UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF MIXED-EFFECTS MODELS FOR PREDICTING EARLY HEIGHT GROWTH AND TIMBER VOLUME OF FOREST TREE SPECIES PLANTED IN SARAWAK, MALAYSIA

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, In Fulfilment of the Requirements for the Degree of Master of Science

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ABSTRACT

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the degree of Master of Science

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July 2014

Chair: Professor Dato' Wan Razali Wan Mohd, PhD

Faculty: Forestry

Indigenous timber species are the most valuable tree in Malaysian tropical forest nowadays. Modeling of height growth and volume for indigenous timber species has been a challenge to foresters in recent years due to the rapid loss of forest biodiversity. The selection of species for afforestation and reforestation program is one of the most crucial tasks as it affects the growth of such forest and hence the financial viability of such program. The challenges in modeling of multi species stand in tropical forest are the large number of species, small number of individuals per species and almost impossible to develop models for every species in predicting height growth and timber volume. The objective of this study is to develop mixed effect models for predicting early height growth and timber volume of forest tree species planted in Sarawak.

This investigation was conducted in the UPM-Mitsubishi Forest Rehabilitation Project area at Universiti Putra Malaysia, Bintulu, Sarawak, Malaysia. The joint research project started in July 1991 between Universiti Putra Malaysia (UPM) and Yokohama National University, Japan on a 47.5 ha forest site at UPM's Bintulu campus, Sarawak. It is located about 600 kilometres northeast of Kuching and 50 meters above sea level. The joint project was

financially sponsored by the Mitsubishi Corporation of Japan. The data used in this investigation were from a permanent growth plot within the project forest area. The project initiated is an excellent example of a highly successful forest rehabilitation project on degraded area. The data came from sapling trees planted in 50m x 5m plot that was established in June 1991. Open planting method was employed in the plot. The planted trees mimic a compact stand of natural forest, equivalent to a Kerangas forest.

Several mixed-effects models were developed to represent the total height growth and volume of standing tree pattern of five Malaysian indigenous timber species planted in Sarawak. The result showed that the Linear Mixed-Effects Model (Model 1) with two random effect parameters is the best fitted model for predicting height growth of five indigenous timber species, and the Nonlinear Mixed-Effects Model (Model 2) with two random effect parameters is the best fitted model for predicting standing volume of the five indigenous timber species. Development of mixed-effects models based mainly on its early height and volume performance will help to overcome the species selection process for afforestation and reforestation in improving productive capacity of such forest. Statistical analysis were done using PROC MIXED and NLMIXED procedures in the SAS® 9.2 program.

The number of trees used to develop models for each species is: *Calophyllum sclerophyllum* (73), *Dryobalanops beccarii* Dyer (84), *Shorea mecistopteryx* Ridt. (74), *Shorea leprosula* Miq. (60) and *Shorea brunnescens* Ashton (72). Based on model comparison and criteria for height models indicates that Linear Mixed-Effects Model (Model 1) has smaller value of AIC (3106.0) and BIC (3104.8) among the other models tested. The goodness-of-fit statistics also indicates Model 1 has the smallest value of RMSE (16.4806), MAE (11.2394) and a highest R^2 (0.93396) compare to other models. Based on model comparison and criteria for volume models indicates that Nonlinear Mixed-Effects Model (Model 2) has smallest value of AIC (4165.7) and BIC (4163.3) among other model tested. The goodness-of-fit statistics also indicates Model 2 has the smallest value of RMSE (70.1363), and a highest R^2 (0.99059) compare to other models.

