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Modelling Growth and Yield of Dipterocarp Forests in Central Highlands of Vietnam

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Abstract

Dipterocarp forests in Vietnam are distinct ecosystems with specific characteristics which are different from other forest types such as evergreen forests, semi-deciduous forests and conifer forests. According to inventory results of the Forest Inventory and Planning Institute of Vietnam in 2005, the area of the Dipterocarp forests is approximately 680.000 ha, accounting about 5.4% the total forest area of the country and concentrates mainly in the Central Highlands of Vietnam.

The main objective of this study is to develop a size class model based on systems of differential equations for supporting sustainable management of the Dipterocarp forests in Vietnam. Two data sets collected in the Dipterocarp forest in YokDon National Park were used in this study to construct the growth model and calculate the main stand level characteristics. They include plot group A consisting of twelve one-hectare permanent plots with two measurements of a 5-year growth interval, and plot group B of 21 one fourth hectare plots with a single measurement. For calibrating the growth model, only data set of group A plots was used. In addition to be used to calculate the main stand level parameters, the group B plots will supply reliable data sources to recalibrate the model in the future. The study area was classified into three site quality levels based on mean height of the 20 largest trees in each plot. The measurements on these permanent plots recorded a total of 4,975 trees belonging to 64 species with diameter at breast height (dbh) from 6 cm and above. Based on biological characteristics, trees on these plots were grouped into three species groups: Dipterocarp species, evergreen tall species, and small-sized, lower species. The diameter distribution of the average stands follows the form of negative exponential distribution for all three species groups in accordance with the distribution rule of natural uneven-aged forests. The number of trees per hectare has a tendency to decrease when diameter increases. Stand basal area ranges from 10.15 to 26.9 m^{2}ha^{-1} and the range of basal area increment is between 0.27 and 0.48 m^{2}ha^{-1}yr $^{-1}$. Standing volume ranges from 53.8 to 208.8 m^{3}ha^{-1} and the range of standing volume increment between 1.5 and 3.86 m^{3}ha^{-1}yr $^{-1}$. The number of tree per hectare ranges from 223 to 1156 trees ha^{-}.

The four major components of the growth model are diameter increment, mortality, recruitment and harvesting. The first three models were developed separately for each species group and site quality level. Multiple linear regression, non-linear regression and logistic regression were used to estimate the parameters of diameter increment, recruitment and mortality functions. Significant stand level variables included stand basal area, basal area in larger trees, tree number, site quality, and significant individual-tree level variables were diameter, diameter squared and reciprocal of diameter. Selecting the model equations was based on the following criteria: suitability of biological interpretation and goodness-of-fit statistics. The results indicated that diameter growth level of three species groups on different site quality levels was significantly different with the exception of species group 3 on good and medium site quality. Trees grow more quickly on good sites than on poor ones. However, the effect of site quality on mortality rate was not obvious in this study. These major components were then embedded to the final growth model which is a size class management-oriented model. The model was implemented in the framework of the modelling software Vensim DSS 5.7a. It consists of 76 one-cm diameter classes ranging from 6 to 81cm dbh for three species groups, the last class gathering all trees with diameter above 80.5cm. Time interval for each simulation step of the model was set one year and diameter class width was one cm.

A thorough evaluation of the growth model showed that the models were fitted very well with the empirical data. Simulation results with the models showed that the difference between observed and predicted values of basal areas and tree number distribution by diameter class for a growth period of five years was small. The long-term performances of the simulation proved plausible states of the stand evolution which is consistent with general knowledge of stand growth over long time. This indicates that the model can be applied in practice.

The example applications of the growth model in determining appropriate silvicultural regimes based on the method of scenario analysis. Given the initial condition of the stand, the model estimated the state of the stand after given years with the alternative assumed prescriptions. The simulation results indicated that, with a selection harvesting cycle of 10 years, different initial stand distributions will produce different sustainable yields. The q-factor method was applied to determine the target diameter distributions that produce maximum sustainable yields on three site qualities. The maximum diameters for each species group were selected based on management purpose and diameter growth level as follows: for species group 1 and 2, maximum diameters are 70, 60 and 50 cm for good, medium and poor site quality, respectively. For species group 3, maximum diameter is 35 cm for all site qualities. From the simulation results of the model, the following target distributions have been defined: on good site quality with following parameters: basal area equal to 20 m^2ha^{-1}, q-quotient (slope of the stem number-diameter distribution of 5 cm classes) equal to 1.4, with the sustainable yield of 3.91 $m^3ha^{-1}yr^{-1}$. For medium site quality: basal area equal to 18 m^2ha^{-1}, q-quotient equal to 1.5, sustainable yield of 3.22 $m^3ha^{-1}yr^{-1}$. And on poor site quality: basal area equal to 16 m^2ha^{-1}, q-quotient equal to 1.6, sustainable yield of 2.75 $m^3ha^{-1}yr^{-1}$. In addition, the model was also used to estimate the return time that regulates a given stand towards the target distribution stand for the twelve plots of group A and to assess effect of wildfires on long-term yields of the Dipterocarp forests.

The example applications presented in this study provide valuable information to the forest managers for supporting decision making in sustainable management of Dipterocarp forests. Other applications of the model need to be further explored in specific contexts of the production practice.

Although there were several studies on growth and yield of natural uneven-aged forests in Vietnam before, those studies modeled only important species in the forests and produced yield tables dependent on the age of trees that provide less information for forest management. In comparison to those studies, this growth model was constructed incorporating competition effects as well as mortality and recruitment so that it has the advantage of being able to estimate the growth of forests dynamically and independent on the tree age for long time spans with reliable results.

However, due to the comparably small amount of data available in this study, all data was used to calibrate the model, there was no data set aside for validating the model. So, it is necessary to obtain more data from permanent plots and when it is available the model should be recalibrated in order to expand the geographic research area and achieve more accurate results. Although the growth model in this study was developed for Dipterocarp forests that are uneven-aged, multi-species deciduous forests, the approach can be applied to develop models for other forest types such as evergreen, semi-evergreen forests or plantation forests.

Zusammenfassung

[german] Das Ziel dieser Arbeit ist die Entwicklung eines differentialgleichungsbasierten Durchmesserklassen-Wachstumsmodells für nachhaltige Bewirtschaftung von Dipterocarpaceenwäldern in Vietnam. Die Daten wurden im YokDon Nationalpark erhoben. Das Programm besteht aus vier Modulen zur Abschätzung des Durchmesserzuwachses, der Mortalität, der Verjüngung und einem Durchforstungsmodell. Als Simulationssoftware wurde Vensim DSS 5.7a verwendet. Das Modell wurde eingesetzt, um über Szenarioanalysen geeignete Behandlungsstrategien zu finden.

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Chapter 1

Introduction

1.1 General Introduction

In Vietnam, as in other countries the forestry sector plays an increasing role to the economy, society, ecology and environment. In the past, the ratio of the forest cover was relatively high, up to 43 % in 1944 (Ministry of Agriculture and Rural Development – Vietnam, 2001). However, forests were lost or badly degraded during the time of wars and heavy exploitation in the last decades causing them to decrease to 28 % in 1992. The increasing importance of forests has led the Vietnamese government to issue several policies to regenerate forests. These policies include decreasing the harvesting volume from natural forests and providing forest, forestland allocations on long-term tenure to local people, program of afforestation of 5 million ha, etc. In parallel with these policies, the Government provided investment for state agencies and private enterprises in afforestation and reforestation. These efforts have resulted in an increase in forest cover. According to the forest inventory results of the Forest Inventory and Planning Institute of Vietnam (FIPT) in 2005, the total forestland covers an area of approximately 12.6 million ha, equivalent 38.2% area of the country. The majority of the forested area is natural forest, comprising of 10.2 million ha, equivalent to 81.5%, and the remaining is plantation with an area of 2.3 million ha, equivalent to 18.5%. Forests provide a remarkable amount of timber to the country's economy. At present, the total standing volume of forests in the country is about 811 million m^3, of that natural forests and plantation forests account for 93.4% and 6.4%, respectively (FIPI, 2005). In the period between 2001-2005, these forests provide a timber amount of approximately 11.6 million m^3 each year contributing a significant part in economy of the country.

Dipterocarp forests cover an area of about 680,000 ha. They are mainly located in the Central Highlands (91% of total area) which include the five following provinces: Dak Lak, Dak Nong, Gia Lai, Kon Tum and Lam Dong with a total area of about 5,451,000 ha (the position of the Central Highland in Vietnam is shown in Fig. 1.1). This is the ecological region whose forest cover is highest (54.5%) in comparison to other ecological regions of the country. This region provides a large amount of timber, the total standing volume is about 228.6 million m^3, accounts for 35.2% of the country, the average volumes of rich, average and poor evergreen forests are 247.2, 164.1 and 86.6 m^3ha^{-1}, respectively.

