for the best sites there was a non-asymptotic trend. However, it is recommended that the site index equation is not used out of the age range of the modeling data; and non-asymptotic equations should deserve more attention.

Accordingly, the polymorphism, base-age invariance, increment height culminates sooner on better sites, and S-shaped curves, making the use of the Sloboda equation to obtain estimates of the site index in *Pinus brutia* stands more accurately and reliably than any other methods. This Sloboda equation can be applied for site index estimation through the stand dominant height and age while building an individual-tree growth model. It serves as a baseline for classifying and comparing Brutian pine stands in different Mediterranean Sea regions, and in land-use decisions, land appraisals and silviculture investment analyses.

4.4 Individual-tree growth model

4.4.1 Diameter increment equation

Ordinary least squares (OLS) approach was used to elaborate the diameter increment equation in this study. Although many publications have used mixed models mainly because of the possible autocorrelation in growth variables between the two successive periods, temporal correlation may, however, not be a significant problem if growth intervals of 5 years or more are used (Gertner, 1985; Quicke et al., 1994).

Tree size is a good indicator of future growth, reflecting past competitive status and different genetic responses to the environment (Perry, 1985; Bevilacqua, 1999). In this study, the diameter growth in PINUS-Syria Model decreases monotonically without culmination as diameter at breast height increases, in the same manner as found in other works (Lick and Sterba, 1991; Monserud and Sterba, 1995; Carus, 2004). The effect of geographical variation on diameter growth is hitherto unclear. For this reason, this study found that it is better to develop a diameter increment equation without slope and aspect, which should be paid more attention in future. One of the solutions we could follow in the future to assess the effect of slope and aspect is to establish a specially designed study that has plots at several aspects and slopes on the same other conditions (site index and density), as recommended by Uzoh and Oliver (2008).

Besides the fact that increasing the competition index decreases the diameter growth, the coefficient of BAL is negative. This result can be interpreted as biologically plausible, since a higher competitive pressure leads to a reduction of the growth. A significantly negative relationship between stand density index and size was observed in all the stands. This behavior may be explained as a search for light and dominance by the larger trees following an asymmetric competition pattern. In the same context, if the competition indices were removed from the developed diameter increment equation, the equation only explains 20 % of diameter increment variation; this result means that the competition in this study plays a crucial role in explaining the diameter increment variation (Figure 4-2).

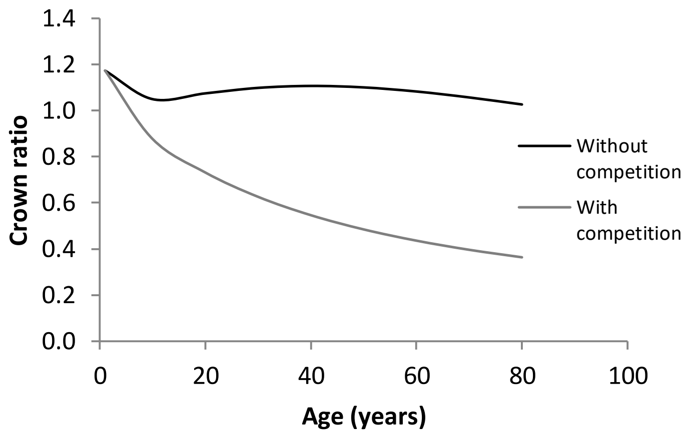


Figure 4-2: Diameter increment development over time with and without competition

The mean annual diameter increment of *Pinus brutia* trees was 0.34 cm in the modeling data, eight-year diameter growth ranges between 0.45 cm to almost 9.4 cm depending on site quality and competition.

These increments are so similar to the ones found for Brutia pine in Turkey (Carus, 2004) where the mean annual diameter was 0.29 cm and eight-year diameter growth varied between 1 cm and 5 cm. In general, similar results were reported elsewhere in the Mediterranean region (Palahí and Grau, 2003; Palahí et al., 2003; Palahi et al., 2008).

4.4.2 Height increment equations

This study presented for the first time, not only in Syria but also in the Mediterranean region and the Middle East, an individual-height increment equation for pure and even-aged stands of *Pinus brutia* using two approaches: potential-modifier and realized height increment using distance-independent competition.

The height growth in the simulation model increases until a certain point and then start decreasing as the tree size increases. This is similar to the results found by Uzoh and Oliver (2006) and Monserud and Sterba (1995). The size of initial diameter and tree height is an indication of a tree's competitive status within a plot or stand, and thus, an expression of tree vigor (Figure 4-3).

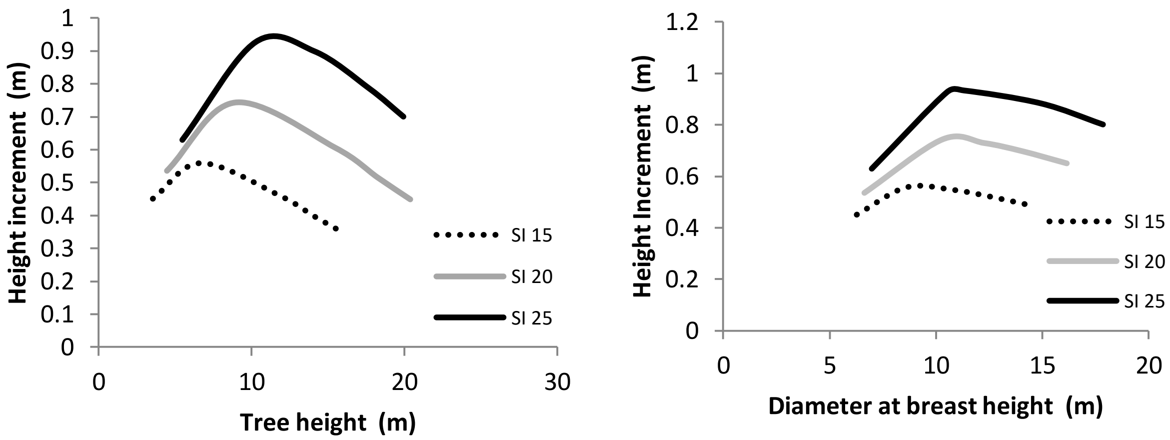


Figure 4-3: Effect of tree height and diameter at breast height on height increment *Pinus brutia* plot representing three different site index values: 15, 20, and 25

The site index was the strongest individual predictors than any other variable, assuming developing the linearized height increment without site index, the equation explains smaller than 2 % of height increment variations. One could have inferred that height increment was affected more with the site index than diameter increment.

Increasing the basal area of trees larger than the subject tree divided by diameter at breast height stimulates the height growth until a certain point before the height growth starts decreasing. Assuming competition is absent (BAL = 0), the equation explains 31 % of height increment variations.

Before discussing the effect of elevation which is considered one of the significant variables in linearized height increment equation, it is worth to mention that 86 % of our plots were located at elevations equal or less than 800 m and the maximum elevation recorded is 975 m.

In the PINUS-Syria Model, height growth increases as elevation increases until 975 m. This result corresponds with the results from the study of Kiaei and Samariha (2011), which tested the effect of elevation on the growth of *Pinus eldarica* in Iran where the tree height increases as elevation increases until 1200 m before a decrease emerged. Similar behavior is expected to be seen in the coastal region of Syria after 1200 m, but none of the plots used in the current study is located above 975 m.

The difference in temperature between Safita, located at 350 m with 17.8°C and Qadmous, which are located at 750 m with 14.3 °C is only 3.5 °C is underpinning to the previous idea. This little change in temperature may be ineffective on growth with the dominance of different effects of site productivity and competition, which have the strongest effects on growth according to linear regression analysis.

In general, the influence of elevation on productivity is a complicated one and attributing such effects to specific factors (e.g., average wind speeds, adiabatic processes operating, atmospheric pressure, precipitations and soil condition changes) is problematic, given the present state of our knowledge. Worrell (1987) stated that the majority of environmental factors influencing tree growth vary with changes in elevation. As suggested by Uzoh and Oliver (2008), distribution of plots should capture several elevations corresponding to similar other conditions that influence growth in order to accurately assess the effect of elevation in greater detail. Based on these results, this study found that it is better to develop additional linearized height increment without inserting topographical factors.

With regard to the potential height increment modifier, the competition factor used, which represented the modifier, is the ratio of stand dominant tree height to tree height within the stand in contrary to other works that used tree height within the stand to stand dominant tree height (Monserud et al.,1997; Pretzsch, 2001). In this study, the ratio value ranged between 0.8 and 2.6, and the average is 1.15. The value 2.6 is equivalent to the value determined by Pretzsch (2001), Monserud et al. (1997) and Ledermann (2010) which found the maximum ratio of individual-tree height to dominant tree height within the stand is about 1.18. By using the dominant height, the approach of potential height increment modifier also appears to be more stable against thinning practices. Because the potential modifier requires less information (only dominant height and tree height), it makes the equations less prone to changes and more stable than linearized height increment. Thus, this could explain why potential height increment modifier showed better results than the linearized height increment.

4.4.3 Crown ratio

The model appears to be well behaved and robust for pure even-aged brutia pine stands. The total variation explained by the exponential equation proposed is 76 %. This agrees with the report by Adeyemi et al (2013) and disagrees with the reports by Soares and Tome (2001), Temesgen et al. (2005), Adesoye and Oluwadare (2008), where the suitability of only the Richards and Logistic equations were established. This may be as a result of the variables used in their studies.

In fact, diameter at breast height is one of the most important tree variables. It is usually applied to account for stand structure, tree vigor, and competition capacity. The choice of diameter at breast height as an independent variable is supported by many studies (e.g., Soares and Tomé, 2001; Leites et al, 2009; Temesgen et al, 2005; Toney and Reeves, 2008) which concluded that increasing diameter at breast height would result in a larger value of the tree crown ratio. This study contradicts these results, but rather indicates that crown ratio decreases as the diameter at breast height increases; this result corresponds with the results of Temesgen et al (2005).

Competition effects are estimated by stand density index (SDI) and basal area of the larger trees. With this, crown ratio decreases as competition increases. This result is supported by some earlier works (Hasenauer and Monserud, 1996; Soares and Tomé, 2001; Temesgen et al, 2005; Toney and Reeves, 2008). The model is only explained to about 62 % if it developed without the competition indices (Figure 4-4).

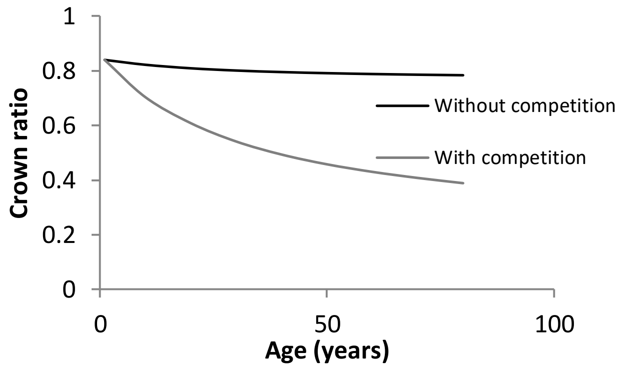


Figure 4-4: Crown ratio development over time with and without competition

In the developed equation, greater values for site index resulted in smaller crown ratio values, and that could be explained by the fact that the site index affects positively on tree height, and the high values of tree height reduce the crown ratio. In a similar manner, site index was found significant in Soares and Tomé (2001). In other studies, however, the effect of Meyer' SI on the crown ratio is insignificant (Fu et al, 2015).

The developed crown ratio models can already be incorporated into developed growth models, but the forest managers should keep in their mind that one could obtain potential improvements to the prediction of the current models using spatial competition measures when such variables can be obtained at a reasonable cost.

4.4.4 Height-diameter equations

The generalized height-diameter relationship equation was developed in the thesis to apply it in inventories where height data is missing for many trees on a sample plot. In the PINUS-Syria Model, height-diameter sub-model includes dominant height as random effects. Dominant height represents the site and age, and that reflects variations at the sample plot-level. In general, the height-diameter relationship varies from stand to stand, and even within the same stand, the relationship is not constant over time (Curtis, 1967). Therefore, a single curve cannot be used to estimate all the possible relationships that can be found within a forest. To minimize this level of variance, height-diameter relationships can be improved by taking into account of stand variables that introduce the dynamics of each stand into the model (Curtis, 1967; Sánchez et al., 2003; Temesgen and Gadow, 2004; Dorado et al., 2006).

The tested models showed overall good behavior, and meets the biological knowledge; where the height increases as diameter increase, the height-diameter curves change its direction, and plausible. On the best sites, the height-diameter curves of *Pinus brutia* were steeper and presented larger asymptotes than in poor sites (Cardoso et al., 1989; Bartoszeck et al., 2004). In spite of some viewpoints, which consider that the height-diameter could indicate forest productivity in different locations and conditions (Huang and Titus, 1993), forest managers should be careful when using height-diameter relationship in relation to productivity because many other factors influence forest yield. These include age, management, density, site, competition (Costa et al, 2016).

In the PINUS-Syria Model, using the individual-tree height led to unreasonable height in the early-aged stand, and that mostly is based on the fact that parameters of diameter and height growth models are usually not estimated simultaneously and therefore model predictions may result in unreasonable height-diameter ratios for individual trees (Hasenauer et al., 1998; Sharma, 2013). Another possible explanation relates to lack of data collected in early age plantations, or non-availability of time to conduct measurements yearly in order to ensure accurate predictions.

This incompatibility could be avoided if the height-diameter models presented here are used together with individual-tree height or diameter models in the PINUS-Syria Model. This reason motivated this study further to develop the generalized height-diameter. The developed generalized height-diameter relationship equation was used to calculate the initial value of height at the initialization of the simulation where implementing the height-diameter submodel prevents problems that may arise with an independent use of individual-tree height growth sub-model in the simulation model. The biological and statistical performance for the generalized height-diameter equation allows applying it to estimate missing heights for sample plots or other sample plots, where measured heights are available.

4.4.5 Mortality equation

For calibrating mortality models, several authors used logistic regression and obtained reasonable results (e.g. Monserud and Sterba, 1999; Yang et al., 2003; Palahí et al., 2003; Jutras et al., 2003; Zhao et al., 2004; Adame et al, 2010). Following these authors, this study used a logistic model to fit the data for *Pinus brutia* stands. The negative parameter of diameter and the positive parameter of diameter squared should supposed to capture the U-shaped mortality trend (Monserud, 1976; Monserud and Sterba, 1999; Yang et al, 2003). It indicated that mortality rates are high when trees are small, and decrease with increasing tree size. This study, however, does not clearly reflect the U-shaped mortality trend due to the low frequency of trees larger than 40 cm diameter at breast height in the available data, and that maybe be considered as weak point.

In this study, the increase of the basal area of trees larger than the subject tree leads to a higher possibility of mortality. This analysis is conformity with the results of Monserud and Sterba (1999), Palahi et al (2008) and Palahi et al. (2003). The site index in this study was a significant predictor in the mortality equation. Stands growing on better productive sites are more vulnerable to overcrowding effects than those growing on poorer sites. Due to faster growth, they are more intensively mortality than those growing on less productive sites. This result corresponds with some previous studies that mentioned the role site effect plays in tree mortality (Weiskittel et al, 2011; Eid and Tuhus, 2001; Murphy and Graney 1998; Bravo-Oviedo et al. 2006). This differs from the finding of Vanclay (1994) who stated that the effect of site productivity on mortality is ambiguous and unclear, Vanclay attributed these findings to lack of suitable experimental data.

By using the intersection point of sensitivity and specificity, the prediction of the number of dead trees was overestimated. This is in conformity with the study conducted by Crecente-Campo et al. (2009). Its advantage is that it gives the most accurate percentage. Hein and Weiskittel (2010) considered the sensitivity-specificity cut- an optimal threshold, whereas the average observed mortality rate gives a much lower accuracy of predicting the correct trees but using the average observed mortality still the most reasonable threshold according to Monserud and Sterba (1999).

One of the major issues in forest science concerns if there is any difference in growth predictions by applying stochastic and deterministic approaches for the same single-tree model and the same initial conditions. This study made a comparison of two different approaches (i.e., deterministic and stochastic) of incorporating mortality into growth predictions. It was found that there are true differences between both approaches on the long-term. The differences ranged from 8-10 %. This difference raises another question: which approach is the best?

To answer this question, some points need to be addressed and taken into account. First of all, there are no significant differences when the individual-tree growth model is applied to the short-term whether it used stochastic or deterministic approaches. On the long-term, unfortunately, we have no data to asses each approach in respect with the observed data, but future re-measurement of the permanent plots would be so helpful to increase our knowledge about this point.

The second point relates to the growth steps. Fortin and Langevin (2011) hypothesized that growth steps affect the differences between stochastic and deterministic approaches more than the uncertainty mortality model. Our study re-parametrized the developed equations (diameter increment, height increment) to make the individual-tree model use 8-year growth and compare between both approaches, by doing this, the differences relatively decreased and ranged between 1.5 and 3 %. Based on these results, this study proved the differences so close correlated with the growth steps. These findings led us into another question: what is the reason behind the differences recorded between the stochastic and deterministic approaches when using the one-year growth step and 8-year growth step? In fact, this study believes the simulation over 100 years requires 100 re-insertions of the predicted variables (diameter increment and height increment), and that may cause error propagation. This could be one main reason for the increasing differences after certain growth steps. In a case where the model used 8-year growth step, the simulation required only 12 re-insertion of the predicted variables and for this, the error propagation seems to be under control. This discussion does not mean that this study presented an exhaustive answer to this question, it needs to be re-visited and further addressed in future studies.

Thirdly, it is generally known that mortality is a stochastic process, but perhaps mortality would appear less stochastic if relevant environmental variables were measured on permanent plots (Monserud and Sterba, 1999). One last point is related to the threshold of Sensitivity-specificity. The mortality equation gave the most accurate predictions, but the prediction was overestimated at the same time. This point should be taken into account when we recommend which approach more reasonable.

Based on these points, the study recommended that the modellers should aware that deterministic simulations may yield different results from stochastic simulations when using the same data and the same model on the long-term, and it is better to use the average observed mortality rate in spite of its low accurate but it is more realistic (Monserud and Sterba, 1999).

In the same context, few studies have addressed the comparison of stochastic and deterministic predictions of single-tree models, e.g., Ek (1980), Weber et al. (1986), Vanclay (1991) who concluded that the differences between stochastic and deterministic predictions were negligible. These results are likely attributed to that at the time these studies were carried out, computing capacities were much more limited than they are today, whereas Zhou and Buongiorno (2004) Fortin and Langevin (2011) also found that there may be substantial differences depending on the response variable and the model.

To summarize, we highlighted in this part that the study tried to explain the behavior of mortality under the most important explanatory variables that were selected to develop the mortality equation. It also discussed which thresholds were used in the study, and the difference in growth predictions by applying stochastic and deterministic approaches.

4.5 Model Applications

The PINUS-Syria Model can be applied effectively in several aspects of forest management. Firstly, it can be used for sustainable forest management as determining the rotation length in the absence of thinning and simulating the effect of different scenarios of thinning regimes on the stand development. Mean annual volume increment (MAI) per unit area is the most important criterion in terms of forest management when wood production is prioritized. Site quality and initial density are key factors explaining the variation in length of the rotation period (Lundgren, 1981; Cao et al, 2006). The better site index, the faster rotation length. However, when economic profitability is maximized are used, the optimal rotation lengths would be different since the economically optimal rotation length depends on the stand establishment costs, prices and dimensions of different timber assortments, and discounting rate; and in this case the stand density will play a crucial role in determining the rotation age, e.g. if economically required trees with diameters 25 cm, the stand with 1500 trees per hectare and site index 25 need 48 years to reach this diameter, while it needs only 21 years to reach this value if the density was 500 trees per hectare, and so the more densely planted stands have longer optimal rotation lengths. The results of mean annual volume increment recorded in this study are similar to that recorded in the Mediterranean region. In Cyprus, the mean annual volume increment of *Pinus brutia* can be over 10 m^3 ha^{-1}/ year site index 20 m (Kitikidou et al 2011). In Greece, the maximum annual volume increment of pine stands on a good site an achieved (around 8.5 m^3 ha^{-1}/year) at 40 years (Palahi et al. 2008). In Turkey, the mean annual increment in good sites of *Pinus brutia* stands ranged between 10-12 m^3 ha^{-1} / year (Gezer, 1986). On the other hand, Table 4-1 showed an approximate comparison of mean annual volume increment in site index 25 with other *Pinus* species in Syria.

Table 4-1: Comparison of mean annual volume increment in site class 25 between *Pinus brutia* in this study with other *Pinus species* in Syria

	Pinus brutia	***Pinus halpensis***	***Pinus pinester***	***Pinus radiata***
MAI (m^3 ha^{-1}/year)	9.6	8.5	13.2	14.8
Reference	This study	Koubaily et al, 2008	Abido, and Koubai-ly,2000	Koubaily et al,2008

The PINUS-Syria Model was used to simulate the optimal stand development that maximizes wood production under different scenarios of thinning regimes. Different thinning regimes have different effects on the stand development, by changing competition included in the growth and yield models. One shortcoming of the growth models is that they have been developed without taking into account the effect of thinning on the growth of stand (basal area, volume, height or diameter at breast height) in field. Thus, the results of thinning treatments are based on the assumption that the growth and yield model developed for even-aged *Pinus brutia* stands is reasonable and works properly because the developed equations were evaluated and validated. Moreover, the equations followed overall patterns of stand development, which in turn has led us to increase our belief that no drastic deterioration in simulation will occur as long as the simulation model is not used for prediction out of the range of the calibration data.

Thinning improved the growth rates for diameter at breast height, tree height and tree volume, the improvement on diameter increment is more clearer than on height increment, in clear agreement with the results revealed when the competition was analyzed. Based on the simulation results, this study suggests one thinning scenarios with heavy intensity in good and very good sites, and one or two thinning with moderate, heavy or very heavy thinning in medium and poor sites depending on the density. Using the heaviest thinning in good sites agrees with the conclusions of Carus and Catal (2009) work, which studied the responses of Brutia pine stands to different thinning intensity in Turkey.

Secondly, the PINUS-Syria Model can be used for teaching students in forest growth and modelling, it can be also used for training people who are responsible for making decisions about forest management. Growth and yield models in forestry are necessary to support stand management research. The model output, consisting of charts and tables can provide forest managers with a wide variety of information and visualizations, to help them planning objectively.

4.6 Outlook on the future

The PINUS-Syria Model was built based on available data sources. Therefore, the use of the PINUS-Syria Model applications in forest management practice is limited to areas whose site conditions are similar to those of permanent plots used in the study. In the future, data collected in research plots should include not only diameter, height, mortality, crown length and crown diameter but also additional parameters such as recruitment, all tree position, temperature, precipitation, as well as consideration for different disturbance factors such as wildfire. Once these additional data are obtained, some following studies need to be implemented to further improve forest management in Syria:

In the light of the large variation in the site, environmental conditions, developing a site index based on environmental and topographical conditions in the future will be a very advanced step to categorize sites more accurately. Besides that, the non-asymptotic trend of the developed site index equation deserves more attention. The reasonable results of competition indices encourage testing of distance-dependent competition indices for *Pinus brutia* in more detail, such this step may improve the model prediction and provide better tools for the decision making process. Analysis of below-ground competition in spite of its effects on tree and stand growth was not considered in this study. Therefore, it should be on the list of studies to be carried out in the future.

The PINUS-Syria Model was developed for pure and even-aged Brutia pine stands. However, the model approach can be tested for application to other forest types such as uneven-aged, multi-species deciduous forests and semi-evergreen forests. With datasets collected from permanent research plots, the model components can be calibrated to fit for such forests. This is an important and necessary work for sustainable forest management because at present there is still no effective model available.

Because the stochastic and deterministic simulations yield different results for the same single-tree model and the same initial conditions, further studies are also recommended to compare the stochastic and deterministic methods for determining mortality. Nevertheless, the mortality equation has very good ability to predict natural mortality of trees. It is recommended for application where it is expected to facilitate the growth and yield prediction for better management of pine forests in the region.

In the future, the probability of ingrowth occurrence on a sample plot could be further developed and incorporated into the current growth model. Besides that, studies on effects of wildfire on all aspects need to be seriously considered in the future.

The PINUS-Syria Model allows managers to simulate plausible management schedule in a given stand, providing very helpful information for decision-making process. This tool could help forest managers in taking decisions on rotation length, and the timing, frequency, and intensity of forest thinning. Overall, models for optimal management become practical and easier to use in forestry practices than old applied methods.