The models developed in this study can be implemented in prediction of sapling tree only. Based on prediction for height (Model 1), it can be concluded that the early height (cm) growth performance of the five species are in the following order: *Shorea brunnescens* Ashton (highest), followed by *Calophyllum sclerophyllum*, *Dryobalanops beccarii* Dyer, *Shorea leprosula* Miq., and *Shorea mecistopteryx* Ridt. (lowest). It indicat that *Shorea brunnescens* Ashton has the best early height growth among the five species compared. Based on prediction for volume (Model 2), it can be concluded that the volume (cm^3) performance of the five species are in the following order: *Shorea brunnescens* Ashton (highest), follow by *Dryobalanops beccarii* Dyer, *Calophyllum sclerophyllum*, *Shorea leprosula* Miq. And *Shorea mecistopteryx* Ridt. (lowest). It indicated that *Shorea brunnescens* Ashton has the best early volume among the five species compared. The results of this study indicated that *Shorea brunnescens* Ashton has good early height growth and volume performance. *Shorea brunnescens* Ashton is thus a better species for afforestation and reforestation program. Other most potential species for rehabilitation in terms of early height growth, volume and survival performance is *Dryobalanops beccarii* Dyer.

Based on the development of mixed-effects models in this study, there is also a limitation need to be considered here where the data came from early growth trees or sapling trees (31 months after planted). The models indicate a good result for predicting species performance based on height and volume as a method to select species for afforestation and reforestation program. However application of the models coefficient to predict (e.g. height and volume) other trees from this data need to be caution beyond the range of basal diameter. This model cannot represent trees beyond the range of basal diameter in this study.

The models error variances in this study shown non-constant based on Breusch-Pagan test and it indicates that the heteroscedasticity presence in the mixed effect models (height and volume). The heterogeneity of error variance presence due to a different of basal diameter size class of trees. Model transformations were also carried out in this study in order to reduce the error variance heterogeneity for height and volume models using Log transformation. However, the model transformation method didn't improving the mixed effect models where the models perform not very well with a reduction of R^2 and highest value of MAE and RMSE compare to a real mixed effect models without transformation. The nature biological of the data in this study is a key factor affect for models development and efficiency. It indicates that development of models using sapling trees are not appropriate and need to be caution when using this model, especially for development of local height and volume table. Based on the results in this study indicate that there is no need for model transformation and the best fitted of mixed-effects models for height and volume are still adequate mostly for predicting timber species performance in this study based on highest R^2 value.

The models developed in this study should be used with caution, that is, they provide a good early height and volume prediction within the range of tree diameters and heights of the data to develop the models. Furthermore, verification models were not developed for all five species due to small number of trees within each species.

ABSTRAK

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Sarjana Sains

PEMBANGUNAN MODEL KESAN BERCAMPUR UNTUK MERAMAL TUMBESARAN KETINGGIAN DAN ISIPADU AWAL POKOK BALAK BAGI SPESIES POKOK HUTAN YANG DITANAM DI SARAWAK, MALAYSIA

Oleh

ABDUL RAZAK BIN HJ.TARIP

Julai 2014

Pengerusi: Profesor Dato' Wan Razali Wan Mohd, PhD

Fakulti: Perhutanan

Spesies kayu asli adalah pokok yang paling berharga di hutan tropika Malaysia pada masa kini. Pemodelan pertumbuhan ketinggian dan isipadu bagi spesies pokok balak asli telah menjadi cabaran kepada perhutanan dalam beberapa tahun kebelakangan ini disebabkan oleh kehilangan pesat biodiversiti hutan. Pemilihan spesies untuk program pemulihan hutan adalah salah satu tugas yang paling penting kerana ia memberi kesan kepada pertumbuhan hutan dan daya maju kewangan program tersebut. Antara cabaran dalam pemodelan spesies pelbagai dirian di hutan tropika adalah seperti bilangan spesies yang banyak, jumlah individu setiap spesies yang kecil dan hampir mustahil untuk membangunkan model bagi setiap spesies dalam meramalkan pertumbuhan ketinggian dan isipadu pokok. Objektif kajian ini adalah untuk membangunkan model kesan bercampur untuk meramal tumbesaran ketinggian dan isipadu awal spesies pokok balak yang ditanam di kawasan hutan di Sarawak.