The total standing volume of the Dipterocarp forests is about 56.6 million m^3, the average volumes are 139.8, 113.6 and 73.3 m^3ha^{-1} for rich, average and poor forests, respectively (FIPI, 2005). They are a distinct ecosystem whose structure of species associations is completely different from other forest types. Distributed in areas whose unfavourable conditions such as poor soil, waterlogged in the rainy season, drought in the dry season and frequently impacted by wildfire, trees often grow slowly. The species association is often quite simple. In each stand there are one to three dominant species accounting for the majority in terms of tree numbers (Diep, 1991). According to Sac (1984), Quan *et al.* (1984), Linh *et al.* (1989), Con (1991), the main species associations frequently found in the Dipterocarp forests are:

- *Dipterocarpus tuberculatus, Shorea obtusa*
- *Dipterocarpus tuberculatus, Shorea siamensis, Shorea obtusa*
- *Shorea obtusa, Terminalia alata*
- *Dipterocarpus obtusifolius, Terminalia alata*
- *Shorea siamensis, Xylia dolabrifomis*

The Dipterocarp forests in Vietnam are considered as dry open deciduous forests with dominant species mainly belong to Dipterocarpaceae family (Trung, 1970; Loc, 1985). They are also different from Dipterocarp forests in Southeast Asian countries such as Malaysia, Indonesia that were considered as evergreen tropical moist forests of the lowlands (Cannon *et al.*, 1994; Bertault and Sist, 1997; Ashton *et al.*, 1988; Huth and Ditzer, 2000), the tree species composition of Dipterocarp forests in Vietnam is considerably different from that of Dipterocarp forests in these countries (see Ong and Kleine, 1996; Kessler, 1996; Huth *et al.*, 1998; Sist and Saridan, 1999; Sist *et al.*, 2002). The basal area and volume in these countries are much higher than those in Vietnam. For example in Malaysia stand basal area of Dipterocarp ranges from 26 to 38 m^2ha^{-1} and in Indonesia basal area and standing volume

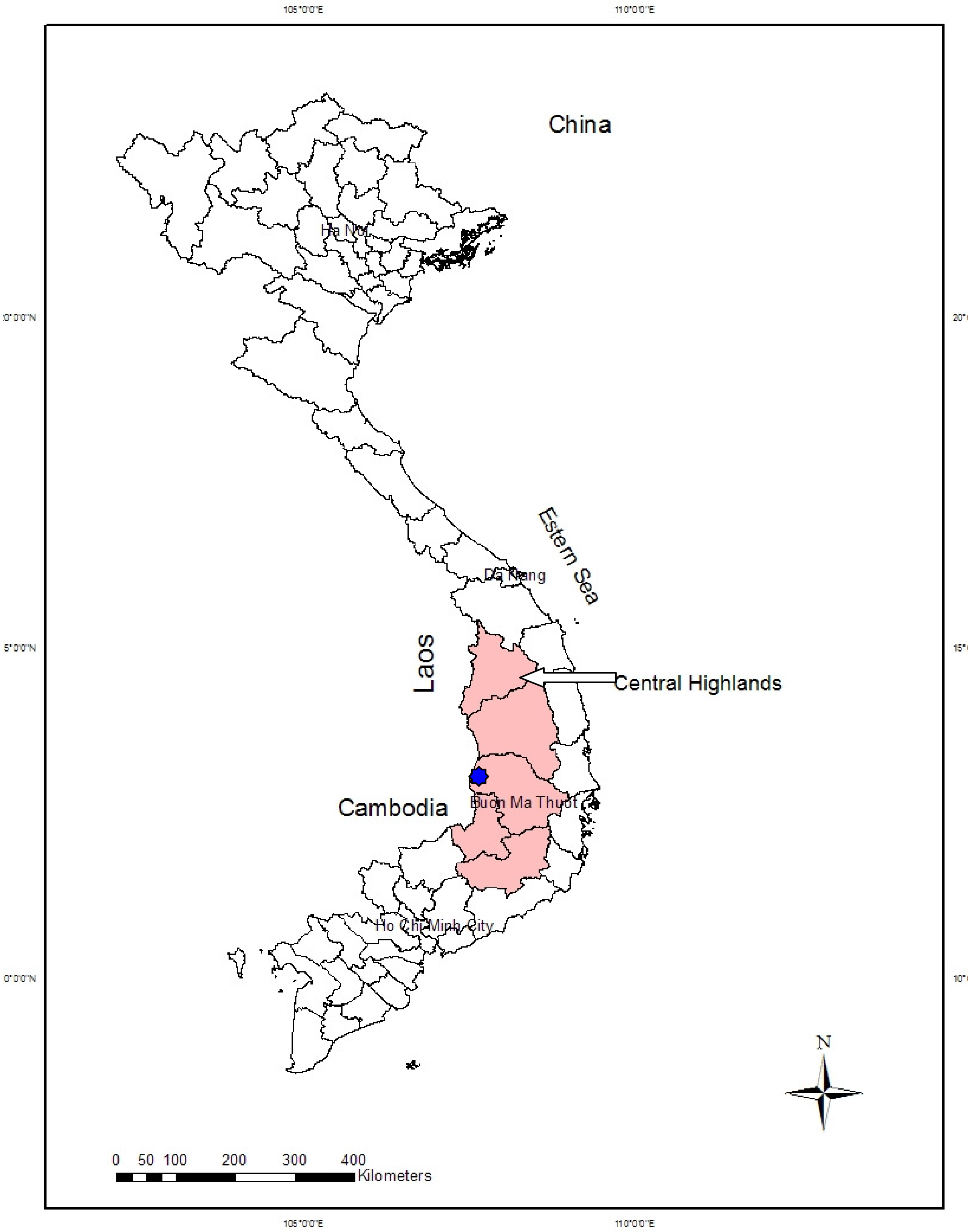

Fig. 1.1 Geographic position of the Central Highlands (coloured) in Vietnam.

✹ The study area position.

are respectively 31.5 m^2ha^{-1} and 402 m^3ha^{-1}. These differences may be attributed that the biological characteristics of the Dipterocarp forest types in Vietnam are different from those of other countries. In addition, the Dipterocarp forests in Vietnam were heavily disturbed in the war time as well as overharvested in the past decades.

Although the area of the Dipterocarp forests does not amount to a very high proportion of the whole forests in the country, they are located on a very important position for socio-economic issues and national defence strategy. They also form an important contribution to the state's economy and generate a remarkable income to the local people who mostly belong to ethnic minorities. The valuable species in the Dipterocarp forests are quite frequent in comparison to other forest types. Several valuable species only occur in the Dipterocarp forests such as: *Shorea obtusa, Shorea siamensis,Terminalia alata, Dipterocarpus tuberculatus, Dipterocarpus obtusifolius*, etc. Therefore, it is necessary to study and use the Dipterocarp forests on a scientific basis.

However, like other forest types in the country, the Dipterocarp forests were heavily disturbed in the past. During a very long time, people were over-optimistic concerning the richness and productivity of the forest resources, leading to an over-cutting in the forests. Besides the overexploitation, under pressure of immigrants from other places coming to the Central Highlands vast areas have been logged or converted to other uses (Sac, 1984; Diep, 1993). In order to deal with that situation, in recent years the Vietnamese government has issued several policies for enhancing forest management including: protection, development, and sustainable effective use of forest resources. Sustainable management has been widely discussed during the last decade as one key strategy for reducing the ongoing depletion and destruction of tropical forests. Different certification systems such as decreasing harvesting quota from natural forests and providing forest and forestry land allocations on long term tenure to farmers have been established to evaluate whether a forest management practice is sustainable. One option that has been proposed towards sustainable management is a transition from state to community forest management. Accordingly, a large area of the Dipterocarp forests and forestlands has been allocated to local people for protection and production. Under forest allocation policies, the forest owners can harvest their forests to enjoy a part of timber products. However, there is still a lack of scientific approaches, mechanism and policy to support communities with sustainable forest planning and benefit sharing from forests (Huy, 2007).

1.2 Research Questions and Objective of the Study

In Vietnam, community forest management was legally recognized in the Law on Forest Protection and Development of 2004 and implementation was guided according to the Decree No. 23/2006/NĐ-CP; however, the matter of how to support the communities to elaborate sustainable forest management plans and to establish a clear, transparent, fair and simple benefit sharing mechanism is an issue that needs to be solved with consideration (Huy, 2007). For making sustainable management plans, forest managers need to know much more about the growth of the forests and how they are affected by alternative management options on the short and the long run.