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APPENDICES

Appendix1: Characteristics of modeling and validation plots in this study

Plot	Size(m^2)	Age2008	N ha^{-1}(2008)	Elev(m)	Asp(degree)	slo%	Soil depth(cm)
1	706.85	54	1089	375	330	45	44.4
2	452.38	66	2144	548	330	30	23.4
3	1963.49	41	535	454	180	11	26.8
4	907.91	40	727	475	180	11	26.2
5	907.91	39	881	485	210	5	30
6	804.24	25	858	934.2	225	10	44.2
7	452.38	28	1348	669	225	12	19.6
9	1256.63	47	493	427	210	0	150
10	1256.63	32	748	787	330	23	30.6
11	706.85	61	891	444	150	0	17.4
12	240	48	2500	780	110	42	28.8
13	254.4	67	3144	673	25	40	35.8
16	706.85	57	622	486	210	14	30.2
17	1963.49	96	224	598	300	6	20.4
18	1256.63	76	454	647	250	10	24.4
19	1593.29	87	383	629	330	5	35.6
20	282.14	55	1753	668	330	20	27.8
21	530.92	55	753	618	120	60	38.8
22	1256.63	60	645	657	200	20	28.8
23	530.92	51	1356	658	160	30	28.8
24	706.85	55	1019	651	180	45	38
25	200	69	2499	590	280	30	28.8
26	706.82	60	934	612	240	75	43.2
27	530.9	51	1394	142	0	55	42.8
28	452.37	49	2476	137	345	40	31.2
29	1963.41	90	275	306	200	25	29.2
30	804.21	93	137	643	330	10	21.8
31	1256.63	82	302	390	310	30	26.8
32	706.85	65	523	964	330	33	29.2
33	452.37	30	1304	899	25	40	37.6
34	314.14	34	2165	839	180	22	44.4
35	706.85	35	806	131	295	10	37.2
36	706.85	36	764	399	310	16	27.2
37	930.99	16	634	505	300	25	29.8
38	706.85	71	622	328	175	20	40.2
39	907.91	60	474	404	115	50	34.8
41	380.13	30	1868	937	195	10	29.2
42	1256.63	74	525	903	315	36	96.4
43	706.85	65	778	624	250	55	28.4
44	690	52	652	341	215	25	22.8
45	380.13	32	1789	268	170	21	44.4
47	530.92	43	1092	522	350	25	42.2

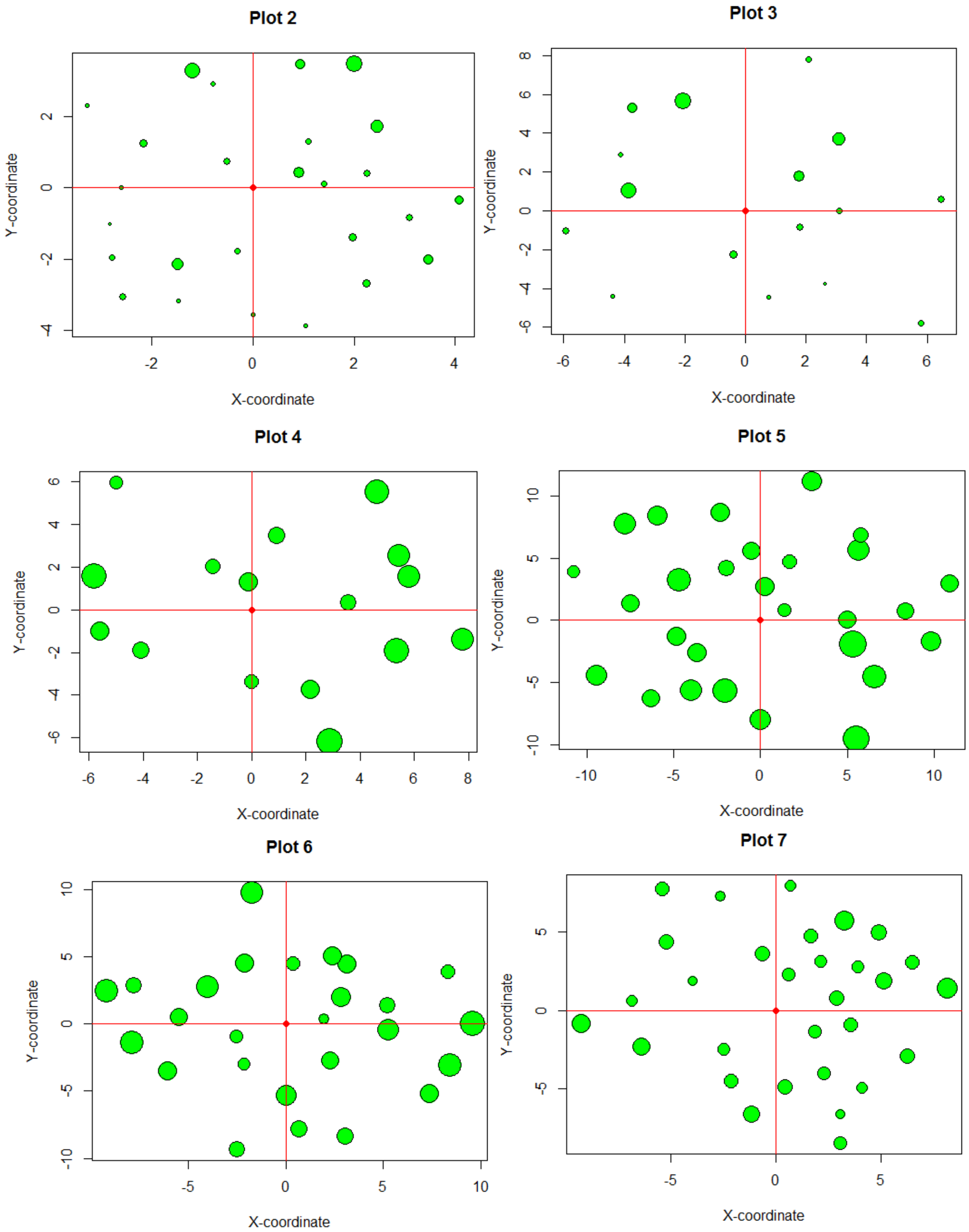
48	907.91	43	672	975	205	25	94.6
49	750	69	440	796	345	45	70.8
50	1661,9	77	301	795	270	30	32.2
51	1256.63	121	509	567	130	40	38
52	452.38	55	1282	328	205	11	44.4
53	380.13	81	1499	590	35	16	21
55	706.85	68	297	590.5	100	17	31.2
56	380.13	64	1184	616	85	33	27.2
57	380.13	30	684	680	20	25	29.6
58	254.46	16	2201	774,2	230	27	32
60	452.38	66	951	796	190	35	27.8
61	452.38	98	420	801	245	25	37.8
62	69.99	37	2429	758	170	21	48
63	452.38	39	707	743	60	15	31.6
64	452.38	36	906	487	200	30	29.2

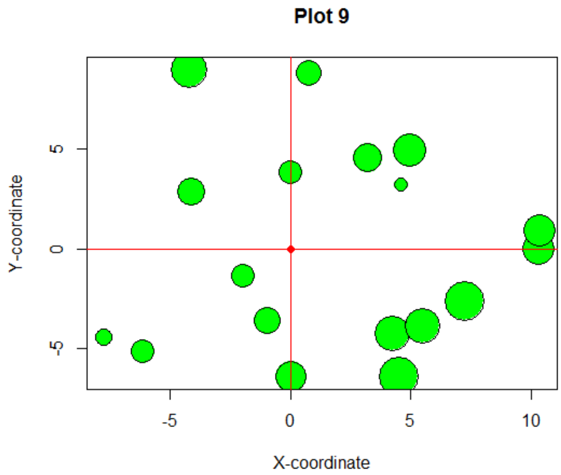
Appendix 2: Characteristics of constructed plot for competition

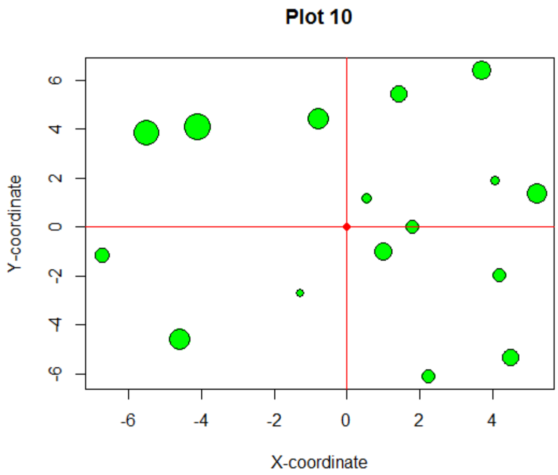
Plot Number	plotsize	radius	number of trees	$d_{1.3}$of central tree	Height of central tree
1	346.4	10.5	31	22.5	21
2	103.9	5.75	27	13.6	11.5
3	254.5	9	17	35.7	18
4	201.1	8	17	19.2	16
5	452.4	12	29	39.6	24
6	314.2	10	27	26.2	20
7	271.7	9.3	31	26	18.6
9	380.1	11	19	34	22
10	176.7	7.5	17	10.9	15
11	191.1	7.8	25	21.7	15.6
12	50.3	4	16	11	8
13	52.8	4.1	28	11.2	8.2
14	63.6	4.5	23	9.7	9
15	113.1	6	26	14.1	12
16	78.5	5	12	13.2	10
17	314.2	10	10	42.9	20
18	408.3	11.4	22	37.7	22.8
19	452.4	12	20	61.8	24
20	95.0	5.5	9	19.8	11
21	380.1	11	27	33.5	22
22	369.8	10.85	29	25.9	21.7
23	136.8	6.6	24	11.4	13.2
24	307.9	9.9	33	31.9	19.8
25	63.6	4.5	14	10.5	9
26	333.3	10.3	34	34.5	20.6
27	181.5	7.6	29	24	15.2
28	55.4	4.2	19	9.4	8.4
29	339.8	10.4	15	43.4	20.8
30	408.3	11.4	8	50.8	22.8
31	380.1	11	14	44.4	22
32	116.9	6.1	11	29.5	12.2
33	314.2	10	39	22.1	20
34	221.7	8.4	51	24.9	16.8
35	227.0	8.5	24	22.2	17
36	326.9	10.2	30	21.2	20.4
37	95.0	5.5	12	11.3	11
38	314.2	10	22	36.7	20
39	346.4	10.5	19	31.1	21
40	132.7	6.5	35	16	13
41	186.3	7.7	39	18.1	15.4
42	254.5	9	18	28	18
43	176.7	7.5	19	23.4	15
44	132.7	6.5	10	26.1	13
45	81.7	5.1	18	10.3	10.2
46	265.9	9.2	35	19.3	18.4
47	265.9	9.2	30	22.9	18.4
48	301.7	9.8	21	24.9	19.6
49	227.0	8.5	11	33.1	17

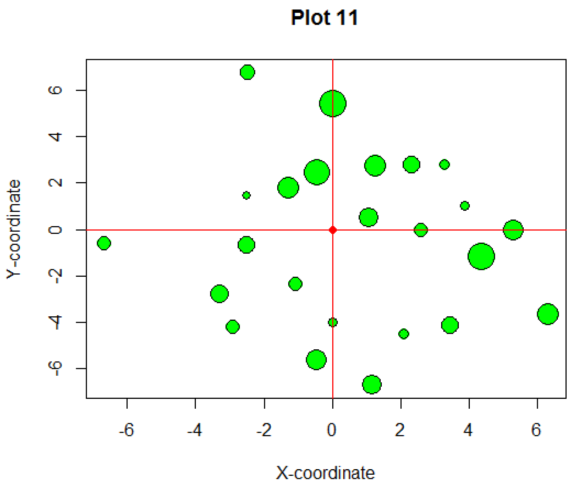
50	201.1	8	11	31.3	16
51	113.1	6	11	27.5	12
52	506.7	12.7	58	34.8	25.4
53	162.9	7.2	30	29	14.4
55	452.4	12	15	37.7	24
56	397.6	11.25	43	35.4	22.5
57	415.5	11.5	26	31.7	23
58	136.8	6.6	35	16	13.2
59	58.1	4.3	7	25.2	8.6
60	153.9	7	14	23.3	14
61	191.1	7.8	9	58.7	15.6
62	102.1	5.7	17	15.3	11.4
63	346.4	10.5	27	30.8	21
64	498.8	12.6	40	26.2	25.2

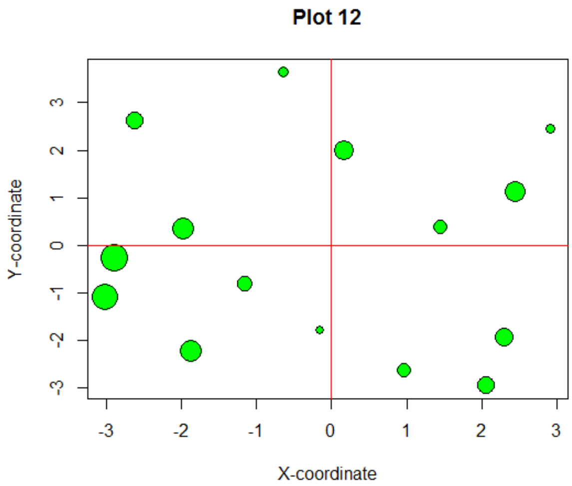
Appendix 3: Positions of central and competitor trees in plots