Kajian telah ini dijalankan di kawasan Projek Pemuliharaan Hutan UPM-Mitsubishi di Universiti Putra Malaysia, Bintulu, Sarawak, Malaysia. Projek penyelidikan bersama ini bermula pada Julai 1991 antara Universiti Putra Malaysia (UPM) dan Universiti Kebangsaan Yokohama, Jepun di kawasan hutan seluas 47.5 hektar di kampus UPM Bintulu, Sarawak. Ia

terletak kira-kira 600 kilometer timur laut Kuching dan berada pada 50 meter di atas paras laut. Kewangan projek ini ditaja oleh Mitsubishi Corporation dari Jepun. Data yang digunakan dalam kajian ini adalah dari plot pertumbuhan kekal didalam kawasan projek. Projek yang dimulakan ini adalah satu contoh yang terbaik dan berjaya untuk pemulihan hutan yang mengalami degradasi. Data dalam kajian ini diperoleh daripada anak-anak pokok yang ditanam diatas plot 50m x 5m yang telah ditubuhkan sejak Jun 1991. Kaedah penanaman terbuka telah digunakan diatas plot ini. Kaedah pokok-pokok yang ditanam adalah bagi menyamaai dirian asal hutan semula jadi di kawasan ini, iaitu hutan Kerangas.

Beberapa model kesan campuran telah dibangunkan untuk mewakili jumlah pertumbuhan ketinggian dan corak isipadu dirian pokok untuk lima spesies kayu asli Malaysia yang ditanam di Sarawak. Hasilnya menunjukkan bahawa Model Linear Kesan Bercampur (Model 1) dengan dua parameter kesan rawak adalah model yang terbaik untuk meramalkan pertumbuhan awal ketinggian lima spesies kayu asli, dan Model Tidak Linear Kesan Bercampur (Model 2) dengan dua parameter kesan rawak adalah model yang terbaik untuk meramalkan jumlah dirian isipadu pokok daripada lima spesies kayu asli. Pembangunan model kesan campuran berasaskan kepada prestasi ketinggi dan jumlah isipadu akan membantu mengatasi proses pemilihan spesies untuk program penghutanan semula dalam meningkatkan kapasiti produktif hutan itu. Analisis statistik telah dilakukan dengan menggunakan prosedur PROC MIXED dan NLMIXED dalam program SAS ® 9.2.

Bilangan pokok yang digunakan untuk membangunkan model bagi setiap spesies adalah: *Calophyllum sclerophyllum* (73), *Dryobalanops beccarii* Dyer (84), S*horea mecistopteryx* Ridt. (74), *Shorea leprosula* Miq. (60) dan *Shorea brunnescens* Ashton (72). Berdasarkan daripada perbandingan dan kriteria model untuk model ketinggian menunjukkan bahawa Model Linear Kesan Campuran (Model 1) mempunyai nilai AIC (3106.0) dan BIC (3104.8) yang lebih kecil berbanding model lain yang diuji. Berdasarkan goodness-of-fit statistik turut menunjukkan Model 1 mempunyai nilai RMSE (16.4806), MAE (11.2394) yang paling kecil dan R^2 (0.93396) yang lebih tinggi berbanding dengan model lain. Berdasarkan daripada perbandingan dan kriteria model untuk model isipadu menunjukkan bahawa Model Tidak Linear Kesan Campuran (Model 2) mempunyai nilai AIC (4165.7) dan BIC (4163.3) yang terkecil di kalangan model lain yang diuji. Berdasarkan goodness-of-fit statistik turut menunjukkan Model 2 mempunyai nilai RMSE (70.1363) yang paling kecil dan R^2 (0.99059) yang lebih tinggi berbanding dengan model lain.