In this thesis on the dynamics of dry dipterocarp forests in Central Highlands of Vietnam, the following general hypotheses were addressed to serve as guidelines:

- the tree species in the Dipterocarp forests show different levels of growth,
- the growth on stand level varies on different site qualities, and
- the growth level of the stand relates to stand density.

In order to clear these issues, this research addresses to build a multi-species size-class-based growth model depending on stand density and site quality. The growth model will be able to predict stand growth, simulate the growth of trees as they compete, die, and reproduce themselves over time and also simulate the effects of alternative management practices.

One way to assist the continued survival of the tropical forest is to manage it for commercial production of timber and other forest products. Two conditions are essential, but not sufficient for its survival. Firstly, to ensure that harvesting leaves the forest in an ecologically and silviculturally good condition. Secondly, to supplement the resource so that harvesting provides a continuing supply of timber and other benefits (Vanclay, 1991). According to Vanclay, growth models, when combined with inventories, provide a reliable way to examine harvesting options, to determine the sustainable timber yield, and to examine the impacts on other values of the forest. A growth model calibrated from reliable data could be an effective tool for foresters in sustainable forest management planning and decision making. With suitable inventory and other resource data, foresters may use growth model to predict the long-term effect on both the forest and on the future harvests, of a particular silvicultural decision, such as changing the cutting limits for harvesting. With a growth model, they can examine the likely outcomes, formulate prescriptions, guide forest policy and make their decision objectively.

The growth model is implemented in the framework of the modelling software Vensim DSS 5.7a. This software has proven to be a very useful framework in this study as it is a visual modelling tool for conceptualizing, building, simulating, analyzing and optimizing models of complex dynamic systems.

The applicability of the complete growth model is demonstrated in this study by addressing the following questions:

1) What growth and yield can be expected from Dipterocarp forests in the Central Highlands?
2) What forest structure does provide the highest sustainable yield?
3) How long does it take to regulate a disturbed stand towards a given target?
4) What are the impacts of the disturbances including overharvesting and wildfire on growth and yield?

1.3 Outline of the Dissertation

This dissertation consists of 9 chapters. The present chapter provides a general introduction about forests in Vietnam in general as well as about Dipterocarp forests in the Central Highlands of Vietnam in particular. The objectives of the study and research questions are also stated in this chapter.

Literature relevant to the aspects of forest growth and yield studies in general and studies on the Dipterocap forests in Vietnam is reviewed in chapter 2. This chapter also provides a historical classification and development of growth models and after that addresses the model approach applied in this study.

Chapter 3 describes characteristics of the study area: its geographical location, climatic conditions, types of vegetation, the establishment of research plots as an empirical data base for modelling growth and yield in Dipterocarp forests.

Chapter 4 gives a description of the data sets for calculating stand characteristics and calibrating the growth model and a description of the research plots' stand characteristics. This includes an ecological classification of the research plots by species composition, relationships between height and diameter as a basis for classifying site quality and calculating standing volume. Stand variables such as basal area, standing volume, mean height, and mean diameter are shown for highlighting typical stand characteristics of the Dipterocarp forests and study area and making the basis for model evaluation.

The model conception, implementation and its working principle are presented in chapter 5. Furthermore, the major components of the growth model including diameter increment, mortality and recruitment are developed and parameterized in this chapter.

Chapter 6 presents the evaluation of the growth model consisting of the following aspects: evaluation of the model approach itself, validation of the mathematical growth model and evaluation of the growth simulator.

Chapter 7 presents example applications of the growth model including: growth and yield estimates for forest stands, estimating the time needed to regulate a given stand towards a certain target, and evaluating the effects of wildfires on the long-term forest yield.

Chapter 8 discusses the study results in the context of current research, and chapter 9 draws general conclusions from this study. Furthermore, future perspectives for the research line initiated in this study are presented.

Chapter 2

Literature Review

2.1. Studies About Forest Structure and Growth in Vietnam in General

2.1.1 Studies about Forest Growth and Yield

Several studies have been conducted about growth and yield of even-aged plantation forests in Vietnam (e.g. Hien, 1970; Phuong, 1985; Lung, 1987; Muoi, 1987; Nham, 1988; Huy, 1988; Thang and Muoi, 1988; Lam, 1994; Huy, 1995; Phuc, 1996). Their work resulted in yield tables for even-aged pure or mixed stands, which were built-up from a flexible system of functional equations. These functional equations were based on natural growth relationships and generally were constructed by means of statistical methods. These biometric models were usually transferred into computer programs to calculate the expected stand development under given growth conditions for different initial stem numbers, and different site classes. They reflected the stand development for a wide range of management scenarios and they are still being widely used to this day. Recently, Sang (2008) used the process growth model 3-PG (Landsberg and Waring, 1997) to simulate biomass and timber growth of *Acacia mangium* plantations. Empirical data gathered from plantations was used to calibrate and evaluate the applicability of the model. However, in that study the ability of applications of the model in production practice was limited as he used only mean annual increment of the stand (MAI) as objective variable.

Studying forest growth and yield is usually connected with site classification. Often, mathematical functions are used for modelling the relationship between stand height and age to determine site classes. For example, Hung (1985), Lung (1987, 1989) applied the Schumacher function to model height growth of dominant trees in *pinus kesiya* plantations, and used this function as a foundation for site classification. Huy (1988) classified the site quality of *Alniphyllum fortunei* forests using the Gompertz function, Nham (1988) applied the Korf function to classify site quality for *Pinus massoniana* forests. For uneven-aged mixed forests, due to the difficulties in defining the age for stands as well as for individual trees, several scientists proposed to use the height-diameter relationship of a dominant species or a species group instead of the height-age relationship (e.g. Quan *et al*., 1981; Sac, 1984; Phuong, 1985). To demonstrate the suitability of this method, Con (1991), Huy (1993) compared both methods on the same sites. Their results indicated that, for the study areas, the difference between two methods was neglectable, and they concluded that in forest production practice it is possible to use the height-diameter relationship to classify site quality.

Up to now there are still few studies about the growth of natural uneven-aged forests. The difficulty of obtaining empirical data is a major impediment for such works. In Vietnam a system of permanent plots was not available until recently. Therefore, research on growth and yield was primarily based on data obtained by means of stem analysis. This is a time consuming and costly work and the measurement accuracy is not very high. Studies about natural uneven-aged forests mainly concentrated on constructing rules of growth and yield for important tree species. Among others, Phuong (1985), Hinh (1988), Thang and Muoi (1988), Huy (1992, 1993), and Dong (2002) conducted such work. Yield functions such as Gompertz, Korf, Schumacher and Verhulst-Robertson were usually applied to model the development of mean diameter, mean height and volume according to age in a stand. Data for constructing these growth models was obtained from stem analyses and fitted statistically with the support of computer programs. The results of these studies provide valuable information about processes and levels of the growth of different species. However, natural forests compose of many species and the age of the trees is usually difficult to estimate, so these results were only restrictedly applied in forest management practice.

Hinh (1987) applied a method for predicting the dynamics of diameter distributions in uneven-aged mixed forests. This size-class- model like method was based on estimating the mean periodic increment of diameter classes in order to predict growth and yield. However, as the model was not implemented in a computer program, it was only possible to make predictions for short growth intervals. In addition, mortality and recruitment were neglected. Nevertheless, Hinh’s study was as a pioneer approach in modelling growth and yield of Vietnamese natural forests, and some authors have applied it (e.g. Con, 1991). Yet, the difficulty of collecting growth data strongly restricted further research following this farsighted approach.

2.1.2 Studies about Diameter Distribution Rules

The diameter distribution is one of the most important forest structure characteristics. As such, it will play an important role in this work. Quantitative studies about the forest structure factors and construction of standard diameter distribution models in order to serve harvesting and fostering forests have been carried out by several scientists. From the 1970s, several study results related to these issues were released such as Hien (1974) and To (1985), who used the Pearson distribution to formulate distribution curves for tree numbers by diameter class in natural forests. Tuat (1986, 1990, 1991) used distribution functions by Meyer and Poisson to illustrate diameter distribution of secondary natural forests. Huy (1993) simulated the diameter distribution for semi-deciduous forests with the dominant species *Lagerstroemia calyculata* using the theory of distribution functions such as: Poisson, Weibull and Meyer. Nham (1988), Giao (1989) and Con (1991) applied the Weibull distribution to model the diameter distribution of different forest types. Truong (1973, 1983, 1984, 1986) released a series of studies about the method of forest inventory, the three-dimensional structure of uneven-aged mixed natural forests and proposed standard structure models based on mathematical methods. These studies focused on discovering the rules behind the diameter distributions based on the present state of the forests.