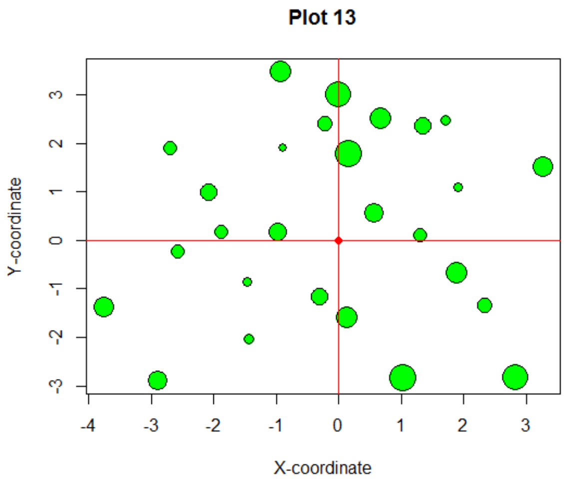


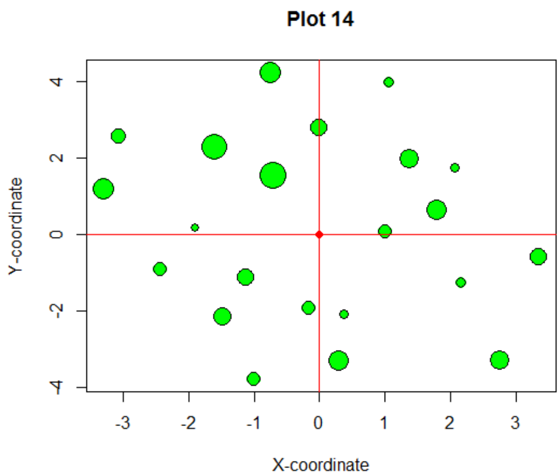

Plot 9
Y-coordinate
-5 0 5
-5 0 5 10
X-coordinate


Plot 10
Y-coordinate
-6 -4 -2 0 2 4 6
-6 -4 -2 0 2 4
X-coordinate

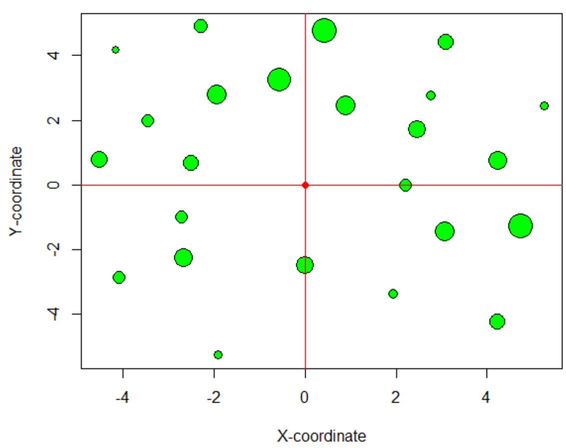

Plot 11
Y-coordinate
-6 -4 -2 0 2 4 6
-6 -4 -2 0 2 4 6
X-coordinate


Plot 12
Y-coordinate
-3 -2 -1 0 1 2 3
-3 -2 -1 0 1 2 3
X-coordinate

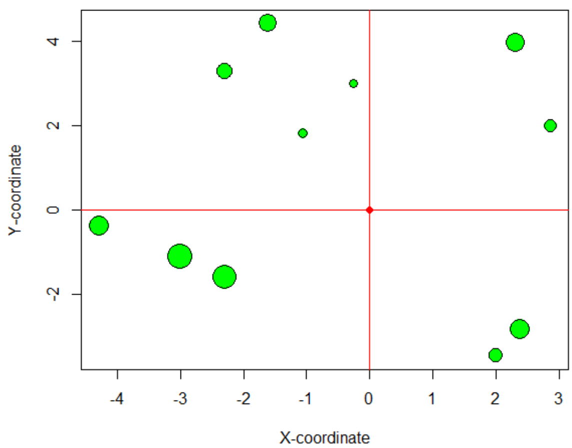

Plot 13
Y-coordinate
-3 -2 -1 0 1 2 3
-4 -3 -2 -1 0 1 2 3
X-coordinate


Plot 14
Y-coordinate
-4 -2 0 2 4
-3 -2 -1 0 1 2 3
X-coordinate

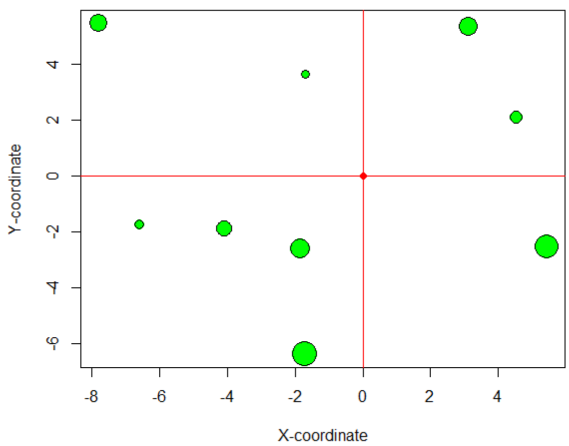
Plot 15



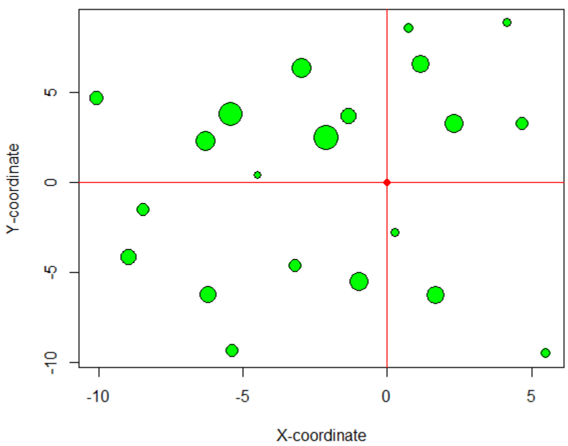
Plot 16



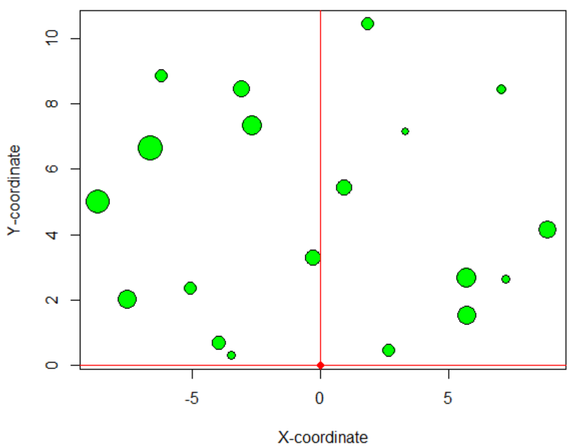
Plot 17



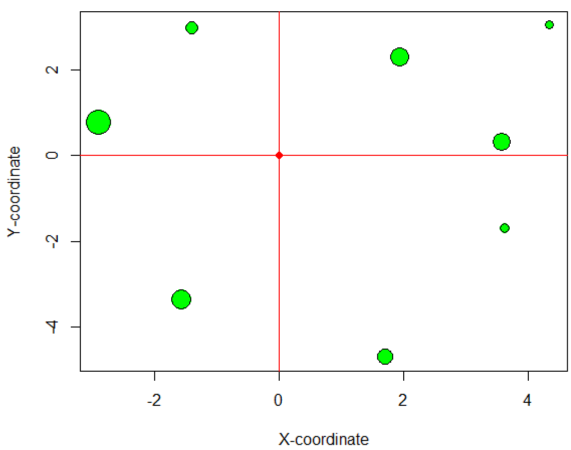
Plot 18



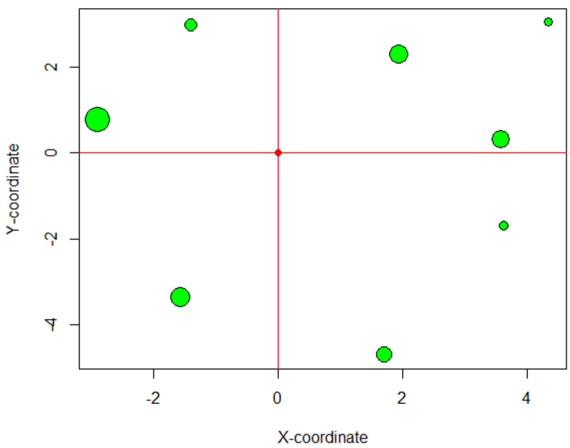
Plot 19



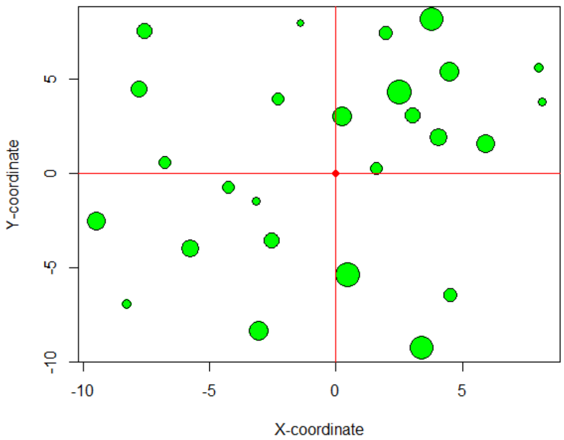
Plot 20



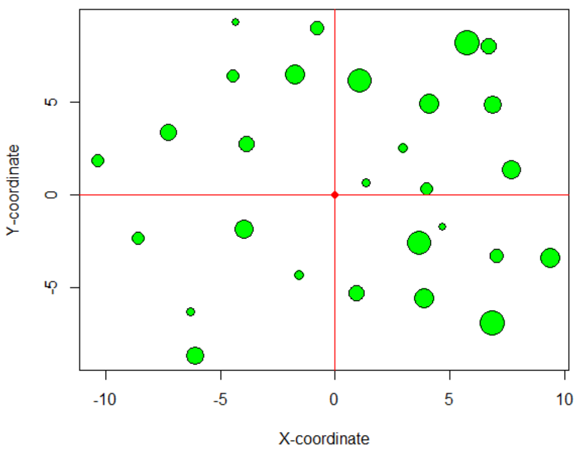
Plot 20



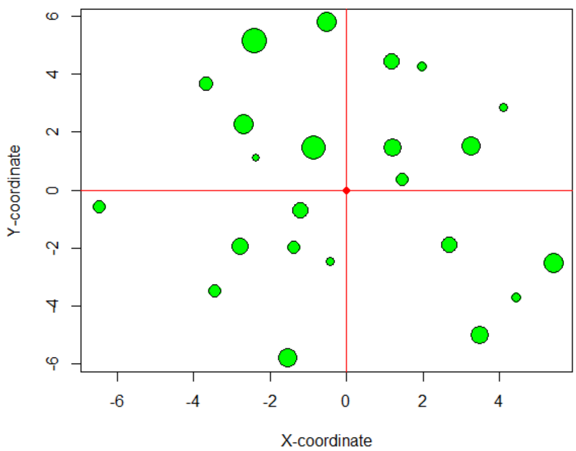
Plot 21



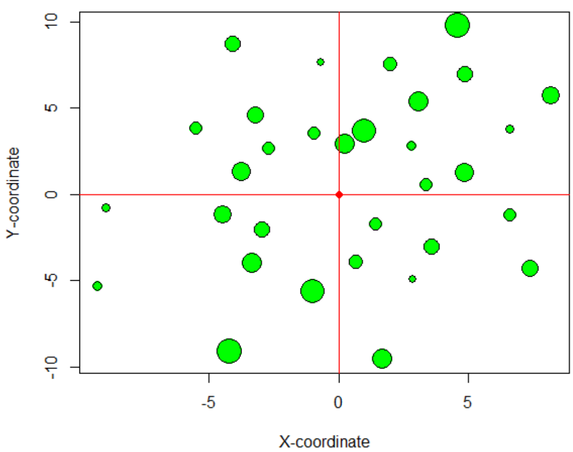
Plot 22



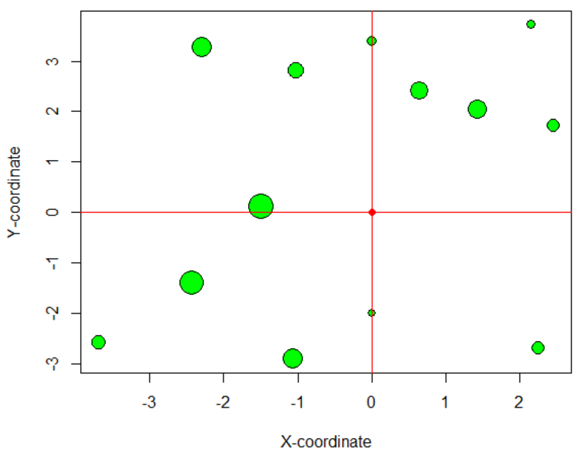
Plot 23



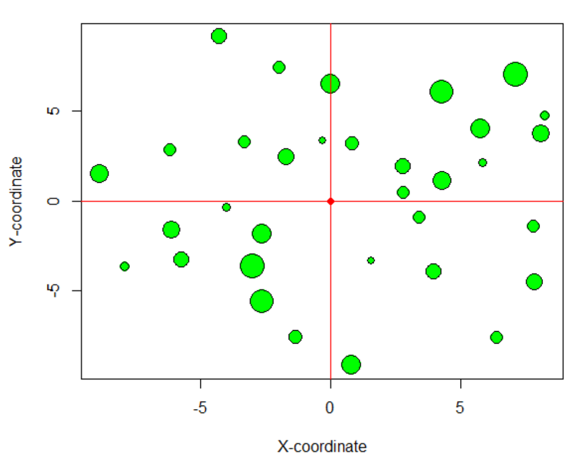
Plot 24



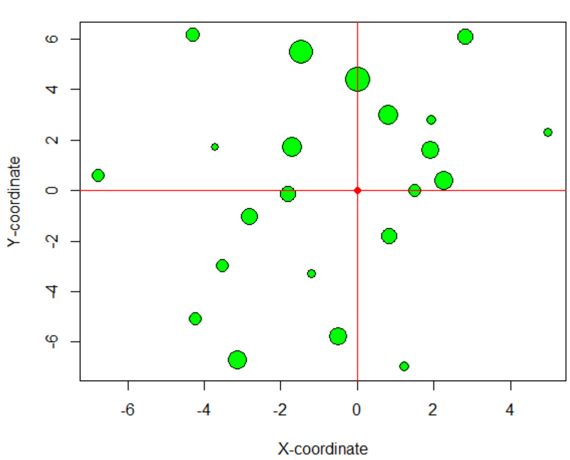
Plot 25



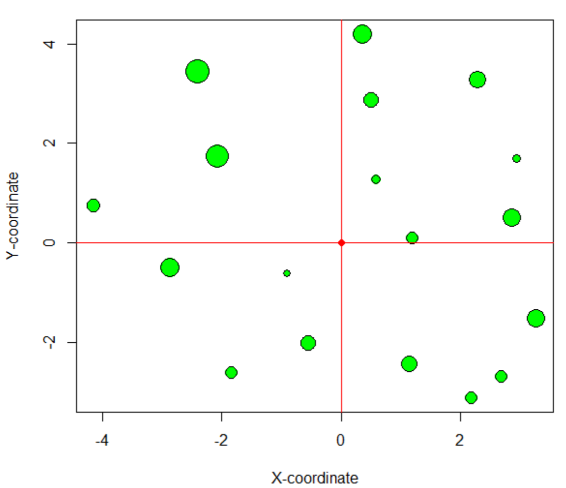
Plot 26



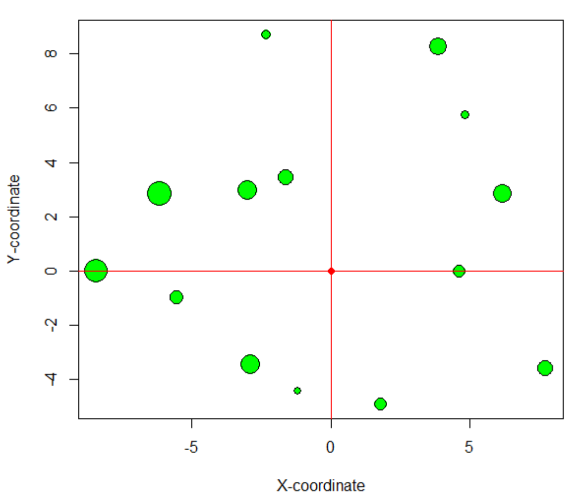
Plot 27



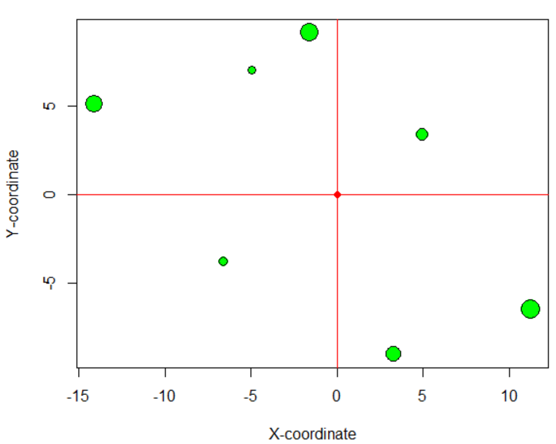
Plot 28



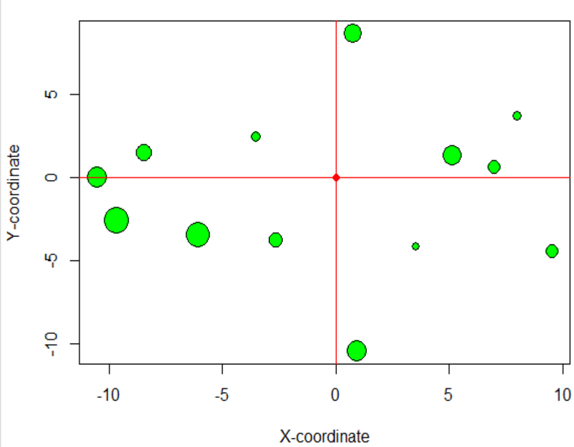
Plot 29



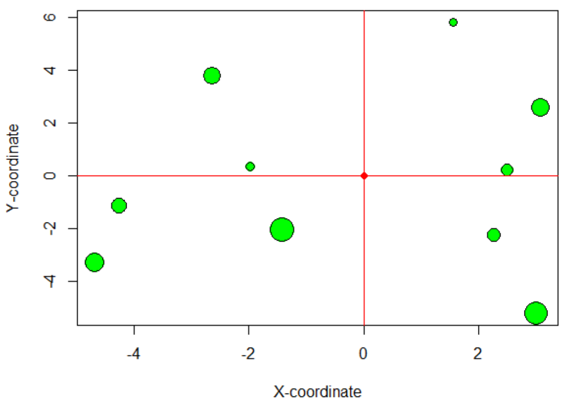
Plot 30



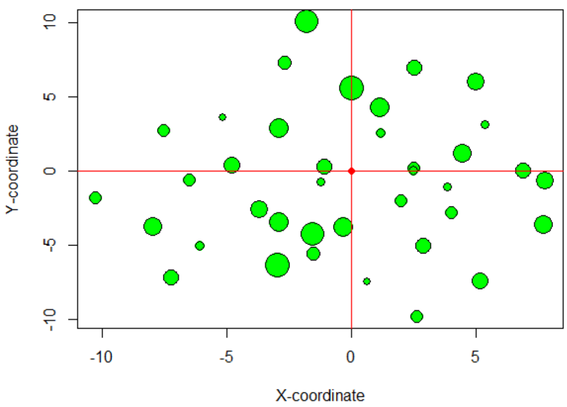
Plot 31



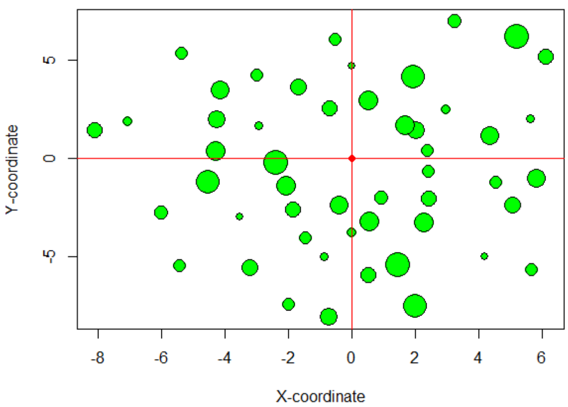
Plot 32



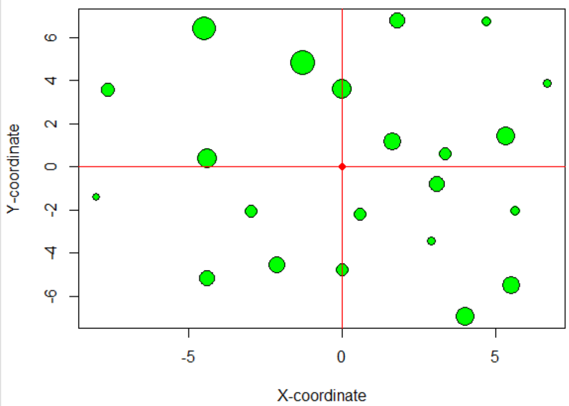
Plot 33



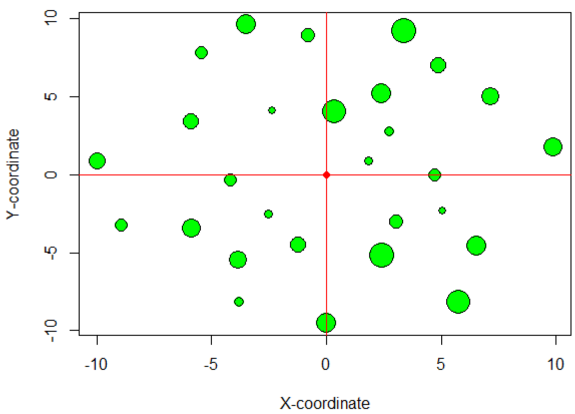
Plot 34



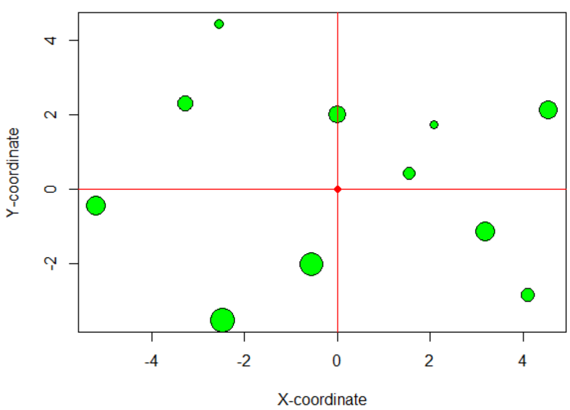
Plot 35



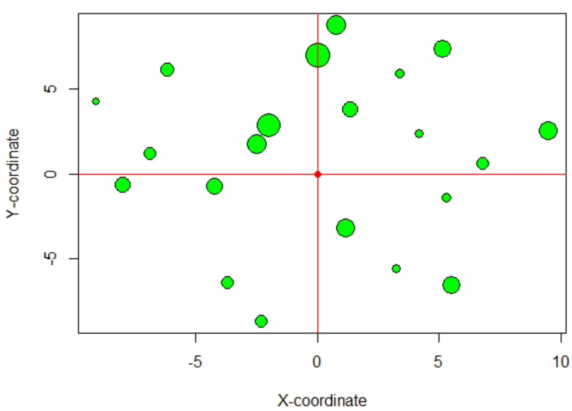
Plot 36



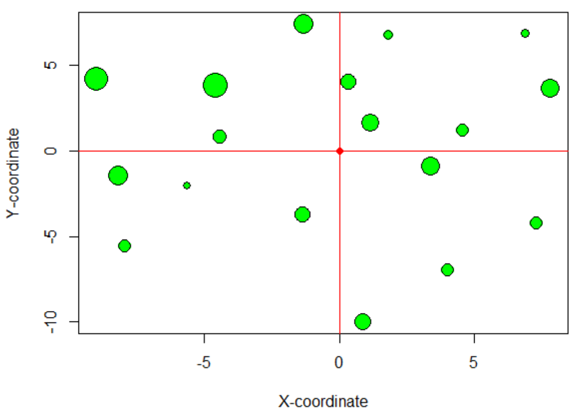
Plot 37