Model yang dibangunkan dalam kajian ini hanya boleh digunakan dalam meramalan anak pokok sahaja. Berdasarkan ramalan untuk ketinggian (Model 1), ia boleh disimpulkan bahawa prestasi ketinggian (cm) awal daripada lima spesies adalah seperti berikut: *Shorea brunnescens* Ashton (tertinggi), diikuti oleh *Calophyllum sclerophyllum*, *Dryobalanops beccarii* Dyer, *Shorea leprosula* Miq., dan *Shorea mecistopteryx* Ridt. (paling terendah). Ini menunjukkan bahawa *Shorea brunnescens* Ashton mempunyai pertumbuhan ketinggian awal yang terbaik di kalangan lima spesies yang dibandingkan. Berdasarkan ramalan untuk jumlah isipadu (Model 2), ia boleh disimpulkan bahawa prestasi jumlah isipadu (cm^3) daripada lima spesies adalah seperti berikut: *Shorea brunnescens* Ashton (tertinggi), diikuti oleh *Dryobalanops beccarii* Dyer, *Calophyllum sclerophyllum*, *Shorea leprosula* Miq. dan *Shorea mecistopteryx* Ridt. (paling terendah). Ini menunjukkan bahawa *Shorea brunnescens* Ashton mempunyai isipadu awal yang terbaik di kalangan lima spesies yang dibandingkan. Hasil dari kajian ini menunjukkan bahawa *Shorea brunnescens* Ashton mempunyai prestasi ketinggian dan jumlah isipadu pada peringkat awal yang baik. Oleh itu, *Shorea brunnescens* Ashton merupakan spesies yang lebih baik untuk program penanaman semula hutan. Lain-lain spesis yang paling berpotensi untuk pemulihan dari segi ketinggian dan isipadu, mahupun prestasi hidup ialah *Dryobalanops beccarii* Dyer.

Berdasarkan daripada pembangunan model kesan campuran dalam kajian ini, terdapat juga had yang perlu dipertimbangkan dimana data ini diperoleh daripada anak pokok dari peringkat awal pertumbuhan (31 bulan selepas ditanam). Model ini menunjukkan hasil yang baik untuk meramalkan prestasi awal spesies pokok berdasarkan ketinggian dan isipadu sebagai kaedah untuk memilih spesies untuk program penanaman semula hutan. Walaubagaimanapun penggunaan model ini perlulah berhati-hati untuk meramal ketinggian dan isipadu pokok khususnya pokok diluar lingkungan basal diameter dalam kajian ini. Dalam kajian ini, model ini tidak boleh mewakili pokok-pokok diluar lingkungan basal diameter.

Error variance untuk model didalam kajian ini menunjukkan keadaan error yang tidak tetap berdasarkan daripada ujian Breusch-Pagan dan ini menunjukkan bahawa berlakunya heteroscedasticity dalam model kesan campuran (ketinggian dan isipadu). Heteroscedasticity ini terjadi disebabkan oleh kelas saiz diameter pokok yang berlainan. Transformasi model juga telah dijalankan dalam kajian ini untuk mengurangkan heteroscedasticity untuk model ketinggian dan isipadu dengan menggunakan kaedah transformasi Log. Walaubagaimanapun, kaedah transformasi model ini tidak dapat memperbaiki model kesan campuran di mana model ini tidak menunjukan prestasi yang baik dengan pnurunan nilai R^2, peningkatan nilai MAE dan RMSE jika dibandingkan dengan model kesan campuran tanpa pengubahsuaian. Sifat biologi data dalam kajian ini merupakan antara faktor utama yang memberi kesan kepada pembangunan dan kecekapan model. Ini menunjukkan bahawa pembangunan model menggunakan anak pokok adalah tidak sesuai dan perlu berhati-hati apabila menggunakan model ini, khususnya untuk pembangunan "local height dan volume table". Berdasarkan daripada keputusan dalam kajian ini menunjukkan bahawa tidak ada keperluan untuk transformasi model dan model kesan bercampur untuk ketinggian dan isipadu pokok ini masih efektif untuk digunakan khususnya untuk meramal prestasi spesies balak dalam kajian ini berdasarkan daripada nilai R^2 yang tinggi.

Model yang dibangunkan dalam kajian ini harus digunakan dengan berhati-hati, data untuk membangunkan model ini memberikan ramalan ketinggian dan isipadu pada peringkat awal yang baik dalam pelbagai diameter pokok dan ketinggian. Tambahan pula, pengesahan model tidak dibangunkan untuk semua lima spesies disebabkan oleh bilangan pokok yang kecil dalam setiap spesies.