From these distribution rules, several scientists (Truong, 1984; Lung, 1987; Phuong, 1987; Huy, 2007) tried to define standard diameter distributions for different forest states and types as a basis for management. Phuong (1987) and Lan (1986, 1992) indicated that the standard structure models should provide a sustainable productivity, and always maintain a plausible diameter distribution. They should lead to populations whose high and stable yields, and protection functions satisfy a given purpose. They agreed that for uneven-aged forests, the standard diameter distribution in equlibrium typically tends towards an inverse J-shaped curve, as described by the negative exponential function (see details in Chapter 5) because this structure maintains transition of enough trees from each diameter class to the next higher one and thus supplies a sustainable yield. Although these works related to the diameter distribution of the forests, they did not reflect the dynamics of the diameter distribution over time, therefore they could not be considered as forest growth studies.

2.2 Studies about Dipterocarp Forests

2.2.1 Studies about the Dipterocarp Forests in the World

Dipterocarp forests are found mainly in the Southeast Asian countries such as Thailand, Laos, Cambodia, Indonesia, Malaysia, Burma and Vietnam. They constitute a dominant and particularly valuable component of the world's tropical forests (Schulte and Schöne, 1996). Aware of the importance of this forest type, there have been several studies carried out since long time ago. The book "Dipterocarp forest ecosystems: towards sustainable management" (Schulte and Schöne [eds.], 1996), with support from the German–Indonesian Governmental Cooperation summarizes typical studies. These studies cover a wide range of different issues including theoretical aspects of ecology and site (Schulte, 1996; Ohta and Syarif, 1996; Malmer, 1996; Kessler, 1996; Margraf and Milan, 1996; Goldammer *et al.*, 1996), decision models for forest management with multiple, possibly conflicting objectives, remote sensing methods for land-use planning, growth and yield simulation, and a combined stand and forest level model (Ong and Kleine, 1996). Reduced impact logging, a very desirable practice all over the world, is discussed in the new context of joint implementation for carbon offsets (Marsh *et al.*, 1996; Moura-Costa, 1996). Rehabilitation and reforestation of the Dipterocarp forest ecosystems (Adjers and Otsamo, 1996; Appanah and Weinland, 1996; Nussbaum and Hoe, 1996; Otsamo *et al.*, 1996). Towards sustainable management (Whyte, 1996; Weidelt, 1996; Sorensen, 1996; Ong *et al.*, 1996).

In 1998, CIFOR (Center for International Forestry Research) published the book "A review of Dipterocarps: Taxonomy, ecology and silviculture" (Appanah and Turnbull [eds.], 1998). The volume covers a wide range of aspects such as biogeography and evolution (Maury-Lechon and Curtet, 1998), conservation of genetic resources of the Dipterocarp forests (Bawa, 1998), seed physiology and seedling ecology (Tompsett and Ashton, 1998), pests and diseases (Elouard, 1998), non-timber forest products from Dipterocarps (Shiva and Jantan, 1998), and management of natural forests (Appanah, 1998).

Forest management practice requires to assess the sustainability of management. Managers need to know about the long-term impact of treatment strategies on the forests. Simulation models are useful tools for estimating this long-term impact based on the state-of-the-art knowledge of tropical forest dynamics. Recently, several studies about growth and yield of the Dipterocarp forests have been published using this approach. In 1997, Kürpick *et al.* studied the influence of logging on a Malaysian Dipterocarp rain forest using a forest gap model. Huth and Ditzer (2000) developed a process-based forest growth model, FORMIX3, describing growth, mortality, recruitment of trees and competition between trees of lowland Dipterocarp forest in Malaysia. In 2001, Huth and Ditzer used the same model to investigate the long-term impacts of different logging scenarios for an initially undisturbed Dipterocarp forest at Deramakot, Malaysia. Köhler *et al.* (2001) used data from permanent plots in Sabah, Malaysia, to develop a new version of the individual-based growth model FORMIND. In 2004 Köhler and Huth used FORMIND to simulate the growth dynamics of Dipterocarp rain forests in North Borneo, Malaysia, threatened by recruitment shortage and tree harvesting. Sist *et al.* (2002) built a matrix growth model to predict the sustainable cutting cycle in the relation with the extraction and damage rates for Dipterocarp forest in East Borneo, Indonesia. Recently, Huth and Tietjen (2007) developed and used two ecological forest models, namely FORMIX3 and FORREG, to analyze the impact of logging on lowland Dipterocarp rain forests in Malaysia and to discuss needs for problems of an economic extension of these models.

The modelling studies cited above form an important background about the growth characteristics of Dipterocarp forests for the growth model developed in this study.

2.2.2 Studies about the Dipterocarp Forests in Vietnam

In comparison to other forest types such as evergreen, semi-deciduous and conifer forests, studies on the Dipterocarp forests in Vietnam are relatively sparse, especially those of growth and yield. However, they cover a wide range of different aspects including botany, soil, climate, forest structure and growth. The main results can be summarized as follows:

Geographic distribution of the Dipterocarp forests in Vietnam

This was provided in the study results of Con (1991), Linh *et al.* (1988), Diep (1990), Sam (1986), Ty (1988). These authors indicated that the range of distribution of the Dipterocarp forests is mainly located in provinces belonging to the Central Highlands of Vietnam from Dakglei (Kon Tum province) to Lang Hanh (Lam Dong province), from eastern Truong Son mountain range to the border between Vietnam, Laos and Cambodia. However, they are mostly found in Dak Lak and the south Gia Lai provinces where the altitudes vary between 150 to 800 m. The maximum altitude for most Dipterocarp forests is 1,000 m on flat terrain: at the altitude of 1,300 m, there are mixed stands *of Dipterocarpus obtusifolius* and *Pinus* species.

Climate

Investigations about climate conditions for Dipterocarp forests were presented in several studies (Loc, 1985; Linh *et al.*, 1988; Diep, 1990). They showed that the

Dipterocarp forests in Vietnam are usually found in the tropical monsoon areas with a total solar radiation between 120 and 140 kcal/year, which is equally distributed throughout the year causing high temperatures (average 23-24^{0}C). The annual precipitation ranges between 1,200 and 1,600 mm/year and concentrates in the rainy season (from April to October). The average atmosphere humidity is 70%. The main climatic characteristics of the Dipterocarp forests are drought in the dry season (from November to March) and waterlogged conditions in the rainy season. Through the special characteristics of climate, some authors attributed that water regime may be a decisive factor to form the Dipterocarp forests in Vietnam.

Soils

Important contributions about soils in Vietnamese Dipterocarp forests came from Thai (1981), Pho (1985), Sam (1986), Ty (1988), and Linh *et al.* (1988). About soil characteristics in the forests, according to their study results, the Dipterocarp forests are mainly found on the poor soil types such as gray soil, stone and gravel soil, black basalt soil, and sometime alluvial soil created along river sides and stream sides. A typical feature of the Dipterocarp forests is that they are often water-logged in the rainy season and drought in the dry season. Therefore, when researching on the soils of the Dipterocarp forests, these authors usually classified Dipterocarp soils into different topographies such as well-draining topographies including hills, low slope and highland areas and water-logged topographies in the rainy season.

Regeneration in Dipterocarp forests

Significant studies in this field (Binh, 1982; Boi and Quyen, 1982; Sac, 1984; Sanh, 1985; Diep, 1989, 1990) usually investigated regeneration starting from the flowering process and the formation of seedlings. They indicated that the seed resources in Dipterocarp forests were plentiful and the season of seed dispersion often occurs at the beginning of the rainy season when the conditions are favorable for germination, so the seed production of the different species was always sufficient. According to Diep (1991) almost all trees with diameter larger than 20 cm can provide seeds, the maximum quantity of seeds is supplied by the trees with diameter from 40 to 60 cm and for the trees larger than 80 cm of diameter, they produce fewer seeds. When studying about the regeneration, these authors usually incorporated to research on wildfire. They indicated that wildfires are the main reason causing the death of the majority of regeneration trees.