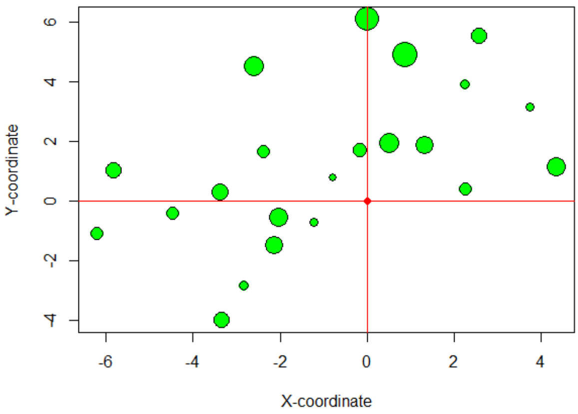
Plot 38



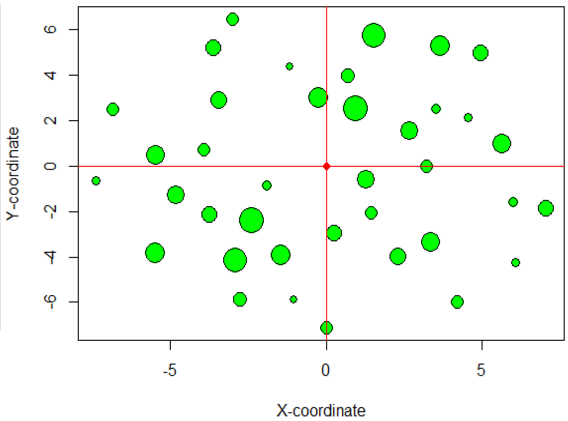
Plot 39



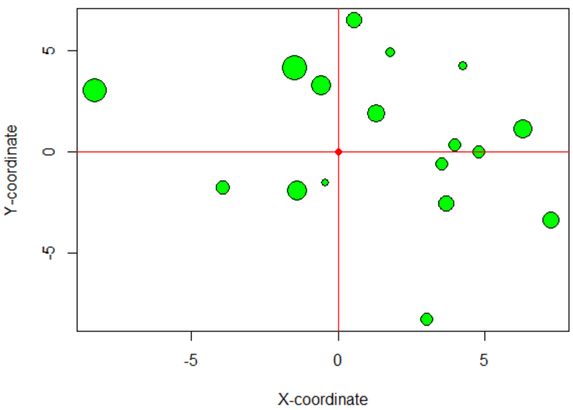
Plot 40



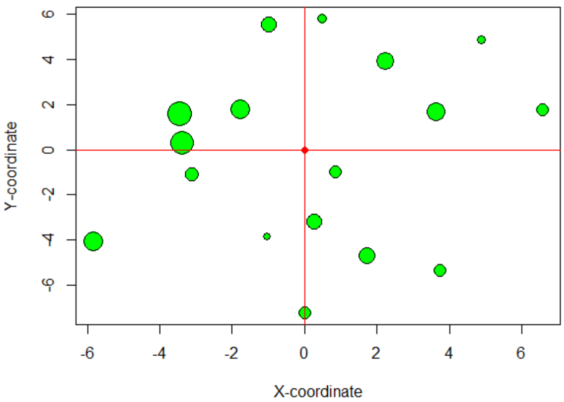
Plot 41



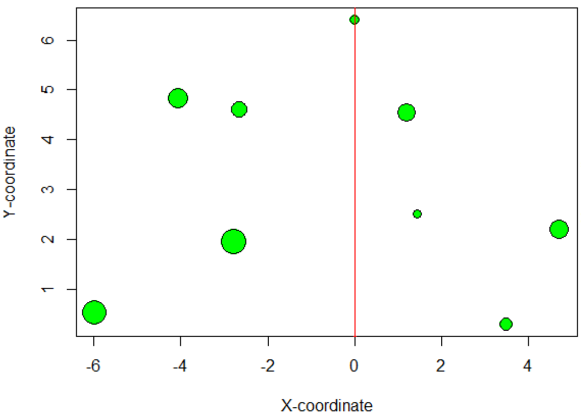
Plot 42



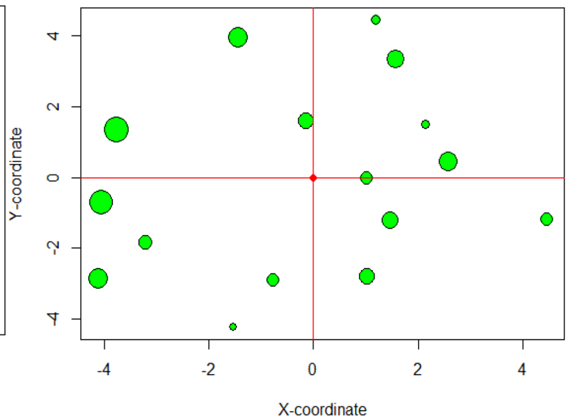
Plot43



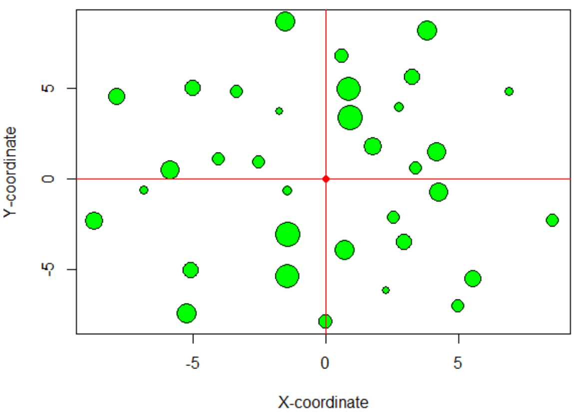
Plot 44



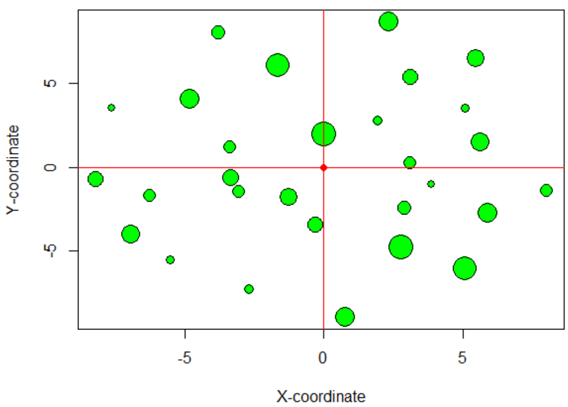
Plot 45



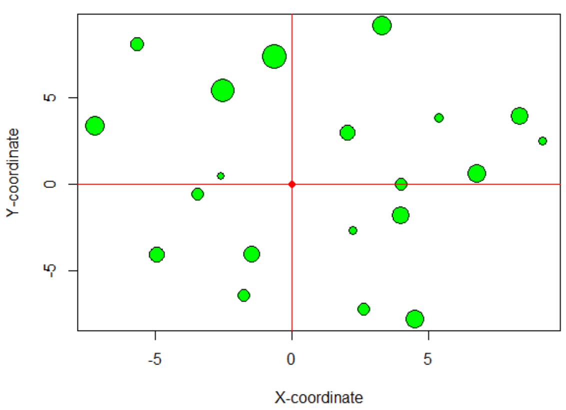
Plot 46



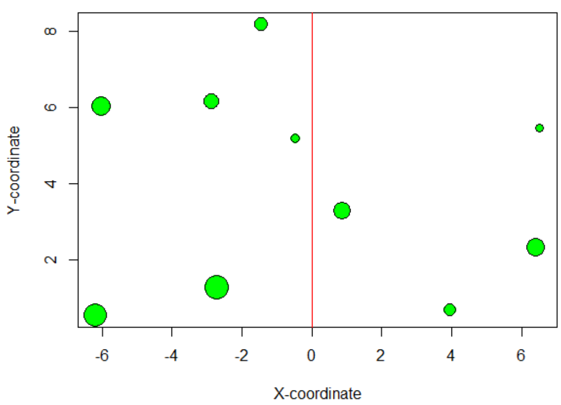
Plot 47



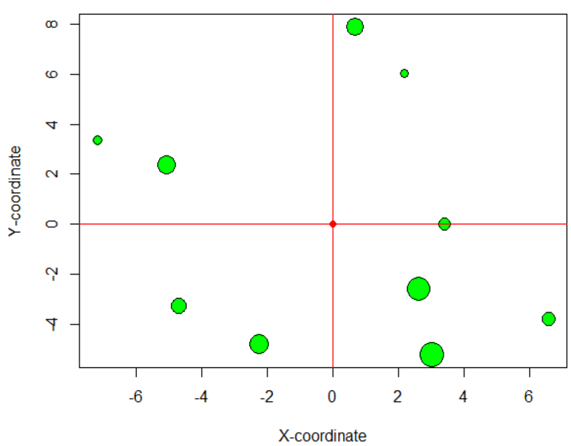
Plot 48



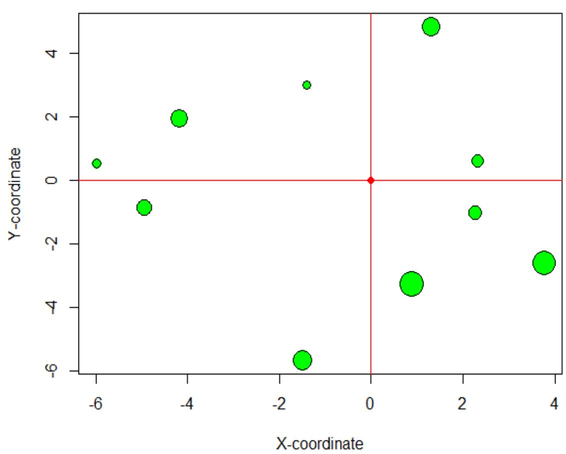
Plot 49



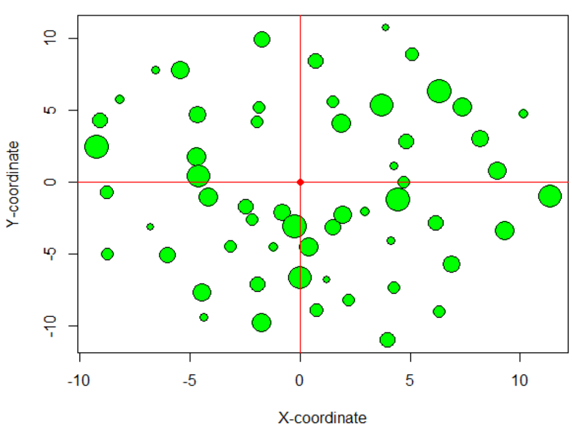
Plot 50



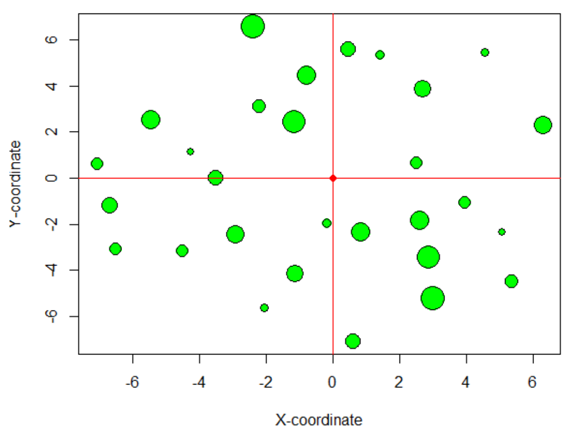
Plot 51

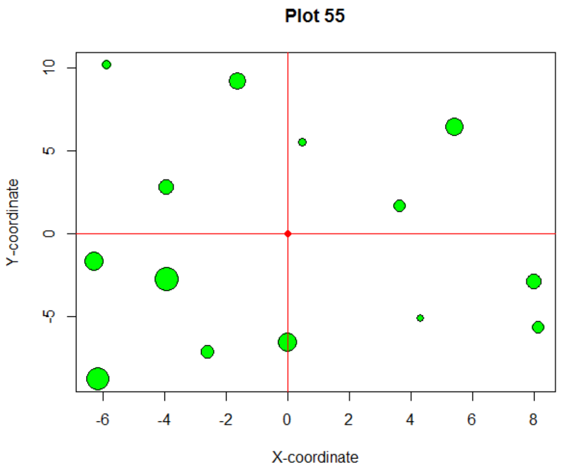


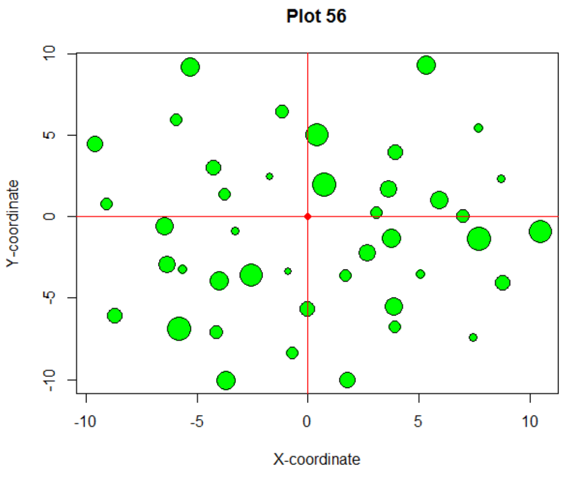
Plot 52

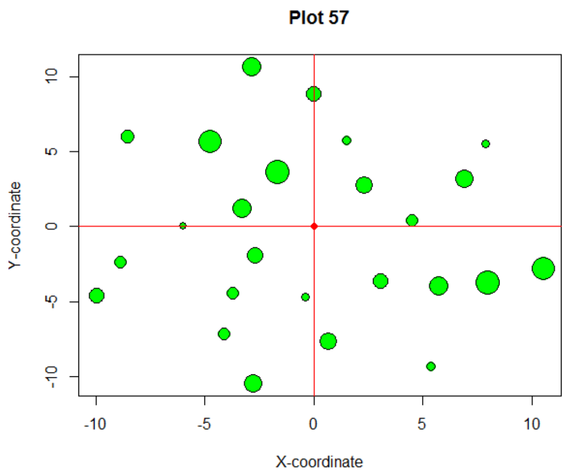


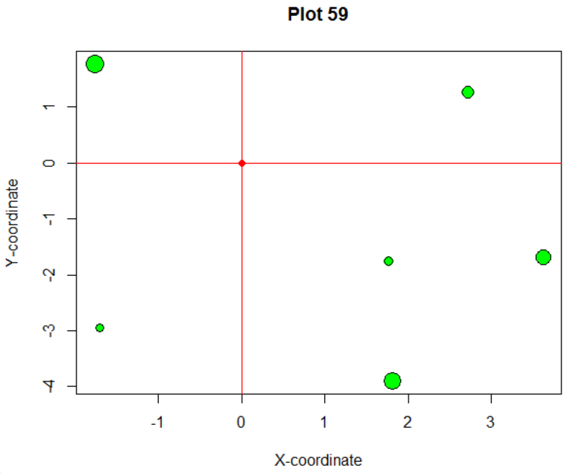
Plot 53

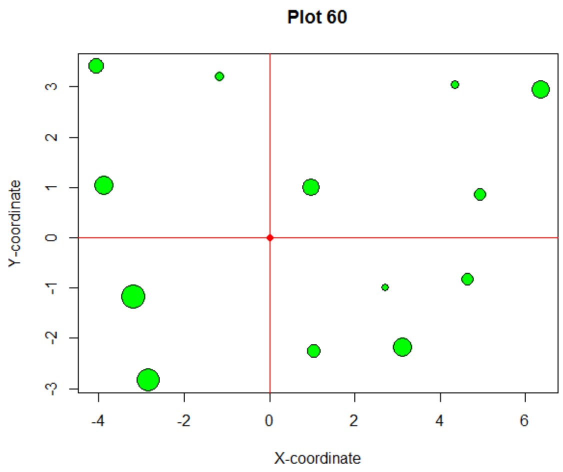


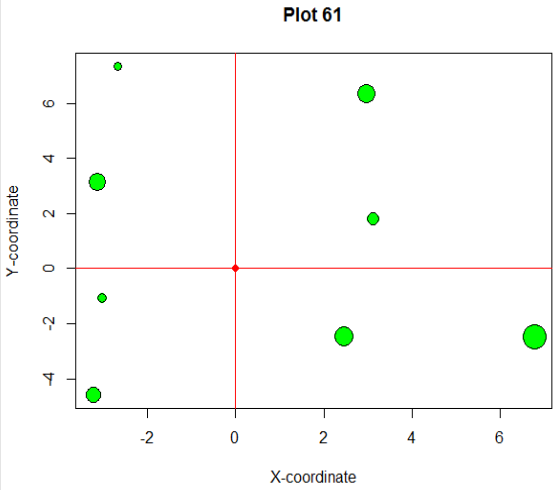

Plot 55
Y-coordinate
X-coordinate

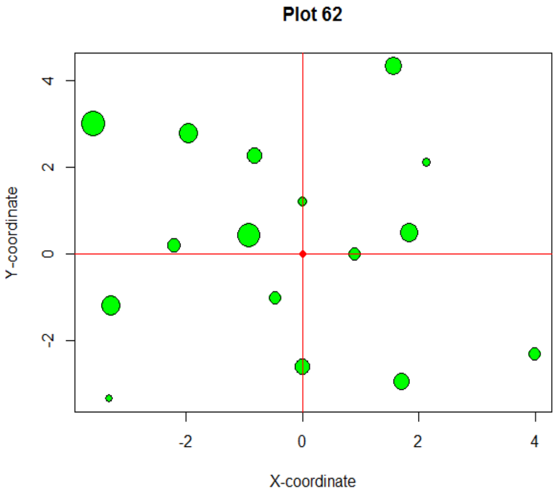

Plot 56
Y-coordinate
X-coordinate

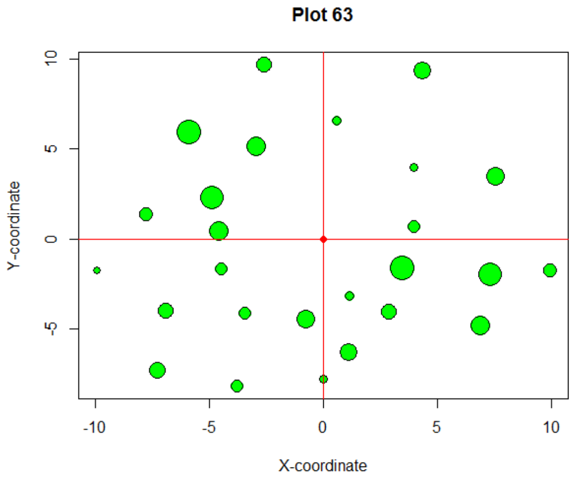

Plot 57
Y-coordinate
X-coordinate

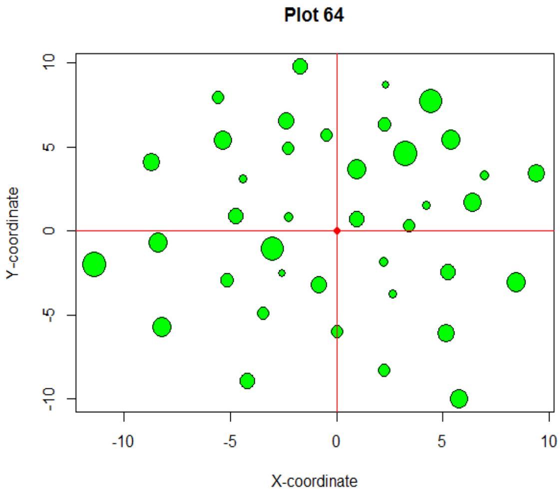

Plot 59
Y-coordinate
X-coordinate


Plot 60
Y-coordinate
X-coordinate

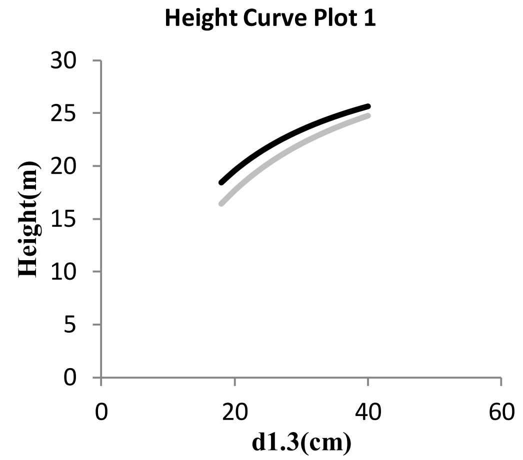

Plot 61
Y-coordinate
X-coordinate

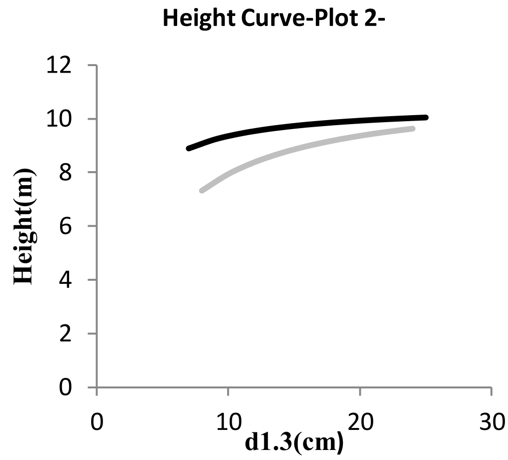

Plot 62
Y-coordinate
X-coordinate
-2
0
2
4

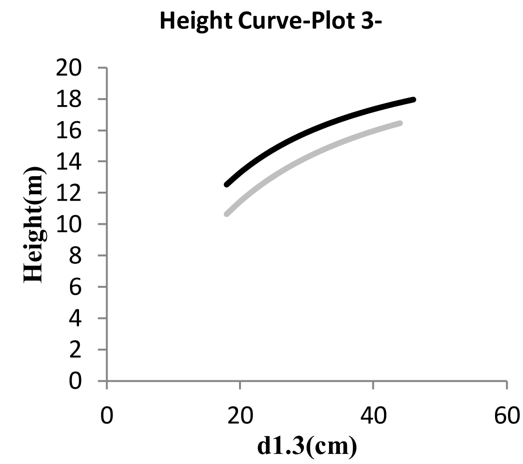

Plot 63
Y-coordinate
X-coordinate
-10
-5
0
5
10

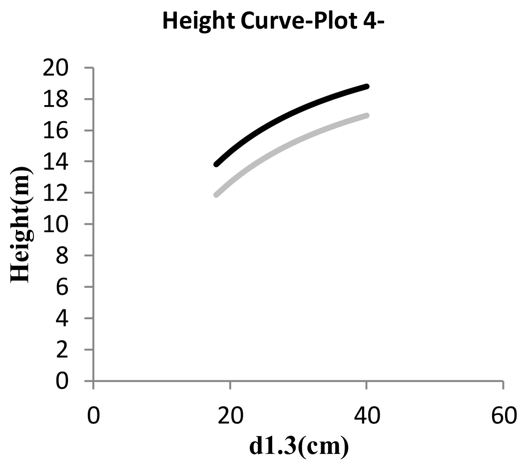

Plot 64
Y-coordinate
X-coordinate
-10
-5
0
5
10

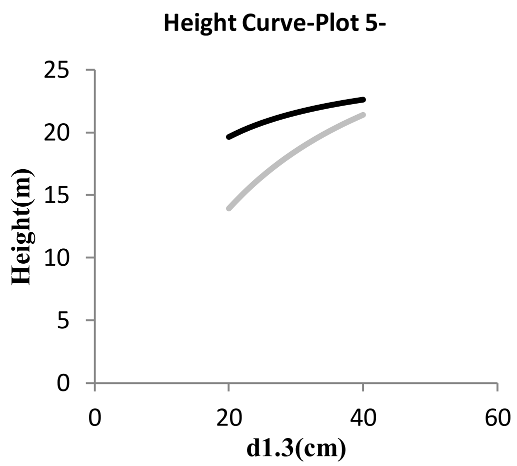
Appendix 4: The fitted stand-height curve of plots used in modeling by applying Michailow (1943) for the first and last inventory