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APPROVAL

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of requirements for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Dato' Wan Razali Wan Mohd, PhD
Professor
Faculty of Forestry
Universiti Putra Malaysia
(Chairman)

Mohamad Azani Alias, PhD
Associate Professor
Faculty of Forestry
Universiti Putra Malaysia
(Member)

Kamziah Abd Kudus, PhD
Associate Professor
Faculty of Forestry
Universiti Putra Malaysia
(Member)

____

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

APPROVAL

I certify that a Thesis Examination Committee has met on 08 July 2014 to conduct the final examination of Abdul Razak Bin Hj.Tarip on his thesis entitled "**Development of Mixed-Effects Models For Predicting Early Height Growth and Timber Volume of Forest Tree Species Planted in Sarawak, Malaysia**" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U. (A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

Members of the Thesis Examination Committee were as follows:

Shukri Mohamed, PhD
Associate Professor
Faculty of Forestry
Universiti Putra Malaysia
(Chairman)

Awang Noor Abd.Ghani, PhD
Professor
Faculty of Forestry
Universiti Putra Malaysia
(Internal Examiner)

Mohd. Zaki Hamzah, PhD
Associate Professor
Faculty of Forestry
Universiti Putra Malaysia
(Internal Examiner)

Abd Rahman Kassim, PhD
Senior Research Officer
Division of Forestry and Environmental
Forest Research Institute Malaysia (FRIM)
Malaysia
(External Examiner)

NORITAH OMAR, PhD
Associate Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

DECLARATION

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I hereby confirm that:

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This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ______________________
Name of Chairman of Supervisory Committee: **Professor Dato' Dr. Wan Razali Wan Mohd**

Signature: ______________________
Name of Member of Supervisory Committee: **Associate Professor Dr. Mohamad Azani Alias**

Signature: ______________________
Name of Member of Supervisory Committee: **Associate Professor Dr. Kamziah Abd Kudus**

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LIST OF ABBREVIATIONS

IPCC	Intergovernmental Panel on Climate Change
PFR	Permanent Forest Reserve
PSP	Permanent Sample Plot
SFM	Sustainable Forest Management
R&D	Research and Development
USDA	United State Department of Agriculture
DBH	Diameter at Breast Height
PROGNOSIS	Prognosis model for stand development
STEMS	Stand and Tree Evaluation and Modeling System
CFI	Continuous Forest Inventory
SLPSS	Shortleaf Pine Stand Simulator
LHW	Light Hardwoods
MHW	Medium Hardwoods
HHW & MISC	Heavy Hardwoods and other Miscellaneous Species
CCF	Crown Competition Factor
FVS	Forest Vegetation Simulator
OAKSIM	Oak Simulator
TASS	Tree and Stand Simulator
CACTOS	California Conifer Timber Output Simulator
DFSIM	Douglas-fir Simulator
MYRLIN	Methods of Yield Regulation with Limited Information
GYMMTF	Growth and Yield Model for Mixed-Tropical Forests
FRIM	Forest Research Institute Malaysia
LME	Linear Mixed-Effects
NLME	Nonlinear Mixed-Effects
SAS	Statistical Analysis System
AIC	Akaike Information Criterion
BIC	Bayesian Information Criterion
RMSE	Root Mean Square Error
MAE	Mean Absolute Error
R^2	Coefficient of determination
D_{10}	Basal diameter at 10 cm above ground
BLUP	Best Linear Unbiased Predictors
ML	Maximum Likelihood
REML	Restricted/Residual Maximum Likelihood
ANOVA	Analysis of Variance
LSD	Least Significant Difference
NFI	National Forest Inventory

CHAPTER 1

INTRODUCTION

1.1 Background

Tropical rainforests are the world's most complex biotic community, the result of supremely favourable condition for plant growth prolonged over millions of years (Kernan 1974). Tropical forest ecosystems are critically important for our well-being. Rainforests are often called the lungs of the planet for their roles in absorbing carbon dioxide and producing oxygen, upon which all creatures depend for survival. Rainforests also stabilize climate, house incredible amounts of plants and wildlife, and produce nourishing rainfall all around the planet. Tropical rain forests display a biodiversity unparalleled by that of other vegetation type. The height species-richness of rain forest floras clearly reflects evolution over periods of time (Morley, 2000).