A typical characteristic of the Dipterocarp forests in Vietnam is that wildfires often occur in the dry season. They often originate from unconcerned activities of the local people and are associated with natural conditions such as: dry season is often long from

November to May, the grass covers strongly develop throughout the forests in the rainy season and they become very dry in the dry season. Together with fallen leaves they create a thick layer of inflammable materials. A study on the permanent experimental plots in the Dipterocarp forests conducted by Diep (1991) during a period of three years indicated that if there were no wildfires, the total of regeneration trees lower than 2 m was 9,040 trees per ha, among that there were 750 good quality trees accounting for 8.3%. If wildfire occurred in one year the total of regeneration was 5,000 trees per ha and the potential trees were 150 trees, accounting for 3%. If the wildfire occurred every year the total of regeneration was 3,400 trees per ha and there were no potential trees.

The flora of the Dipterocarp forests and ecological classification of by species composition

Dipterocarp forests are distinctive ecosystems, and are as such considerably different from other forest types. Therefore, their flora was studied by several researchers (Boi and Quynh, 1981; Loc, 1985; Loc and Hiep, 1987; Quynh *et al.,* 1987; Ly, 2006; Dung, 2008). These studies focused on describing the flora composition and the biological relationship between tree species in the Dipterocarp forests. They showed that there are four important species occurring only in the Vietnamese Dipterocarp forests: *Dipterocarpus tuberculatus, Dipterocarpus obtusifolius, Shorea siamensis* and *Shorea obtusa*. All these species belong to the *Dipterocarpaceae* family. They account for high proportions and create different main species associations, according to the study results of Con (1991), these species account from 30 to 100% of the total tree number.

Other typical species, partly from the Dipterocarpaceae family, have to be mentioned even though they occur less frequently: *Simdora chochinchinenensis, Dalbergia bariensis, Terminalia sp*, *Xylia dolabriformis, Parinari annamensis, Pterocarpus pedatus, Vitex sumatrana, Ceiba pentandra, Irvigia malayana,* etc. In the low layer the following species are frequently found: *Lumnitzera coccinea, Strychnos nuxblanda, Phyllanthus emblica, Bauhinia purpurea, Morinda citrifolia, Ziziphus oenoplia,* etc.

On the ground the grass coverage is well developed with the main species as: *Imperata cylindrica, Arundinaria pusilla, Arundinella setosa.* This grass layer is often less than one meter high. Some types of small bamboo (*Oxytenam Spp*) are sometimes found as bushes near streams (Diep, 1993).

Several classification schemes have been developed for Dipterocarp forests in Central Highland of Vietnam. Linh (1988) classified Dipterocarp forests by tree associations based on some ecological conditions such as: drainage condition in the rainy season, soil and topography. He divided Dipterocarp forests into four ecological groups as follows:

- Group 1: distributed on sunken sites, often water-logged in the rainy season but desiccated in the dry season. The main species found are: *Terminalia alata, Shorea siamensis, Shorea obtuse.* Growth and yield of the forest are very weak because of the main reason of long drainage condition. According to Sac (1984), the average standing volume increment of this type of forest is very low, about 0.7 m^3 per year per ha.

- Group 2: distributed on flat topography sites, often water-logged in rainy seasons. Main species found are: *Dipterocarpus tuberculatus, Terminalia alata, Shorea obtusa.* Growth and yield of the forest are weak and medium because of main reason as drainage condition and thin layer of soil.

- Group 3: this is the main group, accounting for more than 50% area, distributed on gentle slopes and flat topography sites, thick layers of well-drained soil and. The main species found are: *Dipterocarpus tuberculatus, Dipterocarpus obtusifolius, Terminalia alata, Shorea siamensis.* Growth and yield of the forest are good. The depth of soil layer is the main factor effecting growth and yield of the forest.

- Group 4: account for small areas only, distributed on moderate slopes, thin layers of mostly poor soils. The main species are: *Terminalia alata, Shorea siamensis, Shorea obtusa.* Growth and yield of the forest are weak and medium. The depth of soil layer is the main factor effecting growth and yield of the forest.

Con (1991) and Diep (1993) classified different tree associations based on dominant species. They showed that there is a relationship between species composition and site conditions. According to this relationship, Con grouped Dipterocarp forests in to five main associations based on dominant species as follows: association of *Dipterocarpus tuberculatus,* association of *Dipterocarpus obtusifolius,* association of *Terminalia alata,* association of *Shorea siamensis,* and association of *Shorea obtusa.*

Studies about forest structure, growth and yield

Like for other forest types, studies about diameter distribution, growth and yield of Dipterocarp forests in Vietnam are up to now very sparse. A short summary of typical research works in Dipterocarp forests is listed below:

Sac (1984) showed that on the same site condition, the dominant species grow with a quite similar level. As the Dipterocarp forests are distributed on a wide range of site conditions, he proposed to classify their site quality into four levels according to the relationship between mean height and diameter using a base diameter of 36 cm:

- site quality 1: at diameter of 36 cm, mean height is more than 20 m,
- site quality 2: at diameter of 36 cm, mean height is between 17 and 20 m,

- site quality 3: at diameter of 36 cm, mean height is between 14 and 17 m, and
- site quality 4: at diameter of 36 cm, mean height is below 14 m.

For natural mixed forests, it is difficult to identify the age of the stand, therefore his method of site quality classification is practical and widely applied in production practice.

About the tree quality in Dipterocarp forests, Sac's results indicated that the proportion of hollow trees changes with site quality and diameter class. The proportion of the hollow trees increases when diameter increases, on the areas of good site quality the form of trees is straighter, and the proportion of hollow trees is lower on good compared to bad site qualities. This proportion is also different among species, in decreasing order: *Shorea obtuse, Dipterocarpus tuberculatus, Shorea siamensis, Dipterocarpus obtusifolius.*

In addition to his work about diameter distributions as mentioned in 2.1.1, Con (1991) developed growth functions of diameter, height and volume for the mean individual tree according to age for each site quality.

Using the same method that Hinh (1987) applied as mentioned before, he estimated the dynamics of tree number by diameter class and calculated the growth and yield of the stand for a growth interval of 10 years.

Dong studied Dipterocarp forests in Vietnam from 1980 to 2000. A series of his results was published in the book "Broad-leaf deciduous forests and sustainable management in South Vietnam" (Dong, 2002), especially the study results about stand structure rules, growth and yield of individual tree species of *Shorea obtusa* and the growth and yield of stands with dominant species of *Shorea obtusa*. He used the Pearson distribution function to model the rules of distribution of tree number by age classes. Each age class is 10 years and the stands were grouped into two generations: the first is 10 – 70 years of age and the second is 60 – 120 years of age. About the growth of mean individual tree, he established yield models of height, diameter and volume. Data from stem analysis were fitted using mathematical functions, the yield function of height was then used to classify forest stands into five site classes. The yield of height, diameter and volume of mean tree of the stands was estimated according to the five site classes. The range of heights of average trees between worst and best site class is from 12 to 30 m, for that of diameter is from 20 to 42 cm at the age of 100 years.

The study results of the scientists cited above have provided plenty of important information about various aspects relevant to this study, such as forest structure, ecological characteristics, site conditions, and especially about growth and yield of the most important dominant species in natural uneven-aged forests in Vietnam. For Dipterocarp forests, there have been relatively complete studies about defining distribution areas, describing species associations, classifying soils and vegetation. However, for natural mixed uneven-aged forests in general and Dipterocarp forests in particular, the previous growth studies only focused on individual trees, and almost all studies constrained on modelling the average tree values of variables as height, diameter and volume depending only on tree age on different site classes. The competition factors that directly affect an individual's growth were not quantitatively accounted for. In addition, as mentioned above, in natural forests the age of trees and forests is difficult to define and find out in practice. In Vietnam the systematic establishment of permanent research plots began just a few years ago, and their quantity is still limited. On such plots, tree age is measured by means of stem analysis.

None of the cited studies has modeled the growth process of natural forest stands as a whole in which trees belong to different size and age classes and where they interact by means of competition followed by natural mortality and self-regulation of density. Therefore, the applications of such study results in forest management practice are limited. Studying natural uneven-aged forests' growth for forest management practice requires to reflect the growth of whole stand in the relationship of both the growth and competition factors. This way, studies would supply not only the growth characteristics of individual species or a species group, but also the growth and yield of an entire stand. Such an approach will satisfy requirements in practice of forest management and will supply information needed for supporting managers in decision making. It calls for developing dynamic growth and yield simulation models.