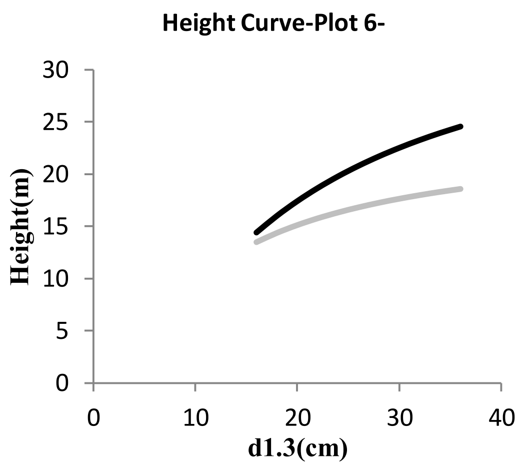


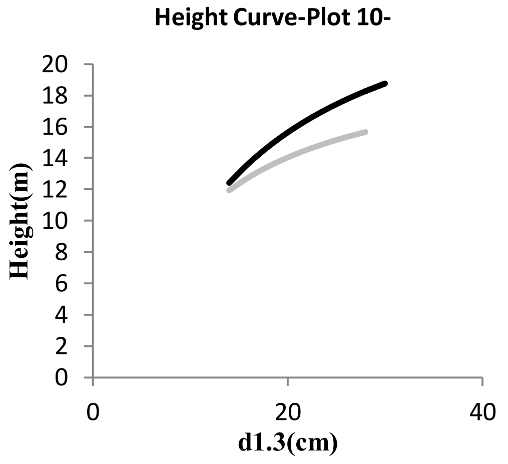


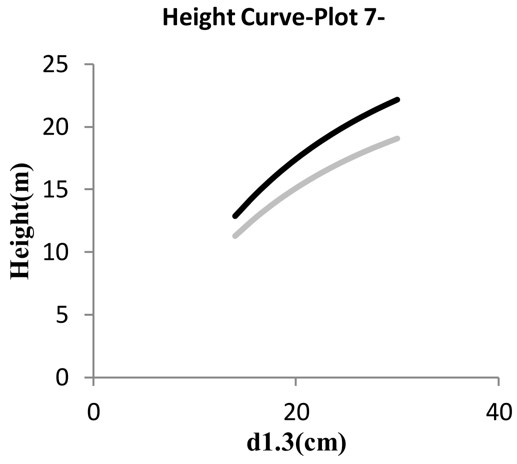


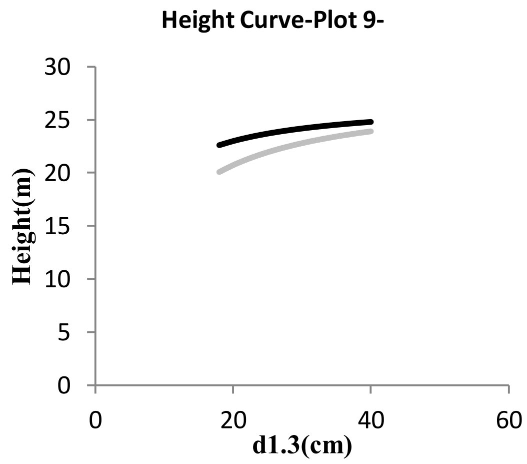


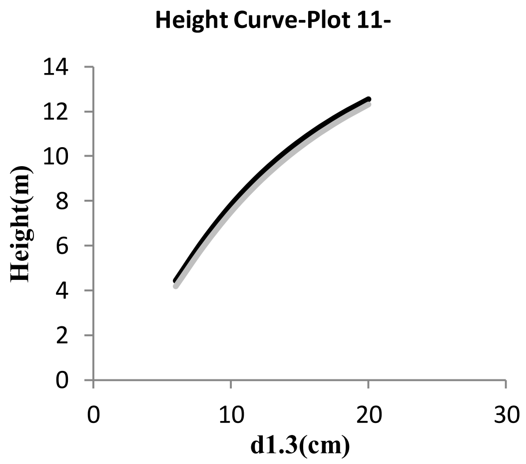


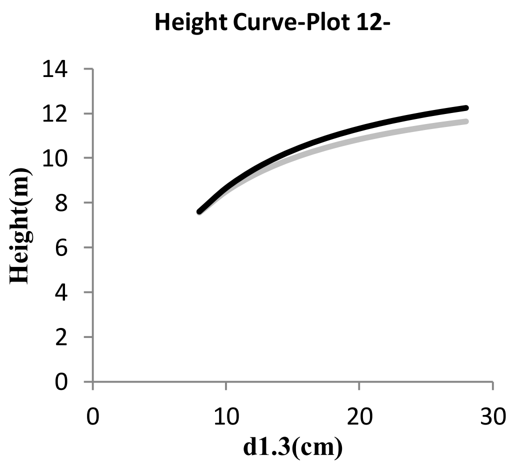


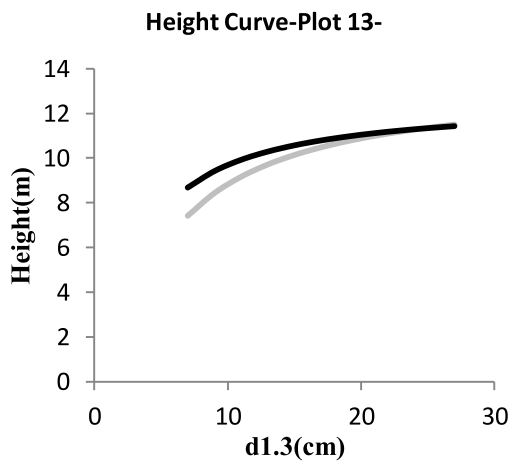

Height Curve-Plot 10-
Height(m)
d1.3(cm)
0
2
4
6
8
10
12
14
16
18
20
0
20
40

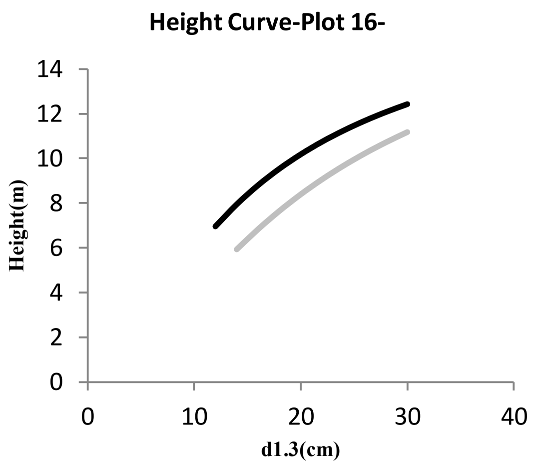

Height Curve-Plot 7-
Height(m)
d1.3(cm)
0
5
10
15
20
25
0
20
40

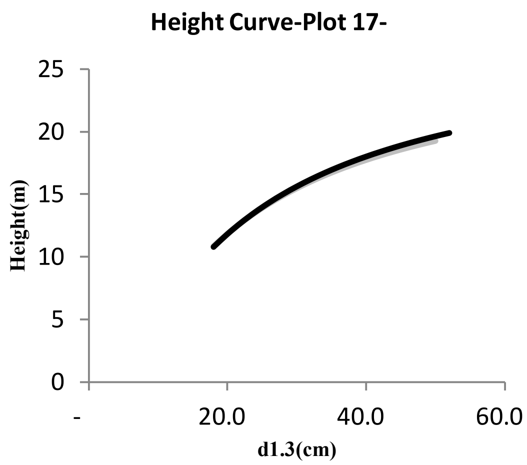

Height Curve-Plot 9-
Height(m)
d1.3(cm)
0
5
10
15
20
25
30
0
20
40
60

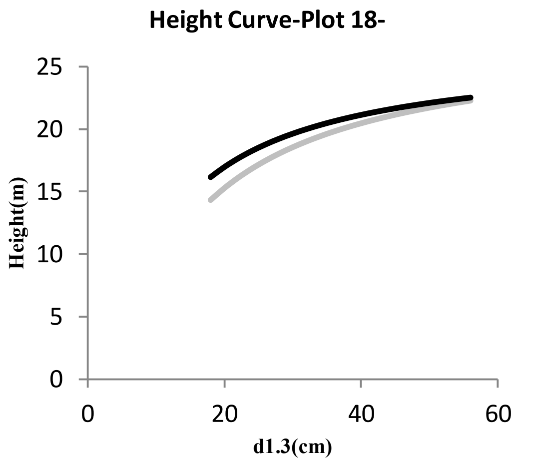

Height Curve-Plot 11-
Height(m)
d1.3(cm)
0
2
4
6
8
10
12
14
0
10
20
30

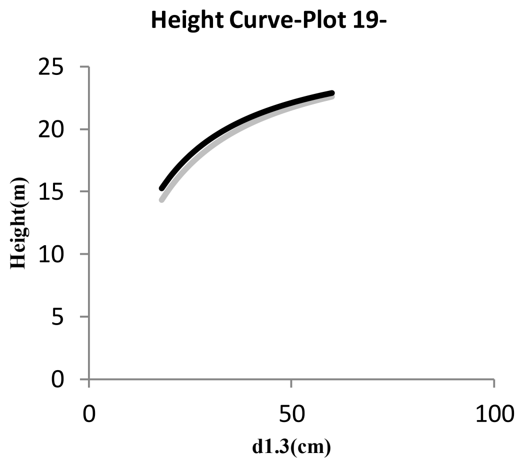

Height Curve-Plot 12-
Height(m)
d1.3(cm)
0
2
4
6
8
10
12
14
0
10
20
30

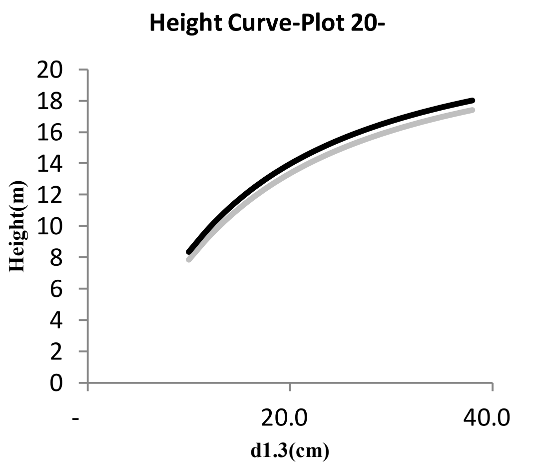

Height Curve-Plot 13-
Height(m)
d1.3(cm)
0
2
4
6
8
10
12
14
0
10
20
30

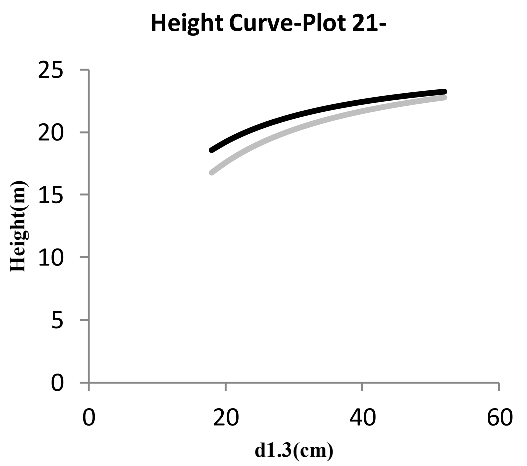

Height Curve-Plot 16-
Height(m)
d1.3(cm)
0
2
4
6
8
10
12
14
0
10
20
30
40

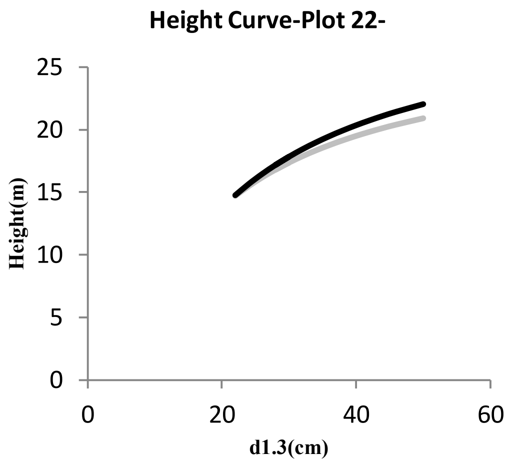

Height Curve-Plot 17-
Height(m)
d1.3(cm)
0
5
10
15
20
25
-
20.0
40.0
60.0

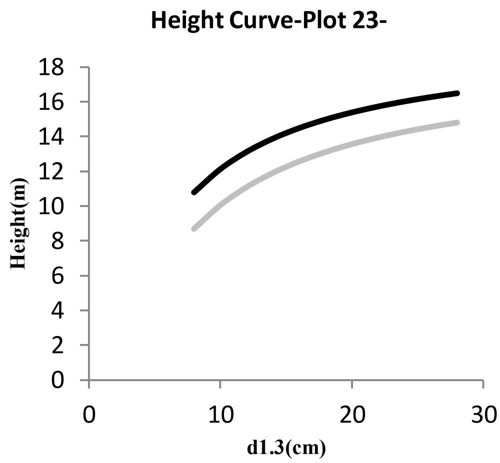

Height Curve-Plot 18-
Height(m)
d1.3(cm)
0
5
10
15
20
25
0
20
40
60

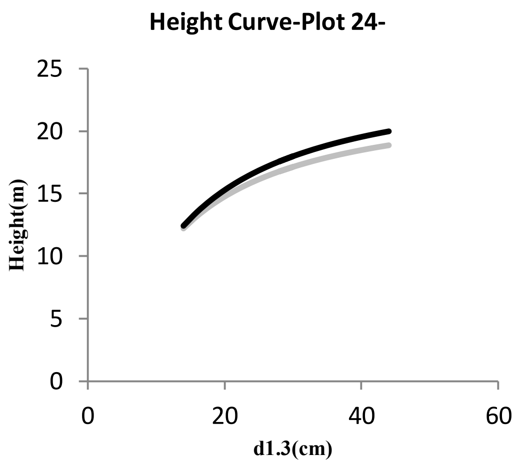

Height Curve-Plot 19-
Height(m)
d1.3(cm)
0
5
10
15
20
25
0
50
100

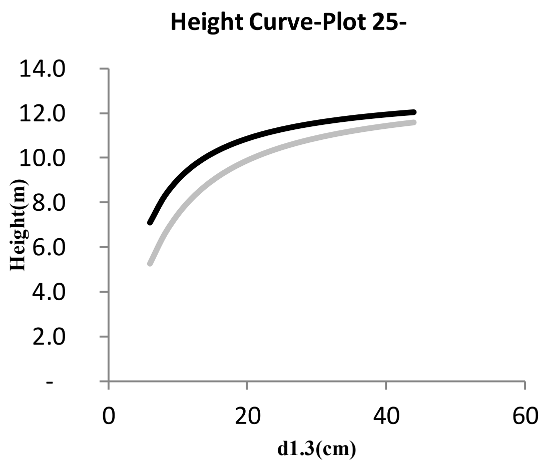

Height Curve-Plot 20-
Height(m)
d1.3(cm)
0
2
4
6
8
10
12
14
16
18
20
-
20.0
40.0

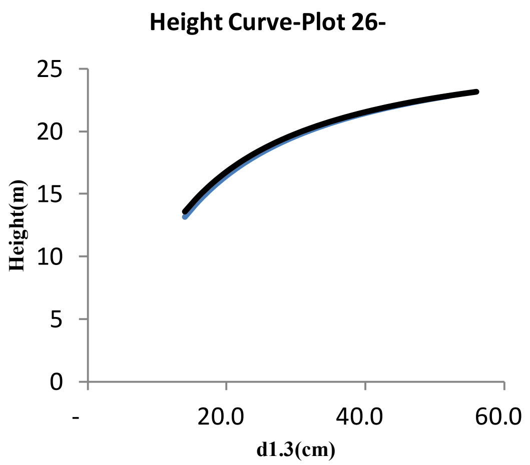

Height Curve-Plot 21-
Height(m)
d1.3(cm)
0
5
10
15
20
25
0
20
40
60

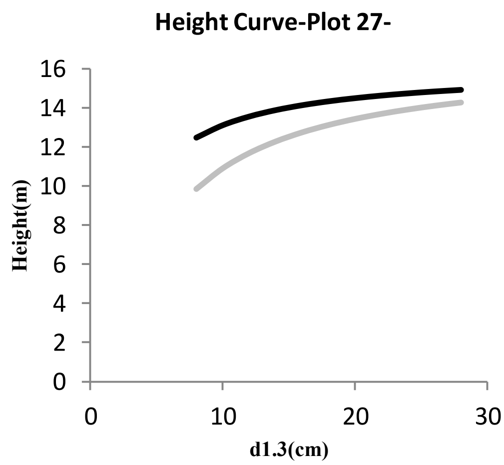

Height Curve-Plot 22-
Height(m)
0
5
10
15
20
25
0
20
40
60
d1.3(cm)

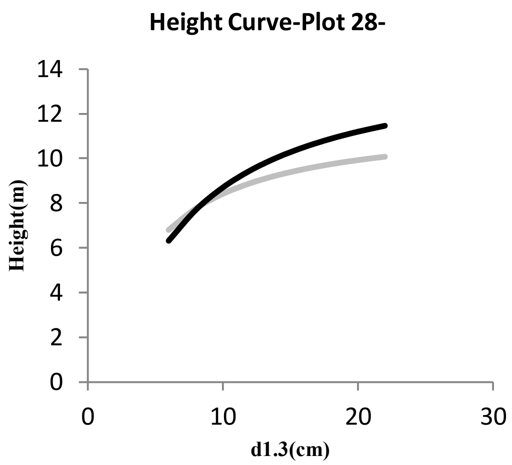

Height Curve-Plot 23-
Height(m)
0
2
4
6
8
10
12
14
16
18
0
10
20
30
d1.3(cm)

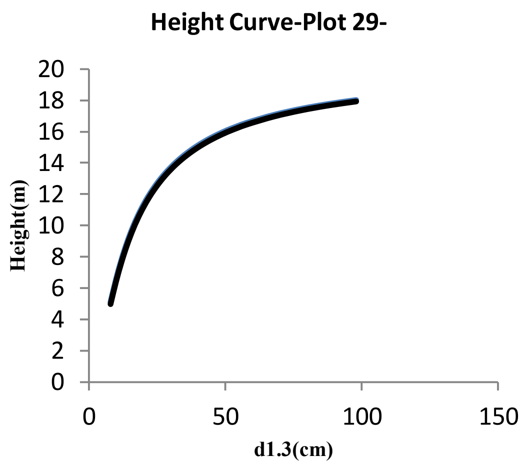

Height Curve-Plot 24-
Height(m)
0
5
10
15
20
25
0
20
40
60
d1.3(cm)

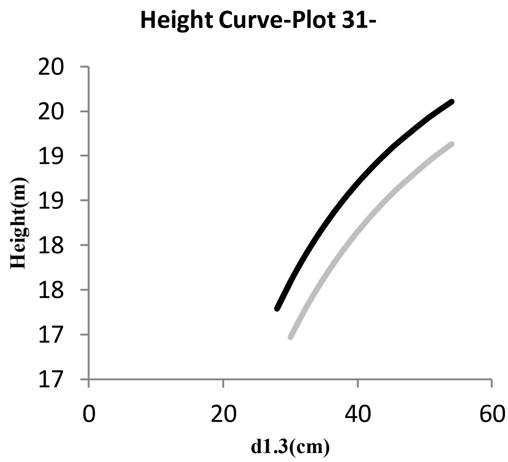

Height Curve-Plot 25-
Height(m)
-
2.0
4.0
6.0
8.0
10.0
12.0
14.0
0
20
40
60
d1.3(cm)

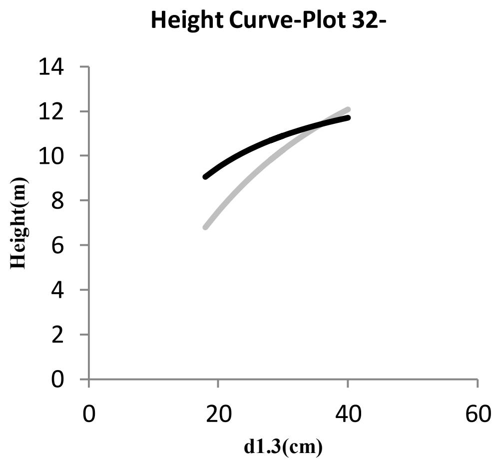

Height Curve-Plot 26-
Height(m)
0
5
10
15
20
25
-
20.0
40.0
60.0
d1.3(cm)

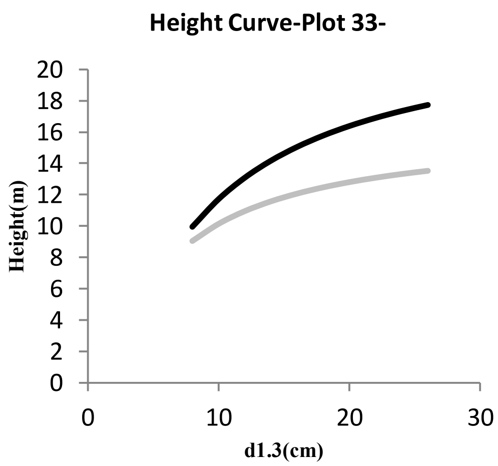

Height Curve-Plot 27-
Height(m)
0
2
4
6
8
10
12
14
16
0
10
20
30
d1.3(cm)

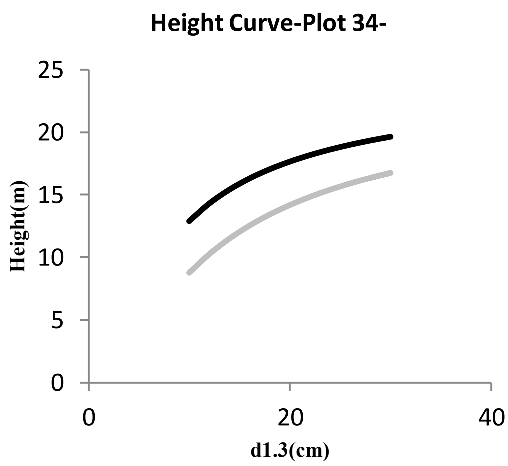

Height Curve-Plot 28-
14
12
10
8
6
4
2
0
Height(m)
0
10
20
30
d1.3(cm)

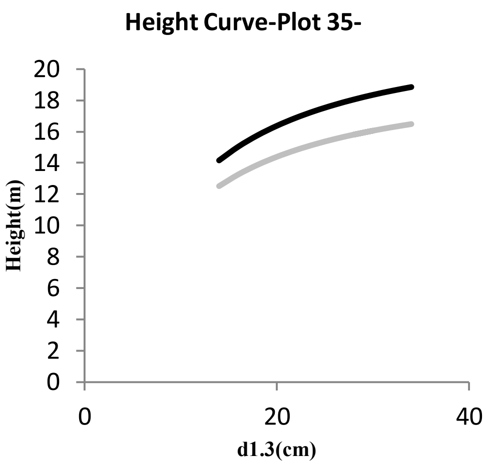

Height Curve-Plot 29-
20
18
16
14
12
10
8
6
4
2
0
Height(m)
0
50
100
150
d1.3(cm)

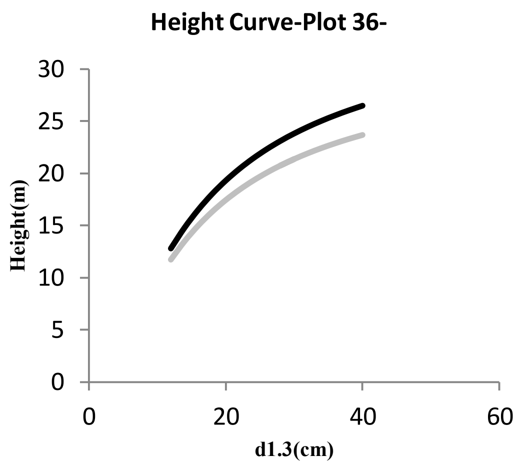

Height Curve-Plot 31-
20
20
19
19
18
18
17
17
Height(m)
0
20
40
60
d1.3(cm)

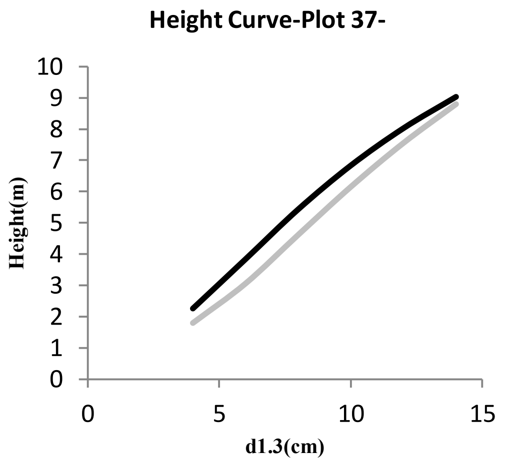

Height Curve-Plot 32-
14
12
10
8
6
4
2
0
Height(m)
0
20
40
60
d1.3(cm)

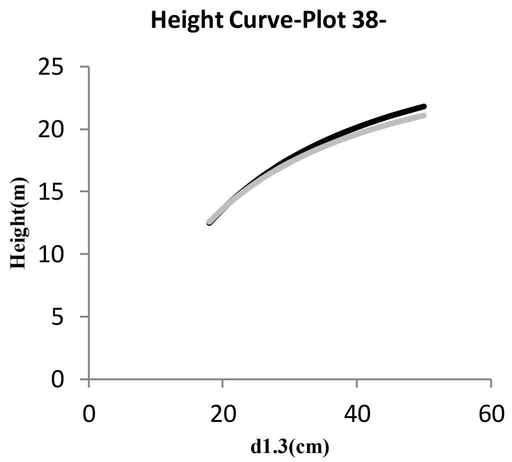

Height Curve-Plot 33-
20
18
16
14
12
10
8
6
4
2
0
Height(m)
0
10
20
30
d1.3(cm)

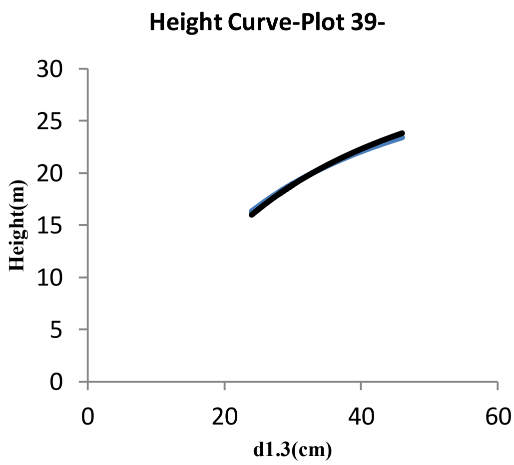

Height Curve-Plot 34-
25
20
15
10
5
0
Height(m)
0
20
40
d1.3(cm)

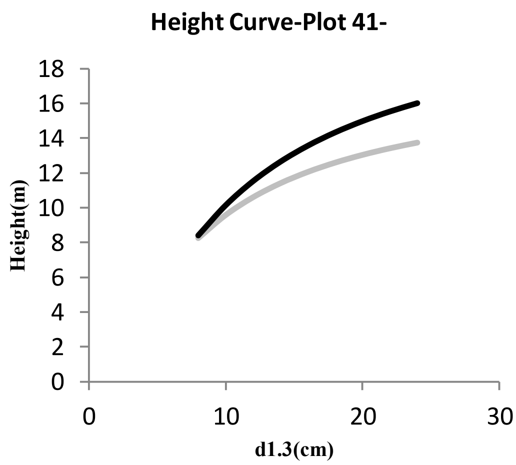

Height Curve-Plot 35-
Height(m)
d1.3(cm)

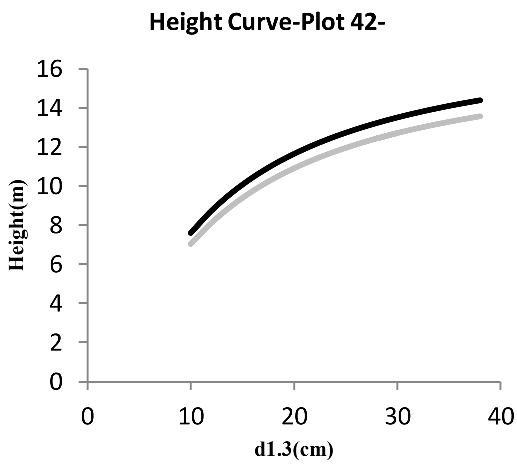

Height Curve-Plot 36-
Height(m)
d1.3(cm)

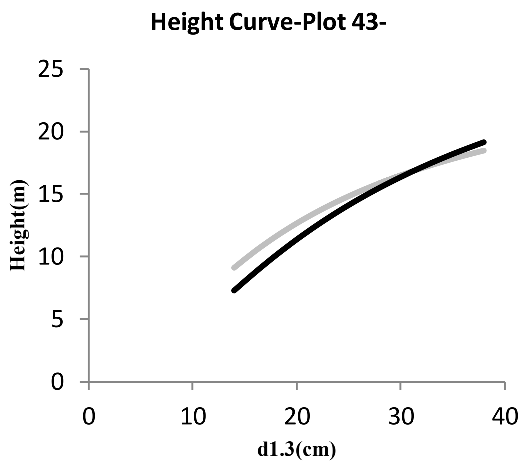

Height Curve-Plot 37-
Height(m)
d1.3(cm)

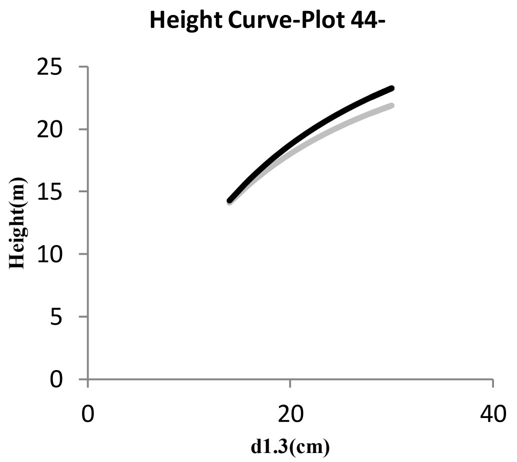

Height Curve-Plot 38-
Height(m)
d1.3(cm)

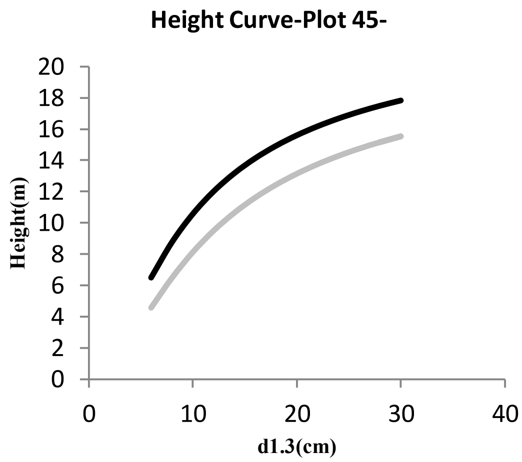

Height Curve-Plot 39-
Height(m)
d1.3(cm)

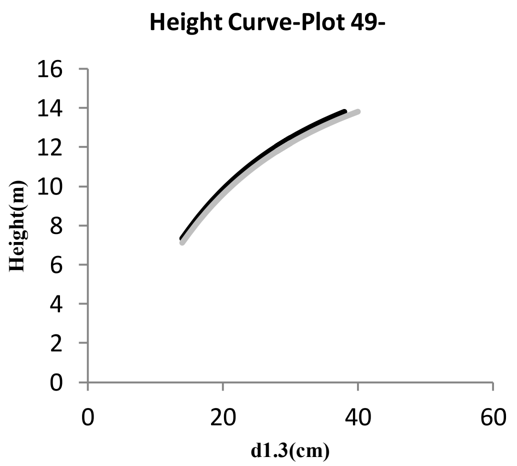

Height Curve-Plot 41-
Height(m)
d1.3(cm)

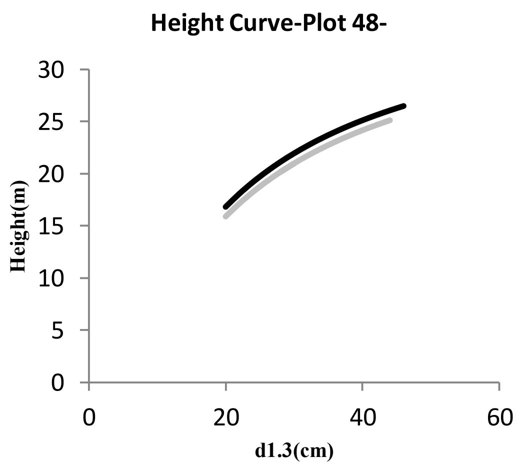

Height Curve-Plot 42-
Height(m)
d1.3(cm)
0
2
4
6
8
10
12
14
16
0
10
20
30
40

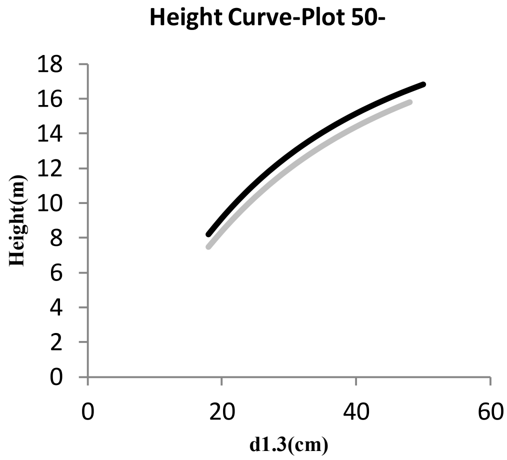

Height Curve-Plot 43-
Height(m)
d1.3(cm)
0
5
10
15
20
25
0
10
20
30
40

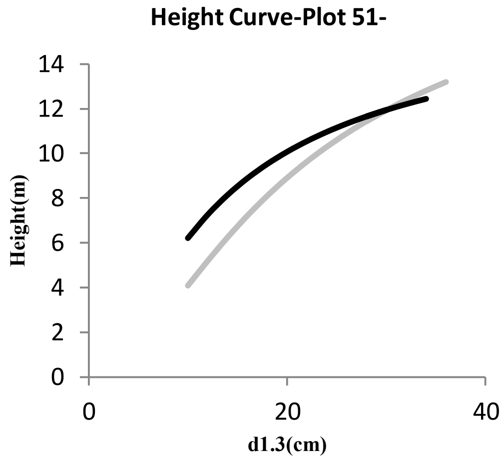

Height Curve-Plot 44-
Height(m)
d1.3(cm)
0
5
10
15
20
25
0
20
40


Height Curve-Plot 45-
Height(m)
d1.3(cm)
0
2
4
6
8
10
12
14
16
18
20
0
10
20
30
40

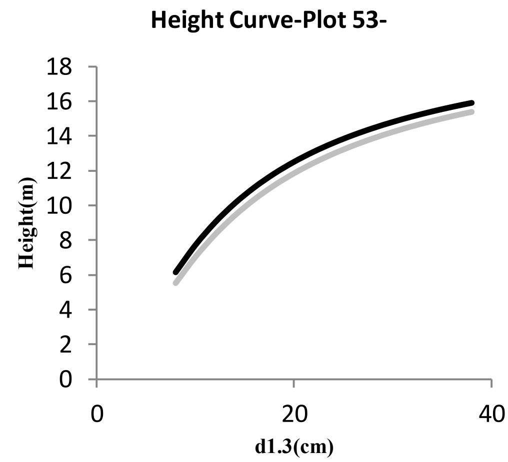

Height Curve-Plot 49-
Height(m)
d1.3(cm)
0
2
4
6
8
10
12
14
16
0
20
40
60

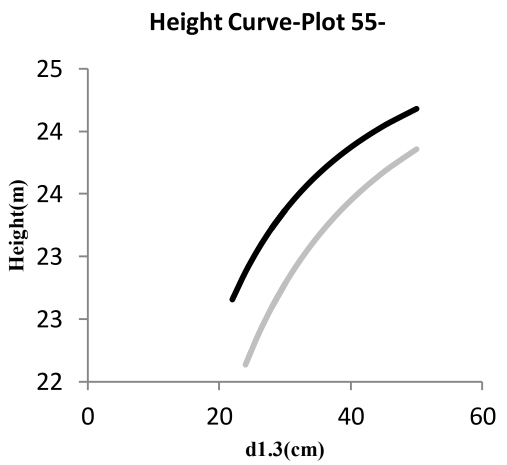

Height Curve-Plot 48-
Height(m)
d1.3(cm)
0
5
10
15
20
25
30
0
20
40
60

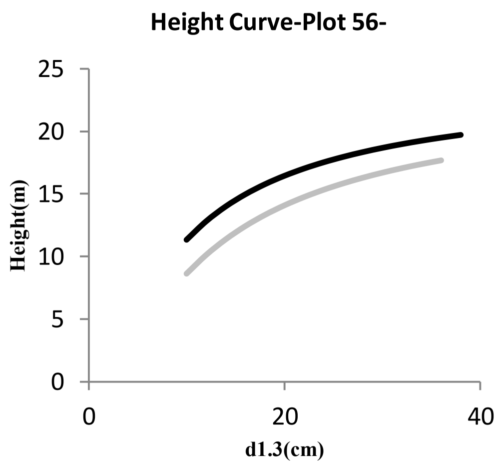

Height Curve-Plot 50-
18
16
14
12
10
8
6
4
2
0
Height(m)
0
20
40
60
d1.3(cm)