The functions of tropical forests can be productive (timber, fibre, fuel-wood, and non-timber forest products), environmental (climate regulation, carbon sequestration and storage, reserve of biodiversity, and soil and water conservation), and social (subsistence and food security for local population and culture). Forests serve a combination of functions and can generate additional revenue for local population and national economic through ecotourism. Forests also have aesthetic, scientific, and religious values (Montagnin and Jordan, 2005). The distribution of tropical rain forests, as the name suggests, is essentially controlled by climate, and from a geological viewpoint, 'tropical' climates are those which today, are characteristic of tropical latitudes.

Forests have been managed since time immemorial for direct benefit of humankind, although some forests are kept untouched for several indirect (or even unknown) reasons. Forest management involves one or more than one objective such as timber production, biodiversity and water supply. With increasing understanding of basic sciences and increasing demand for resources, forest management is becoming more and more important (Davis *et al.* 2001). Progressive forest management requires a good understanding of how individual tree and stand grow over time under different environmental conditions. Therefore, forest growth and yield modelling is an integral part of forest management, at least in developed countries.

Two of the most critical environmental scenarios facing the world today are anticipated increase in temperature (climate change scenario) and loss of forest bio-diversity (biodiversity scenario). Reforestation has been proposed almost by everyone at local, national and international fora and meetings as a mean to negate these two scenarios. Details of both scenarios can be explored in documents published by IPCC (2001) and FRIM (2007). Afforestation and reforestation is one of the ways to increasing or maintaining forest area. It will increase biodiversity by planting multi-species trought reduction of deforestation and degradation (IPCC Working Group III, 2007).

The widespread concern about tropical forests is focused mainly on two issues, deforestation and forest degradation, both resulting in potentially disastrous environmental, economic, social and cultural negative consequences. With the implementing shortage of raw timber supply and the increasing area of degraded natural forest, forest rehabilitation is the key answer to overcome this problem (Mohamad Azani 1998). Kobayashi and Ueda (2003) state, the rehabilitation of degraded forests and lands is a most urgent matter from the viewpoints of both compensation or enrichment of ecosystems and sustainable used of degraded areas in a regional and a global scale. Study and analysis of biological and physiological characteristics of regenerated tree or newly planted tree and of the processes influencing productivity in such areas are necessary in order to make afforestation and reforestation activities successful.

1.2 Forest Growth And Yield Models

According to Vanclay (1994), growth refers to the increase in dimensions of one or more individuals in a forest stand over a given period of time (e.g. volume growth in m^3 ha^{-1} y^{-1}); yield refers to their final dimensions at the end of a certain period (e.g. volume in m^3 ha^{-1}). In even-aged stands, a growth equation might predict the growth of diameter, basal area or volume in units per annum as a function of age and other stand characteristics, whereas a yield equation would predict the diameter, stand basal area or total volume production attained at a specified age. In an uneven-aged stand, yield is the total production over a given time period, while growth is the rate of production.

Growth models are important in both forest management and forest dynamics studies. A forest growth model is a system of mathematical equations that describes forest development and mimics some (or all) stages of its dynamics. Growth models are vital for decision-making in forest management because they predict forest development under several silvicultural regimens, which can be linked to forest optimization techniques and, subsequently, management. Forest growth models can also be used for generalizing specific (or broader) concepts of forest dynamics, as well as dynamics at the ecosystem scale. Growth models have been used not only for predicting timber development, but also as a basis for assessing other forest ecosystem elements such as wildlife habitat, hydrology, and landscape connectivity.

For instance, Sutmöller *et al.* (2011) develop a forest growth-hydrology modelling as an instrument for the assessment of effects of forest management on hydrology in forested catchments at the Oker catchment, northern Harz Mountains of Lower Saxony Germany. The approach adopted in this study necessitated the development of an interactive system for the spatially distributed modelling of hydrology in relation to forest stand development. Consequently, a forest growth model was used to simulate stand development assuming various forest management activities. Selected simulated forest growth parameters were entered into the hydrological model to simulate water fluxes under different conditions of forest structure.