To this day, in Vietnam the forest growth models have been developed in form of yield tables for only even-aged plantation forests. Data for establishing these models was mainly obtained by means of stem analysis. Up to the present day, there are no dynamic growth models for natural uneven-aged forests. Therefore, there is an urgent need to develop growth models for uneven-aged, mixed forests that are suitable to the actual situation of forest production, and satisfy the requirements of sustainable forest management. Only recently, a net of permanent plots was established in different forest types throughout the country by the Forest Inventory and Planning Institute (FIPI) and they are re-measured every five years. The inventories will provide a data base for various studies. This study aims to build such a model for the Dipterocarp forests in Vietnam's Central Highlands. Internationally growth models for even-aged or uneven-aged, pure or mixed forests have been developed for a long time. Starting from simple whole stand models one-and-a-half century ago they evolved to sophisticated models such as hybrid, individual-based models developed recently. Before presenting the model approach followed in this study, a historical overview of forest growth model development in the world will be given in the section below.

2.3 Historical Development and Classification of Forest Growth and Yield Models

Growth and yield modeling has a long history in forestry. According to Vanclay (1994) the first modern, but rather simplistic form of plantation yield table was developed in Germany in 1787. These yield tables were based on normal stands that were neither understocked nor overstocked, and the data were tabulated and summarised to develop a series of alignment charts that were subsequently used to estimate the anticipated volume from forest stands using age and stand productivity. From that time, there are a lot of growth models developed in order to satisfy different purposes of forest management. Models of forest growth, from the initial sketched diagrams to sophisticated computer models, have been and still are important forest management tools. Four major developments affected the forest growth modelling in the past century: (1) the silvicultural focus moving from even-aged monospecific stands towards mixedspecies stands; (2) the growing interest in incorporating causal relationships in models; (3) the changing goals of forest management (not only focusing on growth and yield); and (4) the increasing availability of computers. Therefore, the history of forest growth models can not be simply characterized by the development of continuously improved models replacing former inferior ones. Instead, different model types with diverse objectives and concepts were developed simultaneously (Pretzsch, 2001; Poté and Bartelink, 2002). Several scientists (Pretzsch 1999, 2007; Pretzsch *et al.*, 2008; Vanclay, 1994; Poté and Bartelink, 2002; Monserud, 2003; Peng 2000), etc. generalized the classification and the history of development of growth models systematically. Recently, Pretzsch (2009) provided a detailed overview of the history of model development. In this section, we present the classification of the growth and yield models based on the concept and development history provided by Pretzsch.

2.3.1 Stand Growth Models Based on Mean Stand Variables

A yield table presents the anticipated yields from a even-aged stand at various time, and is one of the oldest approaches to yield estimation. The first yield tables were published in Germany in 1787, and within a hundred years over a thousand yield tables had been published Vanclay (1984). Based on the development history of the yield tables, Pretzsch (2001) identified four generations as follows: the first generation of yield tables were developed from the late eighteenth to the middle nineteenth century by German scientists such as Paulsen (1795), Von Cotta (1821), Hundeshagen (1825), Hartig (1847), Heyer

(1852), and Judeich (1871). These yield tables were based on a restricted dataset soon revealed great gaps in scientific knowledge.

The second generation of yield tables, from the end of the nineteenth century and continued into the 1950s. The list of protagonists involved in this work includes Weise (1880), Grundner (1913), Krenn (1946), Vanselow (1951), Zimmerle (1952) and, in particular, Schwappach (1893), and Wiedemann (1932) who designed yield tables that were conceptually related and is still being used to this day.

The third generation of yield tables with their core is a flexible system of functional equations. These equations are generally parameterized by means of statistical methods. The biometric models are usually transferred into computer programs and predict expected stand development for different spectra of yield and site classes. These models were designed by, among others, Assmann and Franz (1963), Vuokila (1966), Schmidt (1971) and Lembcke *et al*. (1975).

Since the 1960s a fourth generation of yield table models has been created, e.g. the stand growth simulators by Franz (1968), Hradetzky (1972), Hoyer (1975), Bruce *et al.* (1977), and Curtis *et al.* (1981, 1982), which estimate expected stand development under given growth conditions for different stem numbers at stand establishment and for different tending regimes.

While the information yield tables supply is good and sufficient for even-aged mono-specific stands, it is too general and simplified to be of much use in mixed-species uneven-aged forests (Vanclay 1989).

2.3.2 Stem Number Frequency Models

These models were also called size class models, they use stand or tree structures such as diameters, where a given diameter width is used to categorise diameter classes, each of which is usually represented by the mean diameter value of the class in the model. The size class approach is a compromise between whole stand models and single tree models. When the width is infinitely large that all trees are considered in one class, this is a whole stand model and when the class widths are infinitely small that each tree is given a class of its own it becomes a single tree model. Size class models are noted for their high resolution and flexibility with regards to management planning for uneven-aged mixed-species forests. They can perform short-term growth projections using conventional inventory plot data to generate density-based stand yield tables that can be used to evaluate stem diameter distribution in a wide range of silvicultural treatments (Vanclay 1989).

Stand table projection is one of the oldest techniques used to determine the future composition of uneven-aged forests. The method predicts the future stand table from the present stand table by adjusting each entry in the table with the estimated diameter increment (and mortality). Diameter increment estimates may be obtained from several sources, ranging from guesses and simple tabular summaries to regression analyses, depending on the nature of the data available. The method dates from times when data were few and computations difficult, and several researchers offered simple formulae for estimating *upgrowth* from summarized plot data (e.g. Wahlenberg, 1941; Chapman, 1942; Husch *et al.,* 1982;). Now computers have eased the burden of computation, stand tables may be updated with increment equations prepared using regression analyses (Vanclay 1994). A stand table is a tabular summary showing the number of trees in each of several size classes. In mixed stands, there may be rows for each species or species group. Size classes are usually diameter classes of equal width. These tables are commonly used to summarize inventory data, and provide the basis for several popular growth models for mixed forests. In 1974, Ek used the stand table projection method and his model was widely applied in uneven-aged stands.

Poté and Bartelink (2002) differentiated the concept between matrix models and Markov chain models. According to them, there is a confusing classification between these two model types. Several researchers (Buongiorno and Michie, 1980; Solomon *et al.,* 1986; Buongiorno *et al*., 1995; Ingram and Buongiorno, 1996; Lin and Buongiorno, 1997; Favrichon, 1998; Kolbe *et al*., 1999) use the word matrix models to indicate those models that describe the distribution of all trees of a stand over different diameter classes through the fractions of tree numbers per class that will grow up to the next class within one time step. These fractions, often referred to as probabilities, are summarised in a matrix. Matrix models are deterministic models because repeated experiments will result in identical outcomes. Markov chain models, on the other hand, are generally presented as stochastic models (Waggoner and Stephens, 1970; Usher, 1979; Binkley, 1980). The change from one state of the forest to another during a given time is not modeled using a constant fraction, but is a probability. This method permits including variability in the prediction meaning that when coming from a state *j*, the estimated growth can differ from the expected growth. Nevertheless, Markov models used in forest dynamics modelling use fractions rather than probabilities (Bruner and Moser, 1973; Miles *et al*., 1985; Acevedo *et al.,* 1996).

In the mid 1960s, Cluster and Bennett (1965) developed another approach for modeling stand development with frequency distributions. They characterized the stand by its diameter and height distributions, and modeled the stand development as a periodic progression of these frequency distributions. The accuracy of such models is primarily determined by the flexibility of the type of distribution. Distributions often applied were beta, gamma, log normal, and Weibull. The Weibull distribution has proved the most useful distribution due to its adaptability to different diameter and height distribution (Pretzsch, 2009). Models of this type were initially constructed by Clutter and Bennett (1965) for

North American spruce stands and further developed by McGee and DellaBianca (1967), Bailey (1973), Moser (1976) and Feduccia *et al.* (1979).

In the 1960s and 1970s, Buckman (1961), Clutter (1963), Leary (1970), Moser (1972, 1974) and Pienaar, Turnbull (1973), Ek (1974) developed stand-orientated growth models based on differential equation systems. These models predict the change of stem number, basal area and growing stock within a given diameter class dependent on initial stand characteristics. Development of the growth and yield characteristics within the diameter classes results from numerical integration of differential equations. Models of this type have proven a high suitability for modelling growth and yield of uneven-aged forests and they have been consistently developed further by Leak and Graber (1976), Leary et al. (1979), Campbell et al. (1979), Murphy and Farrar (1982), Howard and Valerio (1992), McTague and Stansfield (1994), Alder (1996), Lin *et al.* (1996, 1998), Moser (1986), Favrichon (1998), etc.