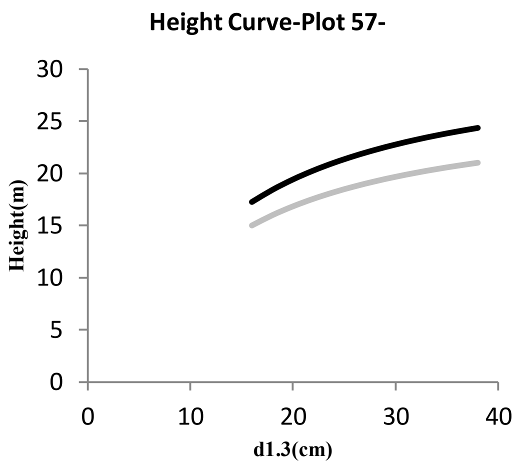

Height Curve-Plot 51-
14
12
10
8
6
4
2
0
Height(m)
0
20
40
d1.3(cm)

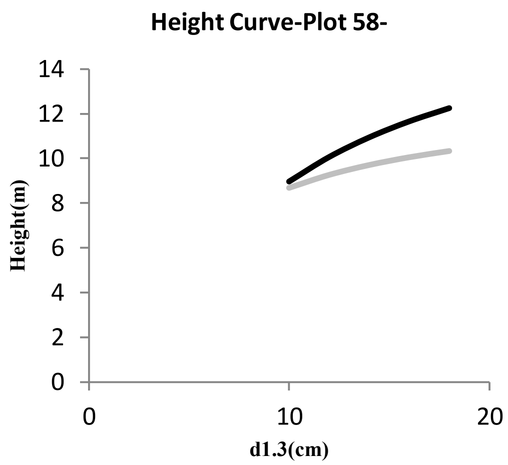

Height Curve-Plot 52-
30
25
20
15
10
5
0
Height(m)
0
20
40
d1.3(cm)

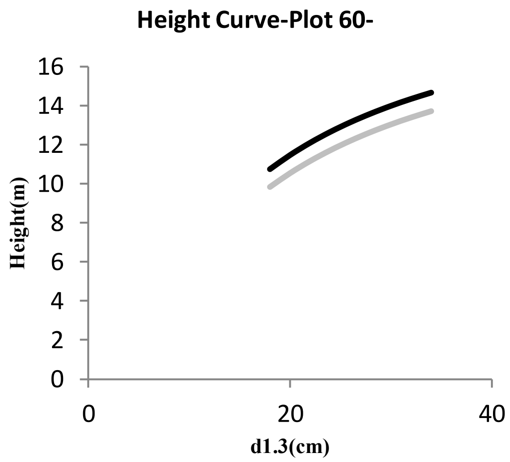

Height Curve-Plot 53-
18
16
14
12
10
8
6
4
2
0
Height(m)
0
20
40
d1.3(cm)


Height Curve-Plot 55-
25
24
24
23
23
22
Height(m)
0
20
40
60
d1.3(cm)

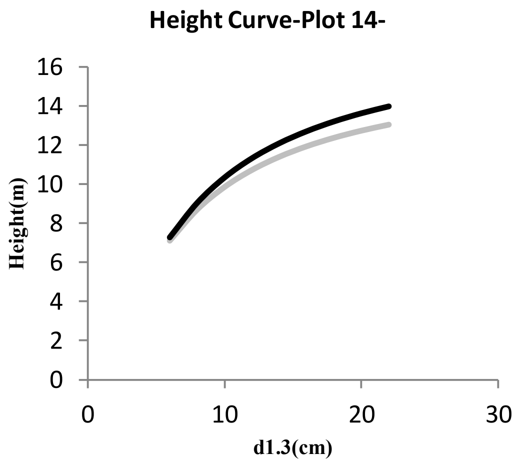

Height Curve-Plot 56-
25
20
15
10
5
0
Height(m)
0
20
40
d1.3(cm)

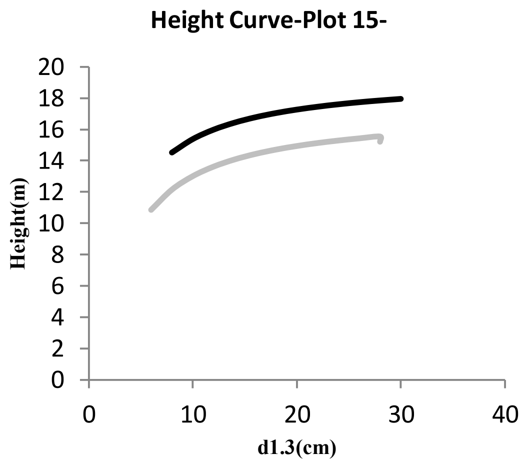

Height Curve-Plot 57-
Height(m)
30
25
20
15
10
5
0
0
10
20
30
40
d1.3(cm)

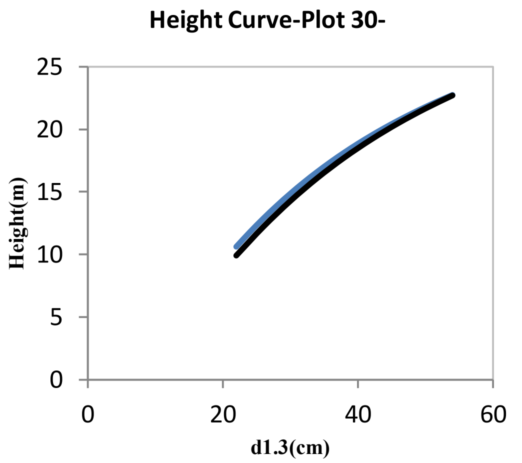

Height Curve-Plot 58-
Height(m)
14
12
10
8
6
4
2
0
0
10
20
d1.3(cm)

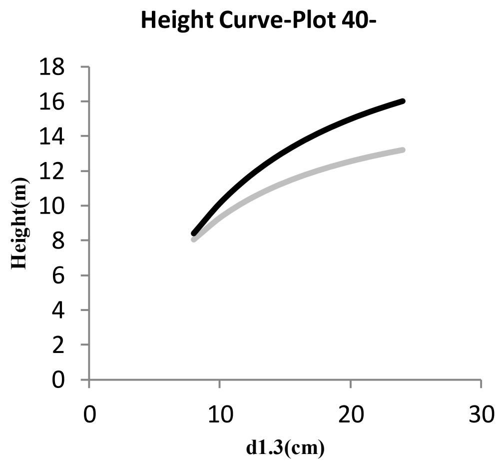

Height Curve-Plot 60-
Height(m)
16
14
12
10
8
6
4
2
0
0
20
40
d1.3(cm)

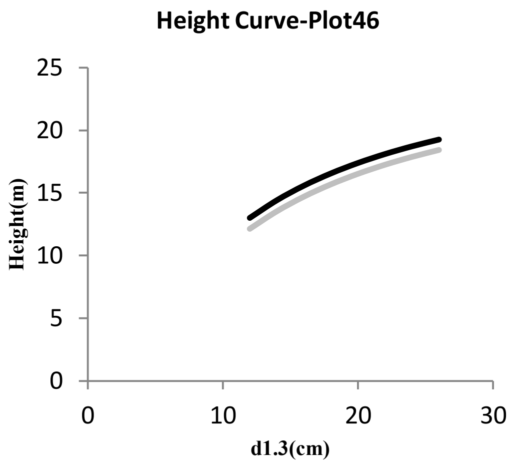
Appendix 5: The fitted stand-height curve of plots used in validation by applying Michailow (1943) for the first and last inventory

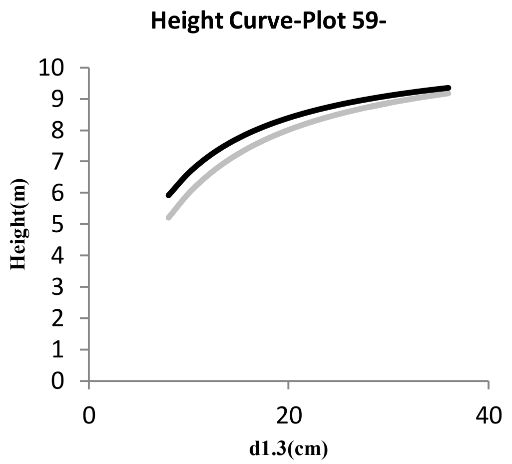


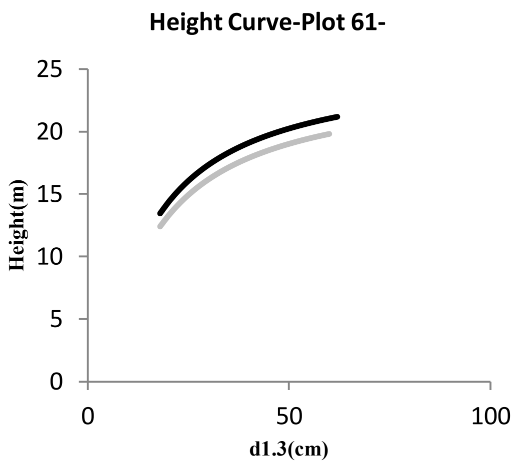


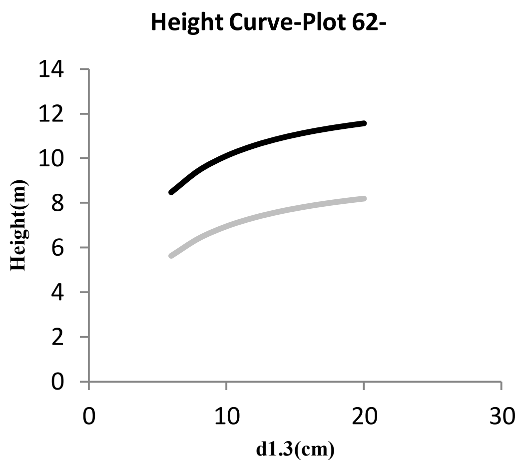


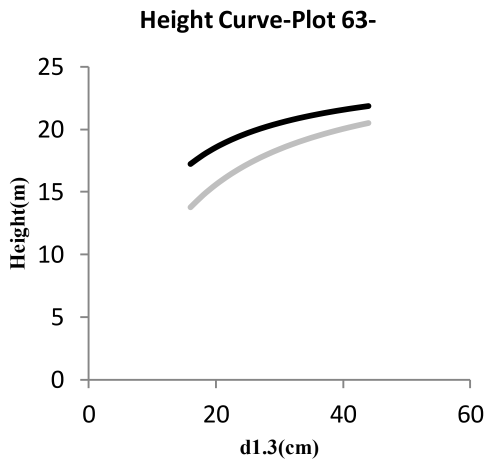


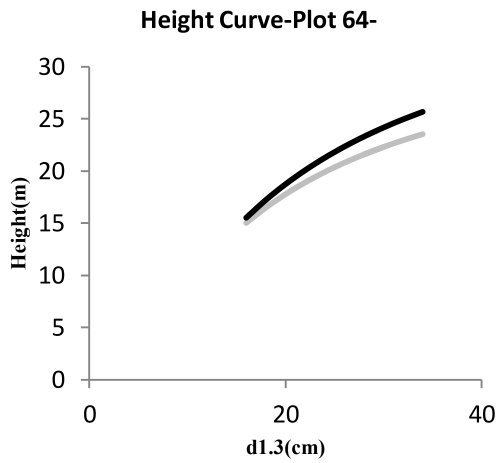





Height Curve-Plot 61-
Height(m)
d1.3(cm)
25
20
15
10
5
0
0
50
100


Height Curve-Plot 62-
Height(m)
d1.3(cm)
14
12
10
8
6
4
2
0
0
10
20
30


Height Curve-Plot 63-
Height(m)
d1.3(cm)
25
20
15
10
5
0
0
20
40
60


Height Curve-Plot 64-
Height(m)
d1.3(cm)
30
25
20
15
10
5
0
0
20
40

Appendix 6: The coefficients of determination of the Michailow (1943) model with the parameters and significance of models for both inventories for all modeling plots

Plot	2016				2008			
	a_0	a_1	R^2	Sign	a_0	a_1	R^2	Sign
1	3.594	-15.183	0.77	0.002195034	3.51	-14.38	0.93	0.002434821
2	2.223472	-1.37584	0.422	0.001792245	2.28	-3.9	0.95	0.001240886
3	3.066326	-11.6674	0.744128	1.008×10^{-5}	3.05	-14.73	0.78	7.06×10^{-6}
4	3.135888	-10.9607	0.819991	2.485×10^{-5}	3.07	-12.83	0.8	1.254×10^{-5}
5	3.209519	-6.02305	0.448	0.000626497	3.47	-18.62	0.68	0.000298494
6	3.380633	-12.3304	0.939342	0.000463386	3.13	-10.07	0.95	0.00026016
7	3.605524	-16.5324	0.8	0.00075556	3.38	-15.15	0.78	0.000120139
9	3.236784	-3.2003	0.314802	0.001321315	3.27	-6.08	0.46	0.001661788
10	3.290147	-12.1742	0.935415	0.002181796	2.96	-8.42	0.97	0.007096973
11	2.968991	-11.3762	0.8692	0.000135389	2.97	-10.96	0.89	0.000348073
12	2.613536	-6.1816	0.781731	0.000880297	2.54	-5.63	0.81	0.001391684
13	2.426197	-2.99328	0.492002	0.004645188	2.5	-4.83	0.68	0.002123884
16	2.860674	-13.5376	0.662	2.257×10^{-5}	2.95	-19.9	0.72	1.81×10^{-5}
17	3.279199	-18.5435	0.786566	2.023×10^{-5}	3.23	-17.36	0.81	0.000114901
18	3.223655	-9.45788	0.711826	9.088×10^{-5}	3.27	-12.64	0.79	0.000128725
19	3.258747	-11.2144	0.817552	0.001468072	3.27	-12.64	0.83	0.001161215
20	3.124899	-11.7291	0.892	0.000193669	3.1	-12.22	0.96	0.000265426
21	3.215087	-6.60067	0.958	0.000517948	3.22	-9.15	0.51	0.000375148
22	3.368203	-16.9139	0.855709	1.63×10^{-5}	3.19	-11.05	0.61	6.71×10^{-5}
23	2.908931	-5.27457	0.942977	0.025515121	2.798	-6.357	0.631	0.013459419
24	3.27858	-12.7353	0.907	0.000512916	3.138	-10.485	0.643	0.000985162
25	2.471723	-4.28799	0.929393	0.00629027	2.512	-6.745	0.849	0.0040257
26	3.301472	-11.5381	0.789697	0.003422127	3.254	-10.92	0.742	0.009860606
27	2.690421	-2.21661	0.98699	0.041626266	2.745	-4.744	0.948	0.044222469
28	2.58337	-5.82894	0.934979	0.001193892	2.328	-3.806	0.738	0.003107493
29	2.94525	-13.162	0.811319	0.002480085	2.948	-12.9	0.816	0.003369088
31	3.241	-13.674	0.320	3.53×10^{-6}	3.233073	-14.0106	0.172	2.242×10^{-5}
32	2.582654	-9.61646	0.875064	1.07×10^{-5}	2.718	-14.968	0.484	9.92×10^{-6}
33	3.084282	-7.41838	0.786012	0.013750582	2.72	-5.988	0.748	0.003584451
34	3.137813	-6.87957	0.625	0.021595327	3.054	-10.348	0.815	0.000869423
35	3.083	-7.405	0.962	0.002001624	2.949	-6.882	0.544	0.003497442
36	3.562361	-13.4527	0.617	0.004461115	3.357	-10.18	0.489	0.013951018
37	3.120	-15.226	0.748	1.37×10^{-6}	3.049	-14.971	0.707	1.41×10^{-5}
38	3.301677	-15.8254	0.88874	4.85×10^{-5}	3.34	-17.114	0.631	7.16×10^{-5}
39	3.809	-28.084	0.778	1.95×10^{-5}	3.446	-17.82	0.549	4.47×10^{-5}
41	3.05306	-8.74	0.86	0.001130718	2.793	-7.054	0.736	0.003773053
42	2.832913	-9.92196	0.806	0.000172624	2.912	-12.3	0.686	0.000233486
43	3.51854	-24.2325	0.865188	8.31866E-06	3.27	-16.961	0.853	6.40189E-05
44	3.247	-16.481	0.906	6.92×10^{-5}	2.975	-10.218	0.7	0.001006172
45	3.094624	-8.69004	0.882	0.005322456	2.947	-10.067	0.894	0.001152158
47	3.778886	-24.4873	0.98388	7.47×10^{-6}	3.858	-25.536	0.829	1.29153E-05
48	3.599022	-17.1539	0.77	0.000101678	3.579	-17.328	0.693	0.000141044
49	2.939071	-16.4971	0.717	1.14596E-05	2.985	-16.729	0.652	2.06349E-05
50	3.199042	-22.8266	0.658	5.1×10^{-6}	3.187	-24.611	0.75	5.66492E-06
51	2.752134	-11.6114	0.754824	0.00043395	2.895	-17.572	0.839	0.000471292
52	3.665671	-16.8607	0.86	0.000484904	3.567	-14.451	0.865	0.001591581
53	2.975643	-11.1758	0.82	0.000138501	2.966	-12.202	0.815	8.93×10^{-5}
55	3.647	-23.204	0.569	1.53×10^{-5}	3.208	-3.868	0.352	6.17×10^{-5}
56	3.129774	-8.24757	0.942	0.004598589	3.105	-11.152	0.749	0.00093184
57	3.405536	-10.1805	0.971	0.000692943	3.246	-10.06	0.49	0.000323887
58	2.839152	-8.02599	0.805	4.04×10^{-5}	2.433	-4.487	0.77	0.007335618
60	2.983079	-13.2794	0.925	6.55×10^{-7}	2.94	-14.338	0.466	7.33×10^{-7}

Appendix 7 : The coefficients of determination of the Michailow (1943) model with the parameters and significance of models for both inventories for all validation plots

	2016				2008			
Plot	a_0	a_1	R^2	Sign	a_0	a_1	R^2	Sign
14	2.821717	-6.20625	0.862597	0.015870897	2.73	-5.81	0.83	0.040419313
15	3.019	-4.664	0.34	0.025685646	2.77	-3.05	0.47	0.003476783
30	3.689829	-33.8336	0.918214	2.6×10^{-5}	3.484	-25.527	0.815	0.000120765
40	3.007141	-7.45018	0.893	0.001351339	2.8	-7.164	0.88	0.002551992
46	3.25487	-9.54807	0.74	0.006179588	3.157	-9.288	0.612	0.013656705
59	2.244415	-5.71344	0.66	0.00016692	2.22	-6.672	0.634	0.000454481
61	3.19086	-12.5034	0.319	5.726×10^{-5}	3.137	-13.154	0.359	5.8×10^{-5}
62	2.482045	-3.0712	0.728957	0.002009088	2.13	-3.991	0.48	0.000184117
63	3.16892	-6.41765	0.96062	0.000301126	3.202	-10.862	0.555	8.83×10^{-5}
64	3.67255	-16.2933	0.74	0.002078619	3.382	-12.041	0.417	0.002079069

Appendix 8: The main variables (Mean stand height, quadratic mean diameter, stand top height, stand top diameter, stand basal area,stand volume, number of trees per hectare) of modeling plots

Plot	Dq		H		BA		V		D_{100}		H_{100}		N	
	2008	2016	2008	2016	2008	2016	2008	2016	2008	2016	2008	2016	2008	2016
1	26.3	28.5	20.7	22.7	62.57	71.19	281.7	360.5	39.1	41.9	24.6	25.9	1089	1032
2	11.7	13.2	8.3	9.6	27.03	32.74	65.2	87.7	20.4	24.7	9.4	10.0	2144	2122
3	28.4	31.0	13.9	16.0	35.58	41.05	106.3	142.8	36.8	39.1	15.4	17.2	535	530
4	28.5	30.3	15.0	17.3	48.12	54.11	158.3	202.6	37.9	39.8	16.7	18.8	727	727
5	27.9	30.3	17.8	21.6	55.56	65.57	217.6	302.8	37.7	40.1	20.9	22.6	881	870
6	26.1	29.4	16.8	20.6	47.76	60.47	178.3	272.2	36.4	39.8	18.6	22.9	858	833
7	21.0	24.1	15.6	19.8	48.33	62.98	179.0	281.0	24.0	26.2	17.0	22.5	1348	1238
9	35.4	38.5	23.5	24.7	51.82	60.67	279.5	352,5	47.9	51.0	24.5	25.2	493	493
10	16.5	21.9	12.9	16.7	17.64	29.79	59,1	116.3	25.1	30.7	15.2	19.3	748	748
11	16.1	19.5	11.2	12.2	20.71	29.05	62.1	85.4	27.4	30.7	14.3	14.5	891	891
12	13.6	14.8	9.7	10.3	40.47	47.04	110.6	132.0	24.1	24.8	11.3	11.9	2500	2500
13	11.7	12.9	9.4	10.3	39.33	43.94	104.7	127.7	21.0	22.5	11.0	11.2	3144	3065
16	14.0	17.1	5.9	9.2	11.03	15.42	20.8	37.8	23.6	26.5	9.5	11.8	622	622
17	33.6	37.0	16.4	17.4	22.97	23.77	80.0	102.6	44.0	45.7	18.4	19.0	224	219
18	34.6	37.6	19.6	20.8	46.11	52.14	201.6	252.0	46.4	48.5	21.3	22.0	454	446
19	36.8	40.0	20.0	21.0	44.42	50.55	205.3	260.8	48.3	50.9	21.5	22.2	383	377
20	22.7	27.0	14.3	16.0	26.58	33.22	81.3	119.9	33.6	35.2	16.9	18.1	1753	1711
21	29.9	31.7	19.7	21.5	55.35	61.83	240.1	290.5	40.4	42.4	21.7	22.6	753	734
22	32.5	33.6	18.6	18.8	55.95	60.35	221.9	254.5	42.3	43.9	20.1	21.0	645	637
23	17.8	20.1	12.8	15.4	38.27	45.22	118.1	164.5	26.6	28.0	14.6	16.5	1356	1337
24	24.0	26.3	16.2	17.6	48.84	56.90	179.9	225.9	37.5	39.3	19.4	20.5	1019	991
25	12.8	14.1	8.6	10.0	42.91	49.72	107.9	135.8	40.0	41.2	11.4	12.0	2499	2399
26	23.5	26.6	17.6	18.9	45.52	53.99	176.3	233.4	37.7	39.7	21.1	21.6	934	892
27	15.6	18.0	12.8	14.3	28.96	37.99	97.5	133.9	24.6	27.2	14.0	14.9	1394	1394
28	10.0	11.8	8.3	9.4	21.47	29.13	58.6	83.7	16.0	17.6	9.5	10.8	2476	2432
29	33.6	36.4	14.3	14.5	31.76	33.03	136.8	159.2	51.9	52.4	16.0	16.1	275	270
31	40.9	42.8	19.3	19.9	42.54	44.74	182.5	223.8	50.7	52.4	19.0	19.5	302	294
32	27.0	29.2	10.0	10.8	31.64	36.76	70.9	87.3	36.0	38.6	11.4	11.6	523	523
33	14.9	17.9	11.5	15.7	24.79	34.35	75.9	134.6	20.3	23.1	12.8	17.1	1304	1238
34	17.9	19.4	13.2	17.5	56.51	63.20	180.0	266.4	27.5	28.9	16.2	19.5	2165	2070
35	21.4	25.2	15.1	17.6	30.68	42.08	107.8	163.1	29.1	33.3	16.0	18.8	806	806
36	24.6	29.4	20.3	23.6	39.2	54.72	178.8	289.2	36.3	41.8	22.9	26.8	764	736
37	10.7	17.7	6.5	10.9	6.07	15.56	13.5	43.4	15.7	23.0	9.7	12.0	634	613
38	31.4	33.4	17.6	18.2	53.15	57.33	210.4	241.6	44.7	46.4	20.5	20.6	622	608
39	30.6	33.1	18.8	20.6	36.35	43.85	155.4	212.2	40.8	44.1	22.3	23.4	474	474
41	14.1	17.5	11.2	14.1	31.82	45.18	94.6	162.6	20.7	23.7	13.2	15.9	1868	1789
42	22.8	26.4	12.0	13.0	23.89	29.98	64.6	87.6	31.4	35.2	12.9	14.1	525	517
43	23.7	27.2	14.2	15.2	36.93	46.66	119.8	161.0	34.5	37.4	17.7	19.0	778	764
44	19.2	23.6	12.8	14.1	20.02	29.64	62.9	95.6	25.1	29.4	20.3	23.0	652	652
45	17.5	19.3	12.0	15.4	47.97	56.36	145.3	210.6	27.8	29.1	15.1	17.7	1789	1736
47	23.9	26.5	17.6	18.7	50.58	62.87	203.8	264.3	30.9	34.6	20.6	22.9	1092	1036
48	32.1	34.6	22.2	23.6	56.26	63.70	263.2	325.3	40.2	42.6	24.2	25.8	672	639
49	27.5	30.5	12.1	12.3	27.72	33.77	75.3	92.7	24.8	27.0	12.1	12.3	440	440
50	30.6	34.2	12.1	13.9	23.47	27.16	61.2	86.2	38.8	41.9	14.1	15.5	301	295
51	22.2	24.5	9.5	11.1	22.27	25.11	48.6	63.5	34.8	36.8	12.3	12.7	509	501
52	25.4	27.6	21.3	22.5	67.37	77.44	323.7	390.1	37.1	38.2	25.8	26.4	1282	1216
53	19.2	20.5	11.6	12.7	48.2	53.96	138.6	166.7	31.9	33.7	14.5	15.4	1499	1473
55	39.1	43.2	23.7	23.7	36.55	44.53	193.0	251.5	45.2	50.0	23.7	24.2	297	283
56	25.1	26.1	15.6	18.0	61.87	64.08	208.3	253.3	31.3	32.0	16.9	19.0	1184	1131
57	28.1	31.5	19.2	23.1	43.46	54.84	179.8	269.3	31.0	35.3	19.9	23.9	684	684
58	9.5	15.9	8.4	11.6	16.33	44.09	122.8	149.4	13.6	19.9	9.6	12.7	951	929
60	24.1	25.5	11.7	13.0	46.64	51.14	281.7	360.5	32.1	33.4	13.42	14.58	1089	1032