The approach enables the spatially differentiated quantification of changes in the water regime (e.g. increased evapotranspiration). The results of hydrological simulations in the study area, the Oker catchment (northern Harz Mountains), show that forests contribute to the protection of water systems because they have a balancing effect on the hydrological regime. As scenario simulations also suggest, however, forestry practices can also lead to substantial changes in water budgets of forested catchments. The preservation of the hydrological services of forests requires a sustainable and long-term forest conversion on the basis of current management directives for near natural silviculture. Management strategies on basis of moderate harvesting regimes are preferred because of their limited impact on the water budget.

The results of the simulations show that forest management may have a distinct effect on water budgets of forests. The findings from the scenario analyses should be regarded with care, since simulation results are equipped with large uncertainty due to uncertainty in input data and possibly weak model formulations. However, the dynamic treatment of forest stand structure in the hydrological model improves the analysis of effects of silvicultural measures on water budgets substantially. A next step for the improvement of the forest growth-hydrology coupling would be the inclusion of a site index model into the growth simulator, which simulates tree growth dependent on climatic and site specific variables (Albert and Schmidt, 2010).

Growth models may also have a broader role in forest management and in formulation of forest policy (Vanclay, 1994). For instance, Vanclay (1989), develop a model for selection harvesting in tropical rain forests. Regression analyses were used to develop a model of current logging practice in the rain forests of north Queensland, Australia. This study has demonstrated a technique which enables selection logging yields to be estimated, and the impact on the residual stand to be quantified. Logistic regression enabled the development objective models for the selection of trees for harvesting, the incidence of defect in the selected trees, and for damage to the residual stand. Important predictors included tree species and size, stand basal area, basal area logged, logging history and topography. There was no evidence to suggest that soil type or site quality influenced current tree marking practice. The approach is applicable to other mixed forest types managed for selection logging.

Forest growth modelling has evolved from yield tables to elaborate equations. The first forest growth models were tabulated values computed as an average of sample plots, known as yield tables, portraying stand volume development. The first yield tables were built at the end of the 1700s in Germany (Pretzsch, 2000), and at the beginning of the 20th Century in the United States of America (USA). Later, the first growth models (i.e., mathematical equations) were developed, and were improved with new available data sets and the fast development of computing power and advance statistics. The period, especially between 1960 and 2000, has been called a revolution in forest growth and yield research (Curtis 2007). Since the 1990s, forest growth modelling has also increased in Europe, and since then several European countries have developed their own growth models. Several types, forms, and levels of resolutions of growth models are available. Current models are able not only to predict stand level variables but also tree-level features.

Growth models offer forest managers a powerful analytical tool to investigate quickly and efficiently, the response of the forest to various management regimes. They allow foresters to determine a regime that should maximize volume or value production, or maximize the production of a particular product. It also enables them to determine the effect of a revised harvest programme to exploit a change in demand. They can investigate effects of many constraints on forest operations, and their effect on yields. But the most powerful feature is the ability of the model to assist managers to make reliable long-term forecasts, so that they can make long term commitments to the capital intensive wood processing industry, secure in the knowledge that the forest will not be over-exploited (Vanclay,1994).

Forest growth and yield models can be developed either for natural stands or plantations. The models for natural stands could be for even-aged and uneven-aged. According to Davis *et al.* (2001), forest growth and yield models can be classified as follows:

i. Whole stand models:

(a) density-free (b) variable-density

ii. Diameter class models

iii. Individual tree models:

(a) distance-dependent (b) distance-independent

These models are reviewed in Chapter 2 (Literature Review).

Globalization put forward the need of quantitative information for management and planning. Reliable quantitative information is required to manage forest lands (Burkhart & Gregoire 1994). In this regard, forest growth models are crucial for not only analyzing forest scenarios at the forest level but also at larger scales (e.g., regions and countries). These scenarios would require precise timber information and, increasingly, other forest ecosystem features (e.g., wildlife habitat, hydrology, and non-timber products) (Salas Eljatib, 2011).