2.3.3 Single-Tree Orientated Management Models

Single tree models simulate each individual tree in a stand as a basic unit with respect to establishment, growth and mortality, and sum the resulting individual tree estimates to produce stand level values. Compared with stand-orientated growth models based on mean stand descriptors and those predicting stem number frequencies, single-tree models work on higher resolution. Single tree models can be further classified into distance independent, where tree spatial locations are not required (e.g., Wykoff *et al.*, 1982; Wensel and Koehler, 1985; Sterba *et al.*, 1995; Sterba and Monserud, 1997) and distance dependent models, where inter-tree spatial locations are required (e.g., Ek and Monserud, 1974 Hasenauer *et al.*, 1994, Pretzsch *et al.* 2002).

According to Pretzsch *et al.* (2008), the first individual-tree model was developed for pure Douglas fir stands by Newnham (1964). It was followed by models for pure stands by Bella (1970), Arney (1972) and Mitchell (1969, 1975). In the mid 1970s, Ek and Monserud applied the same construction principles to uneven-aged pure and mixed stands. The worldwide bibliography of single-tree growth models compiled by Ek and Dudek (1980) lists more than 40 different single-tree models, which are grouped into 20 distance-dependent and 20 distance-independent models. Single-tree models developed since the 1980s (Wykoff *et al.*, 1982; Wensel and Koehler, 1985; Pretzsch, 1992, 1998, 1999; 1995; Nagel, 1996; Pretzsch *et al.*, 2002) in many ways go back to the methodological bases of their predecessors. Only recently has this kind of model been applied in forestry practice for management planning in pure and mixed stands (Pukkala, 1987; 1995; Pretzsch, 2003; Pretzsch *et al.,* 2006).

2.3.4 Gap and Hybrid Models

Gap models imply that forest development in a gap occurs in a fixed cycle: a gap results from exploitation or death of a dominant tree, and thus the growth conditions of understorey trees improve and natural regeneration occurs. Growing trees successively close the gap and a new overstorey develops. The cycle is repeated with further losses of dominant trees. Growth models using this approach were predominantly employed for investigations of competition and succession in semi-natural stands (Pretzsch *et al.,* 2008). In contrast to the models already discussed that calculate potential growth from site conditions and derive individual development from competition, gap models incorporate explicit representation of key ecological processes including establishment, tree growth, competition, death, and nutrient cycling.

According to Peng (2000), gap models were eventually derived from the parental models of JABOWA (Botkin *et al.,* 1972) and FORET (Shugart and West, 1977; Shugart, 1984). They have similar rationale and basic structure. More recently, a number of different forest gap models has been used to evaluate forest sustainability and the effect of harvesting regimes (Aber *et al.*, 1982; Botkin, 1993; Pausas and Austin, 1998), to analyze wildlife habitats and biodiversity (Botkin *et al.*, 1991; Pausas *et al.*, 1997), and to simulate potential effect of climate change on tree species composition (Pastor and Post, 1988; Overpeck *et al.*, 1990; Solomon and Bartlein, 1992; Prentice *et al.*, 1993; Price and Apps, 1996; Shugart and Smith, 1996) and ecosystem structure and function (Pastor and Post, 1986; Smith and Urban, 1988; Friend *et al.*, 1993; Bugmann and Solomon, 1995; Jiang *et al.*, 1999; Price *et al.*, 1999).

The transfer of specific eco-physiological process knowledge to stand or single tree management models that are evaluated with long-term growth measurements results in so-called hybrid growth models (Kimmins, 1993). Their intention is to combine plausible responses to new combinations of environmental conditions with reliable growth estimations suitable to assist forest planning and management. Models of this type were constructed by, among others, Botkin *et al.* (1972) and Kimmins (1993). Only very recently have models created by Pukkala (1987), Pretzsch (1992) and Pretzsch *et al.* (2002) found use in forestry practice for planning work in pure and mixed stands. These are in effect site-sensitive single-tree models constructed from a broad based of ecophysiological and growth and yield data.

2.3.5 Matter Balance Models

Matter balance models focus on describing a key ecosystem process or simulating the dependence of growth on a number of interacting processes, such as photosynthesis, respiration, decomposition, and nutrient cycling. They are therefore also known as biogeochemical or process-based models. A number of process-based growth and yield models have been developed to help predict forest growth and yield under changing conditions (e.g. West, 1987; Dixon *et al.*, 1990; Amateis, 1994; Mohren *et al.*, 1994; Landsberg *et al.*, 2001, 2003; Matala *et al.,* 2003).

While photosynthesis and respiration processes are well understood and documented, the biophysical processes are rather poorly understood, particularly in complex ecosystems such as the rainforests. Photosynthesis is generally regarded as the principal plant physiological process, and data used for this kind of modelling usually describe growth based on daily, monthly or seasonal time steps, using parameters (such as biomass per unit area) derived from specialised sampling, and not conventional inventory data (Landsberg and Gower, 1997; Alder, 1995). In this respect, process based models tend to lack an accurate description of forest tree and stand structure. Although they attempt to identify the cause and explain the changing phenomenon, these mechanistic models are often found lacking in precision and scope with respect to practical forestry (Kimmins, 1988).

The application of process-based forest productivity models in forest management was recently reviewed by Battaglia and Sands (1998). They conclude that a change in the questions being asked in forest management, for example in relation to sustainability, biodiversity, and climate change, has increased the potential use of mechanistic process models. However, there are particular constraints in developing and applying process models due to considerable gaps in our knowledge of part processes in assimilation organs and in the soil. Process-based models will need to be at least as accurate as empirical models across the decade to rotation length time periods commonly considered in forest management.

2.3.6 Landscape Models

Landscape models comprise a broad class of spatially explicit models that incorporate heterogeneity in site conditions, neighbouring interactions and potential feedbacks between different spatial processes. However, they differ widely in how detailed forest structure and matter fluxes are represented, and which interactions between spatial processes are taken into account. In a management context, the role of these models is to assess potential effects of environmental change (climate, deposition, land-use changes) on landscape-scale sustainability of forest functions (resources, protection, socioeconomic). This knowledge is useful to inform responsible decision-making that aims to influence the course of environmental change. On the other hand, it can guide direct management that aims to broaden the range of environmental conditions under which ecosystems services can be sustained (Pretzsch *et al.*, 2008).

According to Pretzsch *et al.*, the landscape models presents following important areas of the application:

The first important area of the landscape models is to analyse the relationship between landscape forest structure and regionally distributed risks such as fire, windthrow, insect diseases, mass movement, air quality, water quality, etc. Typical models for these areas are, among others, those developed by Schaab *et al.* (2000), Mouillot *et al.* (2001, 2002), Matjicek *et al.* (2003), Ancelin *et al.* (2004), Parra *et al.* (2004), Sturtevant *et al.* (2004), Kulakowski *et al.* (2006), Zeng *et al.* (2007).

The second application of landscape models is assessments of effects of regional-scale matter fluxes, e.g. water, carbon and nutrients on specific ecosystem properties such as forest growth (e.g. Lasch *et al.,* 2002; Nuutinen *et al.,* 2006), species change (e.g. Hickler *et al.,* 2004), carbon budgets (e.g. Song and Woodcock, 2003) or changes in the water balance of catchments (e.g. Baron *et al.*, 2000; Wattenbach *et al.*, 2005).

Other applications are more specific areas of investigation such as soil acidification (Alveteg, 2004) or nitrogen emissions (Kesik *et al.,* 2005, 2006), air pollution issues such as ozone concentration, which depends on the emission of biogenic carbohydrates in rural areas. The particular importance of ozone episodes has already been shown (e.g. Derognat *et al.,* 2003; Solmon *et al.*, 2004).

Overall, current developments clearly point in the direction of models that describe growth and regeneration of individual trees or tree cohorts on the basis of physiological processes that are linked to the water and nutrient balances of the particular sites. Such models are sensitive to environmental changes as well as different kinds of disturbances, and can be used for planning short- and long-term corridors of forest management.

2.3.7 Selection of the Model Approach to be used in This Study

As there are several types of growth models, choosing a suitable model approach for this study is a very important issue. The following criteria were applied:

- The model must provide detailed information about the tree dimensions (and their development).
- It must be usable with data available in practice.
- It must be sufficiently flexible in terms of stand management.
- It must be possible to calibrate the model with data from standard research plots.
- The model concept should be easily extendable and it should be generic (flexible to a broad range of forest types).

In order to have chances to be used in practice, the model must be complicated enough to provide the information needed, thus, it must sufficiently cover the feedback between stand structure and tree growth. It also must be simple enough to fit the information flow of forest practice.