Appendix 9: The main variables (Mean stand height, quadratic mean diameter, stand top height, stand top diameter, stand basal area,stand volume, number of trees per hectare) of validation plots

Plot	Dq		H		D_{100}		H_{100}		BA		V		N	
	2008	2016	2008	2016	2008	2016	2008	2016	2008	2016	2008	2016	2008	2016
14	11.1	13.4	10.4	11.9	19.3	20.9	12.6	13.8	30.84	43.72	130.08	101.23	2934	2585
15	15.0	16.9	14.3	16.8	25.0	27.3	15.4	17.8	40.7	50.86	213.97	152.86	2069	1941
30	42.4	47.8	19.2	21	47.6	50.4	21.1	22.5	20.53	23.27	154.28	102.18	137	137
40	14.5	16.8	11.3	14.3	19.2	21.4	12.4	15.6	33.4	45.32	166.53	104.66	1920	1867
46	16.9	21.1	14.9	17.8	22.4	26.3	17.4	19.3	31.95	47.89	199.61	120.54	1342	1236
59	20.8	22.1	8.0	8.6	31.9	32.0	9.0	9.2	28.9	30.85	61.514	52.458	764	750
61	41,3	42,9	18	19.5	47.6	48,6	18,8	20,1	60.36	64.94	331.53	281.54	420	420
62	12	13.5	7.3	10.8	22,1	23.9	8.3	11.8	28.2	35.54	114.38	62.400	2429	2143
63	29.6	31.7	18.3	20.7	33.5	35.4	19.1	21.1	50.54	55.91	249.16	192.90	707	662
64	25.7	29	19.7	23.8	27.4	29.7	21.3	24	47.5	59.86	305.25	203.98	906	839

Appendix 10: The main variables for the removed stands for the brutia pine forests

plot	$Dq_{removed}$	$H_{removed}$	BAremoved	Removed Number of trees per hectare	Vremoved.m^{3}ha^{-1}
1	20.3	17.6	1.87	56.6	7.93
2	5.2	5.9	0.05	22.1	0.14
3	12.5	7.8	0.06	5.1	0.15
5	18.9	13.3	0.31	11.0	1.02
6	16.2	12.6	0.60	24.9	2.15
7	16.9	13.2	2.70	110.5	8.77
10	10.2	5.7	0.03	8.0	0.13
13	7.7	6.5	0.34	78.6	0.97
17	15.1	22.0	0.12	5.1	0.55
18	17.2	10.9	0.20	8.0	0.52
19	18.1	14.4	0.02	6.3	0.59
20	13.9	9.8	1.13	42.4	2.27
21	20.1	14,9	0,91	18.8	2.14
22	24.8	18,1	0.06	8.0	1.53
23	9.9	6.7	0.37	18,8	0.33
24	16.3	15.2	0.35	28.3	2.35
25	7.0	6.0	4.70	100.0	0.96
26	28.1	19.2	1.58	42.4	12.19
28	6.6	5.1	0.45	44.2	0.37
29	14.4	15.9	0.40	5.1	0.37
31	31.5	18.1	0.03	8.0	2.34
33	10.5	8.0	0.73	66.3	1.93
34	12.0	11.5	1.58	95.5	3.88
36	17.4	17.2	0.43	28.3	2.97
37	8.0	5.9	0.29	21.5	0.24
38	16.8	12.9	0.08	14.1	1.06
41	10.3	9.2	0.75	78.9	2.23
42	8. 1	9.0	0.22	8.0	0.14
43	18.6	14.9	0.08	14.1	1.42
45	8.7	5.7	0.42	52.6	0.66
47	17.9	18.3	1.65	56.5	6.48
48	23.2	16.5	1.31	33.0	5.30
50	18.8	10.9	0.05	6.0	0.45
51	9.8	2.8	0.21	8.0	0.06
52	20.2	17. 8	1.67	66.3	9.15
53	8.5	4.8	2.53	26.3	0.27
55	35.0	18.8	0.43	14.1	5.32
56	21.1	17.3	1.13	52.6	7.32
58	7.6	6.6	2.43	157.2	1.96
60	20.5	16.5	0.34	22.1	2.86

Appendix 11: The main variables (Mean stand height, quadratic mean diameter, stand top height, stand top diameter, stand basal area,stand volume, number of trees per hectare) for the removed stands of validation plots

plot	$Dq_{removed}$	$H_{removed}$	BAremoved	Removed Number of trees per hectare	Vremoved.m^3ha^{-1}
14	8.2	8.8	1.95	348.2	6.65
15	7.1	10.6	1.02	127.3	2.38
40	10.9	7.2	0.47	52.6	1.39
46	13.6	12.9	1.93	105.2	5.93
59	13.3	7.9	0.06	14.1	0.46
62	10.6	4.5	16.72	285.8	3.91
63	27.3	22,5	1.50	44.2	12.40
64	21.9	18.9	1.01	66.3	10.92

Appendix 12: The statistical parameters of crown diameter equations of modeling plots

plot	Equation	R^2	Std Error of Coeff		Sign of Coeff		P-value
			a 0	a 1	a 0	a 1	
1	$-3.974+2.601\times\ln(d_{1.3})$	0.82	1.384	0.403	0.018	0.000	0.000
2	$-7.045+3.700\times\ln(d_{1.3})$	0.81	1.685	0.597	0.002	0.000	0.000
3	$-3.341+2.227\times\ln(d_{1.3})$	0.68	1.628	0.470	0.01	0.001	0.000
4	$-3.016+2.373\times\ln(d_{1.3})$	0.73	1.509	0.441	0.01	0.000	0.000
5	$-3.974+2.601\times\ln(d_{1.3})$	0.311	1.633	0.598	0.058	0.000	0.03
6	$-9.281+3.940\times\ln(d_{1.3})$	0.87	1.538	0.463	0.000	0.000	0.000
7	$-8.329+3.633\times\ln(d_{1.3})$	0.79	1.871	0.581	0.002	0.000	0.000
9	$-16.7+6.156\times\ln(d_{1.3})$	0.87	2.639	0.718	0.000	0.000	0.000
10	$-5.297+2.727\times\ln(d_{1.3})$	0.93	0.705	0.231	0.000	0.000	0.000
11	$-4.688+2.774\times\ln(d_{1.3})$	0.90	0.853	0.279	0.000	0.000	0.000
12	$-3.853+2.779\times\ln(d_{1.3})$	0.95	0.458	0.160	0.000	0.000	0.000
13	$-5.414+3.268\times\ln(d_{1.3})$	0.87	1.000	0.373	0.000	0.000	0.000
16	$-3.501+2.486\times\ln(d_{1.3})$	0.71	1.486	0.487	0.04	0.002	0.000
17	$-10.057+4.25\times\ln(d_{1.3})$	0.73	2.669	0.729	0.003	0.000	0.000
18	$-13.147+5.25\times\ln(d_{1.3})$	0.793	2.907	0.799	0.001	0.000	0.000
19	$-11.798+4.79\times\ln(d_{1.3})$	0.89	1.855	0.511	0.000	0.000	0.000
20	$-5.55+2.756\times\ln(d_{1.3})$	0.95	0.645	0.194	0.000	0.000	0.000
21	$-8.367+3.693\times\ln(d_{1.3})$	0.84	1.766	0.502	0.001	0.000	0.000
22	$-8.287+0.462\times\ln(d_{1.3})$	0.85	1.655	0.462	0.001	0.000	0.000
23	$-3.712+2.16\times\ln(d_{1.3})$	0.93	0.549	0.186	0.000	0.000	0.000
24	$-5.083+2.582\times\ln(d_{1.3})$	0.95	0.610	0.18	0.000	0.000	0.000
25	$-2.786+2.014\times\ln(d_{1.3})$	0.91	0.550	0.18	0.000	0.000	0.000
26	$-9.358+4.063\times\ln(d_{1.3})$	0.87	1.617	0.484	0.000	0.000	0.000
27	$-4.644+2.696\times\ln(d_{1.3})$	0.92	0.697	0.242	0.000	0.000	0.000
28	$-3.205+2.213\times\ln(d_{1.3})$	0.76	1.039	0.384	0.013	0.000	0.000
29	$-7.730+3.743\times\ln(d_{1.3})$	0.91	1.323	0.367	0.000	0.000	0.000
31	$-18.75+6.44\times\ln(d_{1.3})$	0.86	3.101	0.813	0.000	0.000	0.000
32	$-2.923+2.365\times\ln(d_{1.3})$	0.73	1.484	0.437	0.04	0.000	0.000
33	$-5.442+2.942\times\ln(d_{1.3})$	0.79	1.384	0.468	0.003	0.000	0.000
34	$-11.005+4.74\times\ln(d_{1.3})$	0.89	1.678	0.545	0.000	0.000	0.000
35	$-5.301+2.787\times\ln(d_{1.3})$	0.91	0.853	0.263	0.000	0.000	0.000
36	$-5.191+2.776\times\ln(d_{1.3})$	0.71	1.862	0.540	0.02	0.001	0.000
37	$-4.003+2.314\times\ln(d_{1.3})$	0.85	0.894	0.304	0.000	0.000	0.000
38	$-6.603+3.146\times\ln(d_{1.3})$	0.72	2.143	0.596	0.000	0.000	0.000
39	$-7.826+3.467\times\ln(d_{1.3})$	0.91	1.209	0.335	0.000	0.000	0.000
41	$-6.838+3.394\times\ln(d_{1.3})$	0.91	0.955	0.324	0.000	0.000	0.000
42	$-7.91+3.617\times\ln(d_{1.3})$	0.95	0.804	0.241	0.000	0.000	0.000
43	$-5.858+2.952\times\ln(d_{1.3})$	0.94	0.749	0.222	0.000	0.000	0.000
44	$-4.424+2.403\times\ln(d_{1.3})$	0.86	0.942	0.298	0.001	0.000	0.000
45	$-3.826+2.313\times\ln(d_{1.3})$	0.87	0.831	0.274	0.001	0.000	0.000
47	$-8.751+3.817\times\ln(d_{1.3})$	0.887	1.416	0.427	0.000	0.000	0.000
48	$-8.003+3.547\times\ln(d_{1.3})$	0.84	1.679	0.473	0.001	0.000	0.000
49	$-7.012+3.489\times\ln(d_{1.3})$	0.937	0.968	0.284	0.000	0.000	0.000
50	$-12.97+5.094\times\ln(d_{1.3})$	0.83	2.580	0.714	0.001	0.000	0.000
51	$-5.143+2.816\times\ln(d_{1.3})$	0.92	0.778	0.249	0.000	0.000	0.000
52	$-6.462+3.141\times\ln(d_{1.3})$	0.83	1.478	0.431	0.002	0.000	0.000
53	$-4.196+2.309\times\ln(d_{1.3})$	0.96	0.459	0.143	0.000	0.000	0.000
55	$-22.54+7.532\times\ln(d_{1.3})$	0.94	2.072	0.551	0.000	0.000	0.000
56	$-3.106+2.036\times\ln(d_{1.3})$	0.89	0.709	0.222	0.002	0.000	0.000
57	$-9.479+3.996\times\ln(d_{1.3})$	0.86	1.707	0.499	0.000	0.000	0.000
58	$-3.255+2.085\times\ln(d_{1.3})$	0.74	1.093	0.384	0.015	0.000	0.000
60	$-4.311+2.459\times\ln(d_{1.3})$	0.56	2.213	0.663	0.08	0.000	0.000

Appendix 13: The statistical parameters of crown diameter equations of validation plots

plot	Equation	R^2	Std Error of Coeff		Sign of Coeff		Sign
			a_0	a_1	a_0	a_1	
14	$-5.884+3.200\times\ln(d_{1.3})$	0.80	1.319	0.495	0.002	0.000	0.000
15	$-4.980+2.678\times\ln(d_{1.3})$	0.91	0.747	0.259	0.000	0.000	0.000
30	$-3.826+2.313\times\ln(d_{1.3})$	0.87	0.831	0.274	0.001	0.000	0.000
40	$-2.670+1.783\times\ln(d_{1.3})$	0.81	0.766	0.263	0.007	0.000	0.000
46	$-2.757+1.830\times\ln(d_{1.3})$	0.75	1.023	0.329	0.02	0.000	0.000
59	$-3.762+2.312\times\ln(d_{1.3})$	0.95	0.509	0.163	0.000	0.000	0.000
61	$-16.08+5.941\times\ln(d_{1.3})$	0.90	2.284	0.609	0.000	0.000	0.000
62	$-3.235+2.097\times\ln(d_{1.3})$	0.84	0.760	0.281	0.002	0.000	0.000
63	$-4.797+2.757\times\ln(d_{1.3})$	0.90	0.975	0.280	0.001	0.000	0.000
64	$-4.487+2.442\times\ln(d_{1.3})$	0.72	1.563	0.463	0.018	0.000	0.001

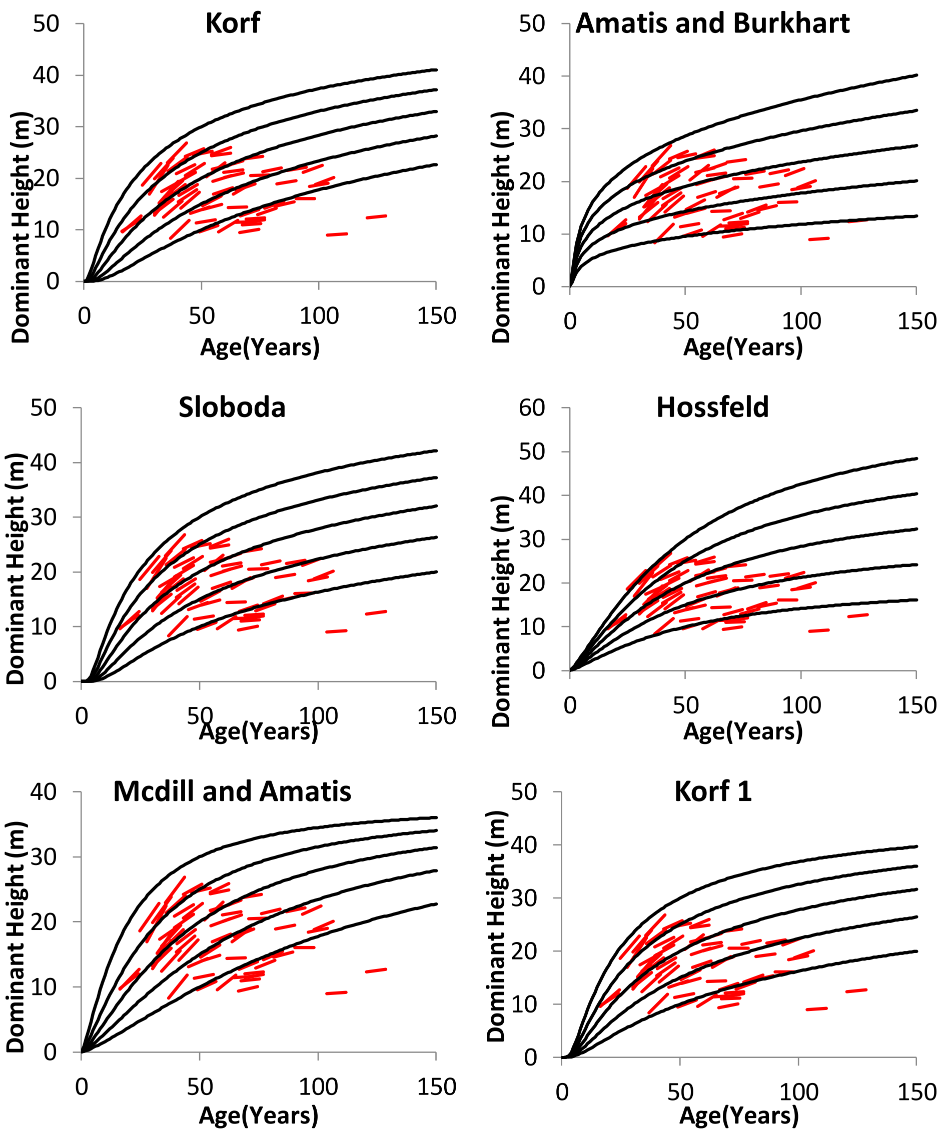
Appendix 14: The statistical parameters of tree crown length models for each permanent experimental plot in the second inventory of modeling plots.

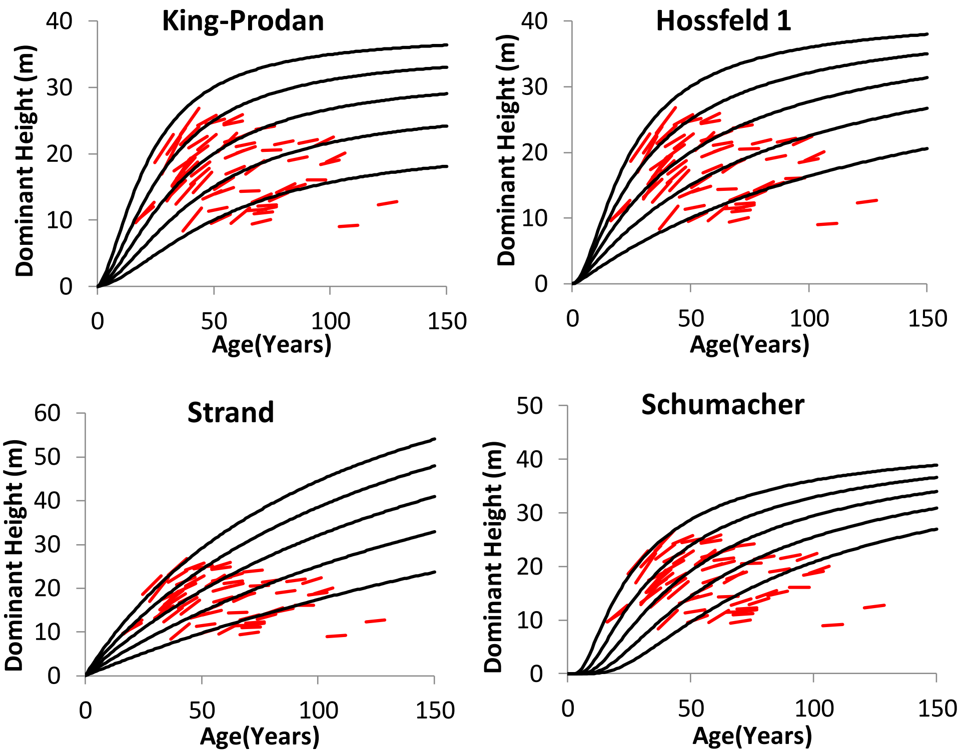
plot	R^2	sign	Intercept	a_1	Std Error of coeff
1	0,87	0,0000	-9,093	6,352	0,33
2	0,75	0,0000	-4,459	4,867	0,41
3	0,89	0,0000	-9,713	6,871	0,293
4	0,89	0,0000	-8,053	6,232	0,33
5	0,85	0,0000	-6,347	5,505	0,31
6	0,87	0,0000	-15,364	8,385	0,56
7	0,71	0,0000	-6,499*	5,319	0,63
9	0,44	0,02	-12,94	7,679	0,709
10	0,64	0,003	-3,111*	4,031	0,8
11	0,83	0,0000	-2,386*	3,999	0,53
12	0,78	0,0000	-4,061	4,523	0,56
13	0,921	0,0000	-5,774	5,356	0,33
16	0,73	0,0000	-4,326	4,736	0,77
17	0,68	0,03	-8,740	6,651	1,322
18	0,79	0,0000	-15,768	7,866	0,595
19	0,67	0,0000	-14,566	8,373	0,8
20	0,75	0,0000	-13,762	8,511	0,86
21	0,795	0,0000	-12,555	7,613	0,451
22	0,902	0,0000	-12,129	7,610	0,354
23	0,69	0,004	-6,310	5,491	0,788
24	0,606	0,0000	-12,861	7,979	1,4
25	0,647	0,0000	-1,609*	3,683	0,635
26	0,46	0,0000	-10,538	6,735	1,3
27	0,88	0,0000	-12,498	7,794	0,30
28	0,97	0,0000	-4,318	4,755	0,194
29	0,61	0,02	-6,488*	5,735	1,7
31	0,7	0,0000	-4,625*	5,254	0,6
32	0,49	0,0000	-0,223*	3,22	0,7
33	0,83	0,0000	-4,813	4,729	0,424
34	0,874	0,0000	-7,993	6,005	0,352
35	0,87	0,0000	-8,322	6,176	0,34
36	0,65	0,003	-9,914*	6,655	1,3
37	0,89	0,0000	-10,924	7,667	0,58
38	0,75	0,0000	-7,802	6,167	0,95
39	0,68	0,0000	-11,639	7,614	1,1
41	0,742	0,0000	-7,476	5,966	0,7
42	0,78	0,0000	-6,593	5,635	0,88
43	0,70	0,0000	-3,326	4,366	0,842
44	0,68	0,006	-6,192*	5,485	0,99
45	0,75	0,0000	-5,319	5,073	0,909
47	0,72	0,03	-6,132	5,478	1,096
48	0,614	0,004	-7,791	5,924	0,862
49	0,89	0,0000	-6,512	5,778	0,596
50	0,89	0,0000	-8,625	5,615	0,51
51	0,79	0,0000	-6,199	5,607	0,72
52	0,75	0,006	-20,189	9,928	1,1
53	0,82	0,0000	-10,26	7,154	1,02
55	0,44	0,0000	-8,596*	6,398	0,53
56	0,7	0,003	-17,176	9,421	1,071
57	0,84	0,0000	-10,734	6,906	0,34
60	0,753	0,002	-10,633	7,167	0,618

Appendix 15: The statistical parameters of tree crown length models for each permanent experimental plot in the second inventory of validation plots.