Most developing countries lack standardized quantitative forestry information (Saket 2002, Thuresson 2002, Holmgren *et al.* 2007); on the other hand, in developed countries like the US and Germany, there are well documented historical data sets (Curtis 1995, 2007, Buckman *et al.* 2006 and Pretzsch *et al.* 2007). Furthermore, as climate change has become an important topic for many scientific disciplines, re-engineering of previous growth models or building new ones are needed, in such a way that is appealing to have a model able to handle climate effects in their predictions.

Vanclay (1991a), states that the development of growth models requires data obtained from the remeasurement of permanent sample plots (PSPs). The most reliable and flexible modelling techniques require data in which the individual trees are identified. This requires that all trees on the PSP are permanently tagged and uniquely numbered. Irrespective of the modelling approach, unique numbering and tagging of trees is the only sure way of detecting measurement errors. Growth modelling also requires homogeneous plots, and this means minimising within plot variance: the ability of the PSPs to quantify the present resource is irrelevant. Thus the same plot series cannot be efficiently used for both resource inventory and growth model development.

He also noted, if the growth model is to be used to investigate silvicultural and management alternatives, the data base must include experimental data with paired treatment and control plots, both with adequate isolation. In contrast to continuous forest inventory plots, it is not necessary for PSPs to be representative or numerically proportional to forest type areas, but it is essential that they sample the full range of stand conditions.

1.3 Problems Statement

There are several problem statements in this study in order to develop models for predicting growth of indigenous tropical timber species:

a) The selection of species for afforestation and reforestation with indigenous species became an obvious alternative in improving the productive capacity of such degraded forest. Forestry is characterized by long terms between implementation and result, and most of the Research and Development do not last that long. Hence, a research question in this study would be to develop models that are able to predict the future height and volume, vis-a-vis. The species characteristics information (31 month in field after planted) will be used for predicting future early height and volume performance, thus as a main characteristic for species selection for afforestation and reforestation program.

b) Tropical forests are characterized as a multi-species or mixed species stands. In order to develop model for predicting growth of indigenous timber species, a better model are required. Mixed-effects models are one of the ways for modeling multi-species in our tropical forest. The advantages of employed mixed effect models in tropical forests are to solve the challenges in modeling of multi-species stand such as large number of species, small number of individual per species and almost impossible to run analysis for every species (Wan Razali, 2009).

c) Development of models with more precise, accurate and reduce bias. As noted by Calegario *et al*. (2005), the mixed-effects models approach is a statistical technique that has been used in many fields of study, generating improvements in parameter estimation. Several method will be used in this study in order to choose the best fit models (e.g. AIC, BIC, R^2, RMSE, MAE, residual plot, normality distribution, heteroscedasticity test, etc).

1.4 Limitation of the Study:

a) Based on the development of mixed-effects models in this study, there is a limitation need to be considered here where the data came from early growth trees or sapling trees (31 months after planted). The models indicate a good result for predicting species performance based on height and volume as a method to select species for afforestation and reforestation program. However application of the models coefficient to predict (e.g. height and volume) other trees from this data need to be caution beyond the range of basal diameter. This model cannot represent trees beyond the range of basal diameter in this study.

b) Development of height and volume models herein, there is no validation of the model due to scarcity of data of the five species. For further research, collection of new data is required to test the model prediction accuracy using an independent set of data (validation data).

c) As the height and volume model developed herewith used a limited range of diameter, height and volume, its application beyond the original range of data and outside the range of Bintulu campus, Sarawak needs some tests and validation for the model application.

d) The nature biological of the data in this study is a key factor affect for models development and efficiency, especially for development of local height and volume table. It indicates that development of models using sapling trees are not appropriate and need to be caution when using this model. Based on the results in this study indicate that there is no need for model transformation and the best fitted of mixed effect models for height and volume are still adequate.

1.5 Research Objectives

This thesis concerns development of mixed-effects models for predicting early height growth and timber volume of forest tree species planted in Sarawak. There are two main objectives in this research:

a) To construct mixed-effects models for predicting early height growth of indigenous timber species; and

b) To build mixed-effects models for predicting early volume of such timber species.

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