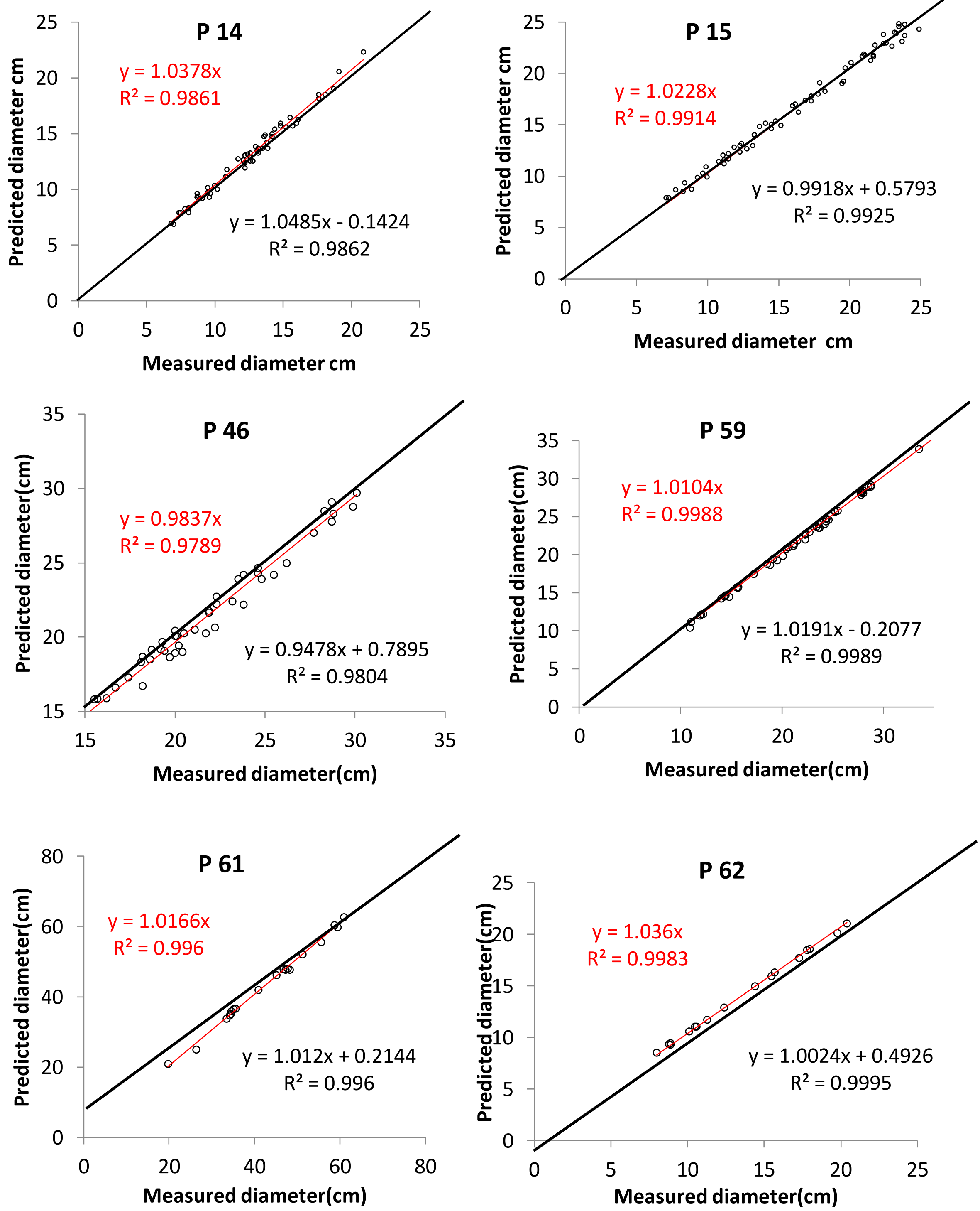
plot	Equation	R^2	Std Error of Coeff		Sign of Coeff		Sign
			a_0	a_1	a_0	a_1	
14	0,93	0,0000	-4,891	4,888	0,253	14	0,93
15	0,67	0,0000	-7,637	5,815	0,453	15	0,67
30	0,94	0,0000	-6,117	5,77	0,4	30	0,94
40	0,99	0,0000	-7,119	5,72	0,1	40	0,99
46	0,95	0,0000	-7,26	5,738	0,247	46	0,95
59	0,92	0,0000	-6,646	6,124	0,31	59	0,92
61	0,74	0,001	-9,147	6,779	0,74	61	0,74
62	0,90	0,0000	-5,362	5,126	0,21	62	0,90
63	0,86	0,0000	-13,148	7,803	0,356	63	0,86
64	0,91	0,0000	-6,057	5,37	0,354	64	0,91

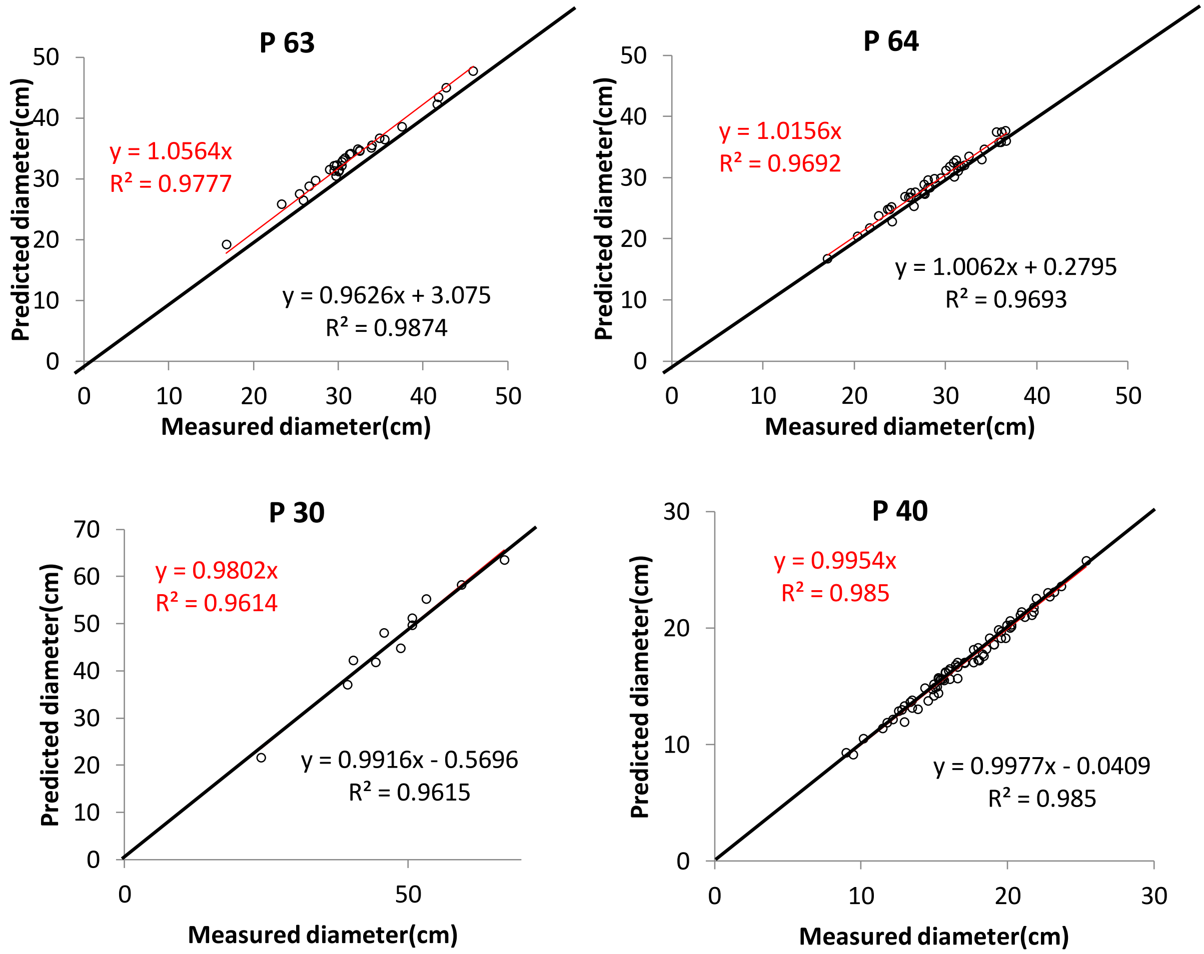
Appendix 16:Distribution of dominant height development (2008-2016) with the developed site index equations which categorized into five site classes (10, 15, 20, 25, and 30)



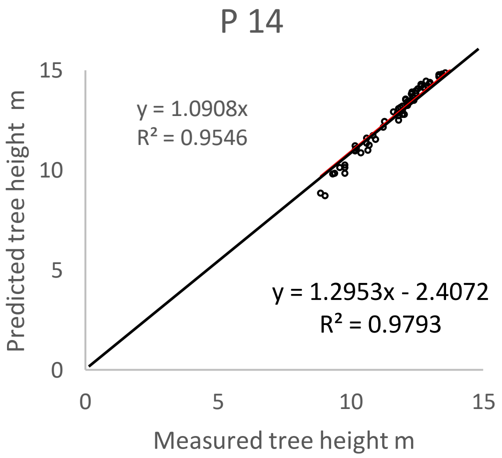

King-Prodan
Hossfeld 1
Strand
Schumacher
Dominant Height (m)
Age(Years)
0
50
100
150
10
20
30
40
60

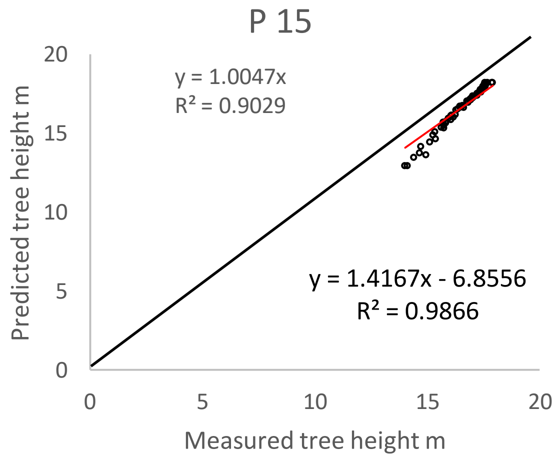
Appendix 17 :The relationship between measured (2016) and predicted diameter at breast height ($d_{1.3}$) values in test plot, produced by diameter increment equation for validation plots

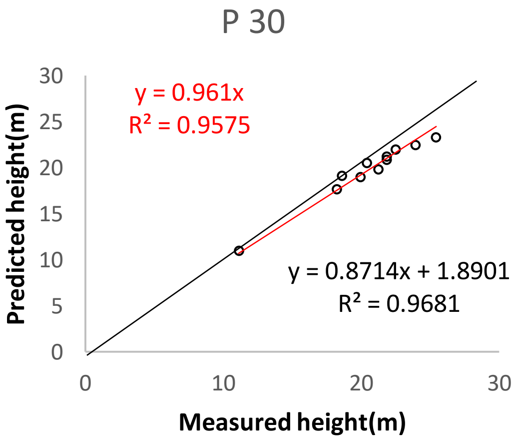


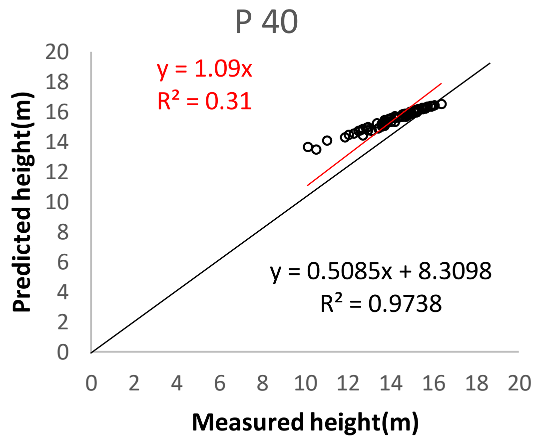

P 63
y = 1.0564x
R² = 0.9777
y = 0.9626x + 3.075
R² = 0.9874
Predicted diameter(cm)
Measured diameter(cm)
P 64
y = 1.0156x
R² = 0.9692
y = 1.0062x + 0.2795
R² = 0.9693
Predicted diameter(cm)
Measured diameter(cm)
P 30
y = 0.9802x
R² = 0.9614
y = 0.9916x - 0.5696
R² = 0.9615
Predicted diameter(cm)
Measured diameter(cm)
P 40
y = 0.9954x
R² = 0.985
y = 0.9977x - 0.0409
R² = 0.985
Predicted diameter(cm)
Measured diameter(cm)

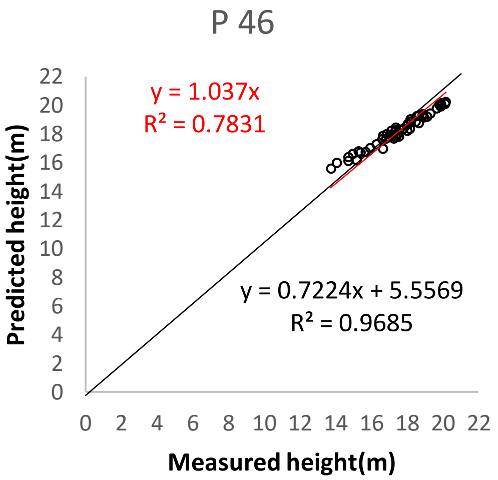
Appendix 18 :The relationship between measured (2016) and predicted height values in test plot, produced by linearized height increment equation for validation plots

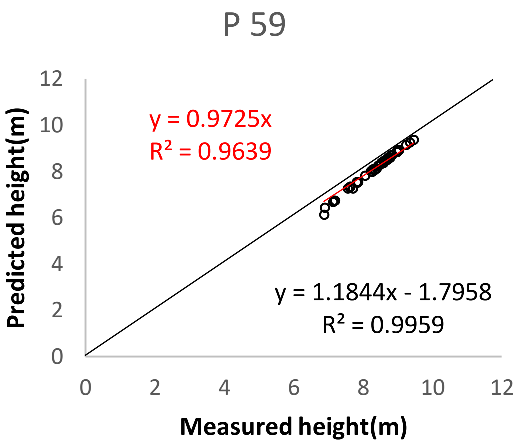


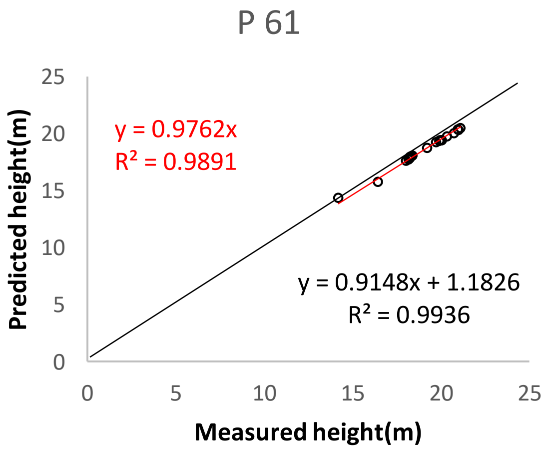


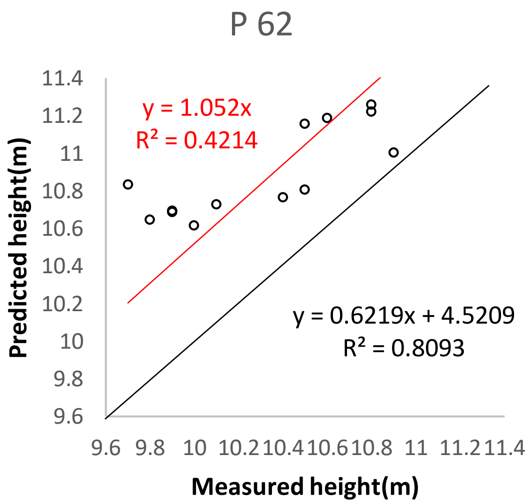


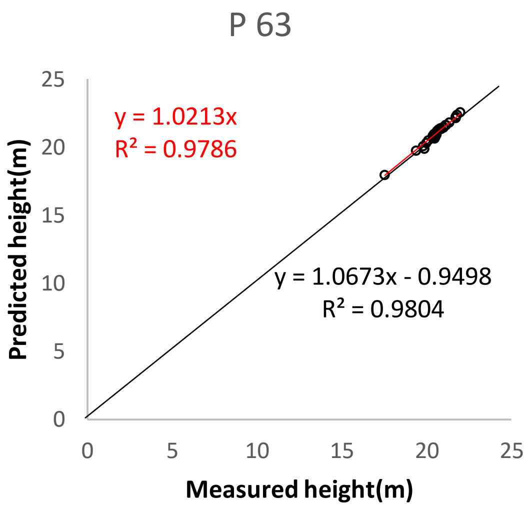


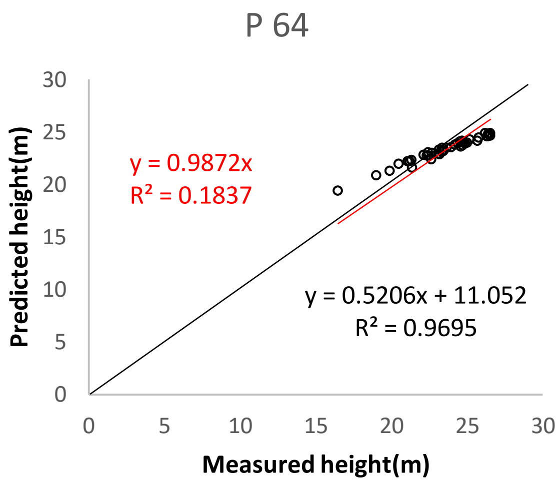




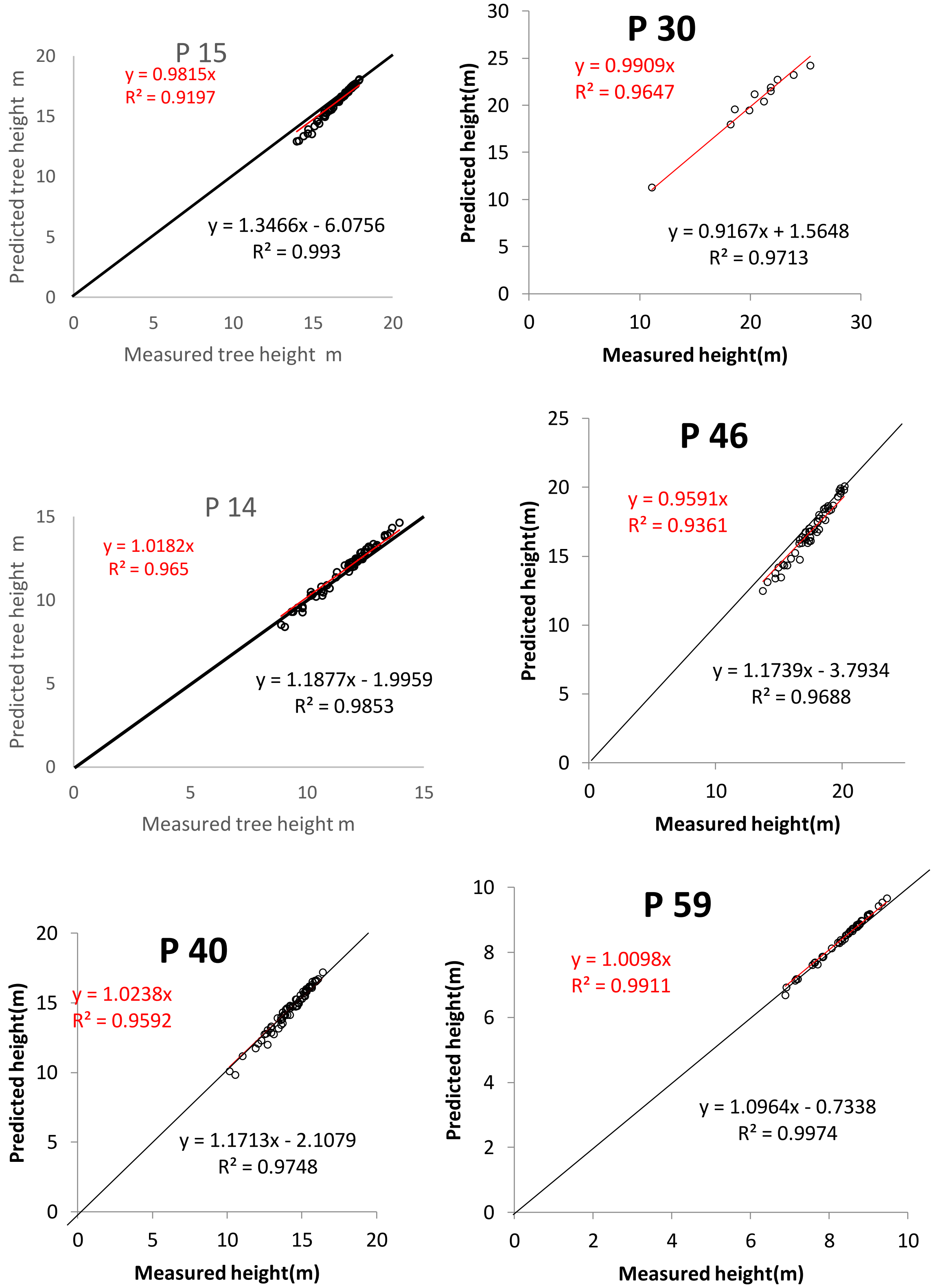

P 61
y = 0.9762x
R² = 0.9891
y = 0.9148x + 1.1826
R² = 0.9936
Predicted height(m)
Measured height(m)
0
5
10
15
20
25

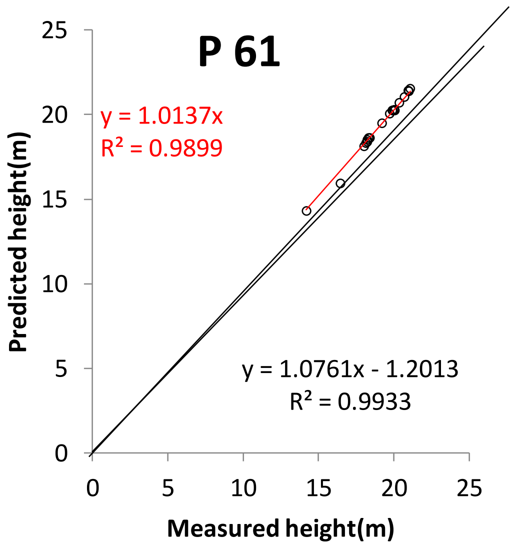

P 62
y = 1.052x
R² = 0.4214
y = 0.6219x + 4.5209
R² = 0.8093
Predicted height(m)
Measured height(m)
9.6
9.8
10
10.2
10.4
10.6
10.8
11
11.2
11.4

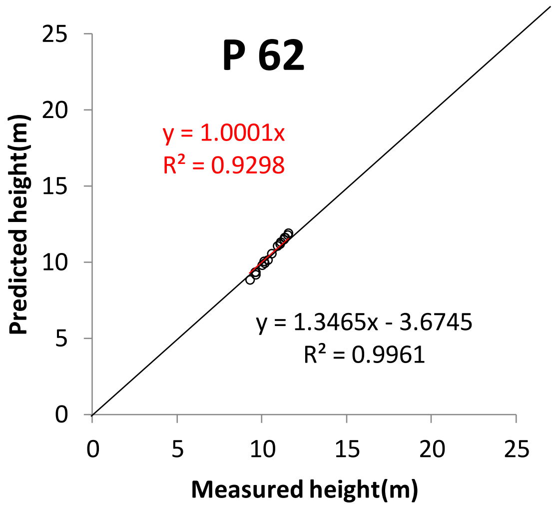

P 63
y = 1.0213x
R² = 0.9786
y = 1.0673x - 0.9498
R² = 0.9804
Predicted height(m)
Measured height(m)
0
5
10
15
20
25

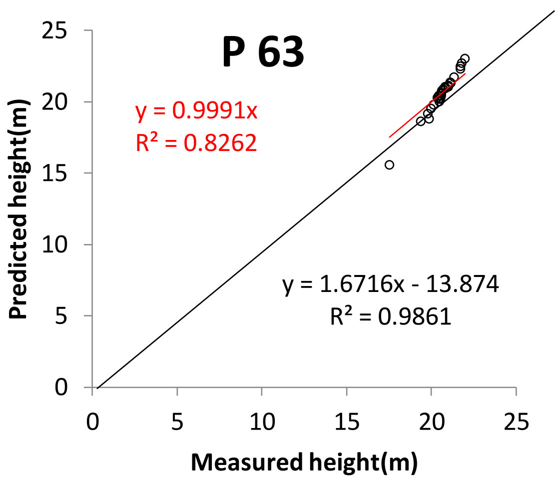

P 64
y = 0.9872x
R² = 0.1837
y = 0.5206x + 11.052
R² = 0.9695
Predicted height(m)
Measured height(m)
0
5
10
15
20
25
30

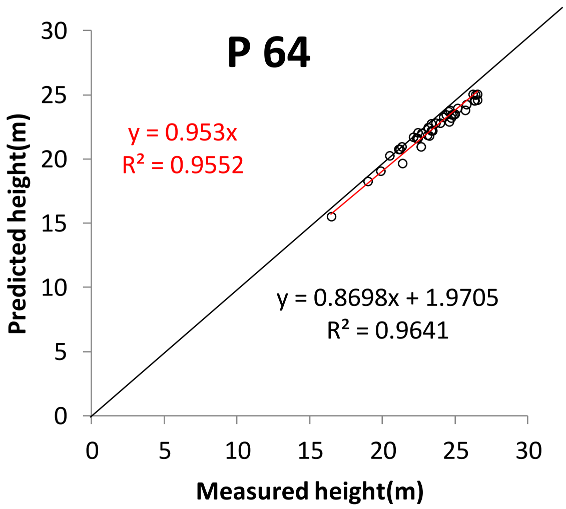
Appendix 19 :The relationship between measured (2016) and predicted height values in test plot, produced by Potential modifier height increment equation for validation plots




P 61
y = 1.0137x
R² = 0.9899
y = 1.0761x - 1.2013
R² = 0.9933
Predicted height(m)
Measured height(m)


P 62
y = 1.0001x
R² = 0.9298
y = 1.3465x - 3.6745
R² = 0.9961
Predicted height(m)
Measured height(m)


P 63
y = 0.9991x
R² = 0.8262
y = 1.6716x - 13.874
R² = 0.9861
Predicted height(m)
Measured height(m)


P 64
y = 0.953x
R² = 0.9552
y = 0.8698x + 1.9705
R² = 0.9641
Predicted height(m)
Measured height(m)