From the criteria defined above, we choose a stem number frequency model or a size class model dependent on differential equations for predicting the growth and yield of the Dipterocarp forest in Central Highland of Vietnam. This model approach fits the tradeoff between complexity and simplicity best. According to Pretzsch *et al.* (2002), the development of forest growth models based on stand-level, diameter class and individual-tree models is a response to changing management objectives. It is also a response to changes in the availability, the needs and the flow of information in forestry practice. Yield tables were well adapted to the state of information in forestry practice at the time they were first established as they were based on available data on tree species, age, height and stocking density. Today, forestry practice expects prediction instruments to provide more than just a statement on the assumed stand development under standardized stand treatment regimes as is the case with yield tables. When comprehensive stand and site data exist as a result of forest inventories, they may be used for constructing the new generation of growth models to achieve better and more relevant predictions. Apart from tree and stand attributes such as growth, assortment yield and financial characteristics, other structural, economic and socio-economic variables become increasingly important, which should be taken into account in forest growth simulation in the future.

In Vietnam, only recently a system of permanent experimental plots has been established. Thus, the information obtained from these plots is to be considered preliminary. However, this information is suitable to construct a growth model of the selected type. As Pretzsch (2001) stated, with the shift from stand and tree management models with low resolution to more complex ecophysiological models, different source data are needed for model construction and for the determination of model parameters. Standard datasets derived from research plots (diameter, height, etc.) were used for the development of stand growth models for applied forestry. For the construction of single-tree models, additional data are required (crown dimension, tree position, etc.). The transition to ecophysiological models requires an additional database that can only be provided by broadening experimental concepts and cooperation with neighboring disciplines.

A detailed description about the structure and working principle of the selected type of growth model will be presented in Chapter 5.

Chapter 3

Study Area and Establishment of Research Plots

3.1 General Information about the Study Area

The study area belongs to the YokDon National Park. This sanctuary was established in 1991 and at that time it had an area of 58,200 ha, of which 56,192 ha was forest, accounting for 96.5% of the total area. The Park was divided into three functional zones: a strictly protected zone (40,638 ha), an ecosystem rehabilitation zone (13,579 ha), and a service and administration zone (3,983 ha).

In order to meet the requirements of biodiversity conservation and Park development, in 2002 the government expanded the park's area up to 115,545 ha, including 80,947 ha in the strictly protected zone; 30,246 ha in the ecosystem rehabilitation zone; and 4,172 ha in the service and administration zone, making it one of the most largest National Parks in Vietnam.

3.1.1 Geographic Position and Boundary of the YokDon National Park

The Park is located in the Dak Lak province, and there, its area is mainly in the Buon Don district. A small part lies in the Easup and the Cu Jut district. It is in the west and about 40 km away from Buon Ma Thuot city. The geographic coordinates are between $12^{o}45'$ and$13^{o}10'$ north, $107^{o}29'30''$ and$107^{o}48'30''$ east (Fig. 3.1).

To the north, a part of the Park belongs to the Easup district. To the south, it is adjacent to the Cu Jut district. To the east, it is in the Buon Don district and to the west is the border of Vietnam and Cambodia with a length of about 100 km.

The park lies in the area of four communes belonging to three districts, which are Krong Na (including two state forest enterprises: Buon Don and Drang Phok, Buon Don District), Ea bung and Cu M'lanh (Ea Soup district) and a part of Dak Wil (Cu Jut district).

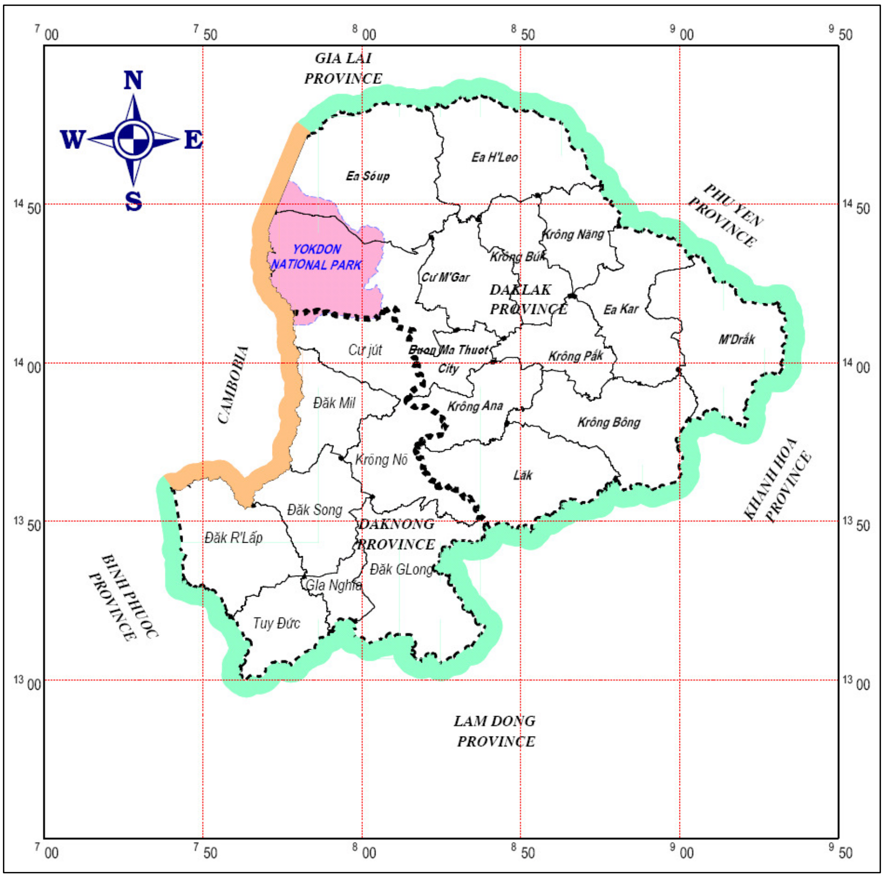

Fig. 3.1 Geographic position of the YokDon National Park in the Dak Lak province (the grid size is 50 km x 50 km). The geographic coordinates shown in the map use UTM unit.

3.1.2 Forest Types in the Park

The areas of the forest types in YokDon National Park are presented in table 3.1. There are two main forest types: evergreen broad-leaf and Dipterocarp forests. The Dipterocarp forests, the research objective of this study, are the major forest type of the YokDon National Park with an area of 106,685.5 ha accounting for 95.8% of the Park's total forested area. In addition, there are other types of land such as non-forested, agriculture and housing accounting for a small area.

The forest types were classified by standing volume levels. According to the classification of Forest Inventory and Planning Institute of Vietnam, for the Dipterocarp forests, the rich forests have an average standing volume about 140 m^3ha^{-1}, medium forests have a standing volume about 110 m^3ha^{-1}, and poor forests have a standing volume under 70 m^3ha^{-1}. In contrast, while the levels of standing volume in evergreen forest in Central

Highland are higher: about 250 $m^3ha^{-1}$for rich forests, 160 m^3ha^{-1} for medium forests and 85 m^3ha^{-1} for poor and rehabilitation forests. Young forests comprise of mainly regeneration trees.

Table 3.1 Areas of different forest types in the YokDon National Park.

Forest type	Area (ha)	Proportion (%)
1. Forested area	**111,295.8**	**96.3**
1.1. Evergreen broad-leaf forest	4,610.0	
Medium forest	780.0	
Poor forest	2,650.0	
Young forest	1,180.0	
1.2. Dipterocarp forest	106,685.5	
Rich forest	662.7	
Medium forest	24,920.8	
Poor forest	78,291.3	
Young forest	2,811.0	
2. Non-forested area	**3,573.9**	**3.1**
3. Agricultural area	**369.2**	**0.3**
4. Other areas	**306.1**	**0.3**

3.1.3 Topography and Hydrography

Topography

The National Park lies in an old and large peneplain, comprising of low hills and mountains distributed along the Serepok River, which is a big river originating from Vietnam, running through Cambodia and then flowing into the Me Kong River. The whole area is divided into two main geographical terrain forms: fairly smooth peneplain, being lower towards the Me Kong River, forming a large and deep river-bed with an average elevation of 200 m. The other terrain form, low hills and mountains, is lying along the north riverbank.

Hydrography

YokDon National Park is located in the Me Kong river valley along the branch of Serepok river. The river runs through the park with a length of about 60 km and has more than 60 branches, forming a dense river and stream system with lots of rapids all over the park (e.g. Dak Nor stream, and Dak Kenn stream, and other shallow and seasonal dry streams which overflow their banks in the rainy season) (see Fig. 3.2). In the dry season, the water level of Serepok river is just 2-3 m high, but in the rainy season, or during flooding events, the water level may reach to 5-10 m. This dynamic is very important for the wildlife in the park.

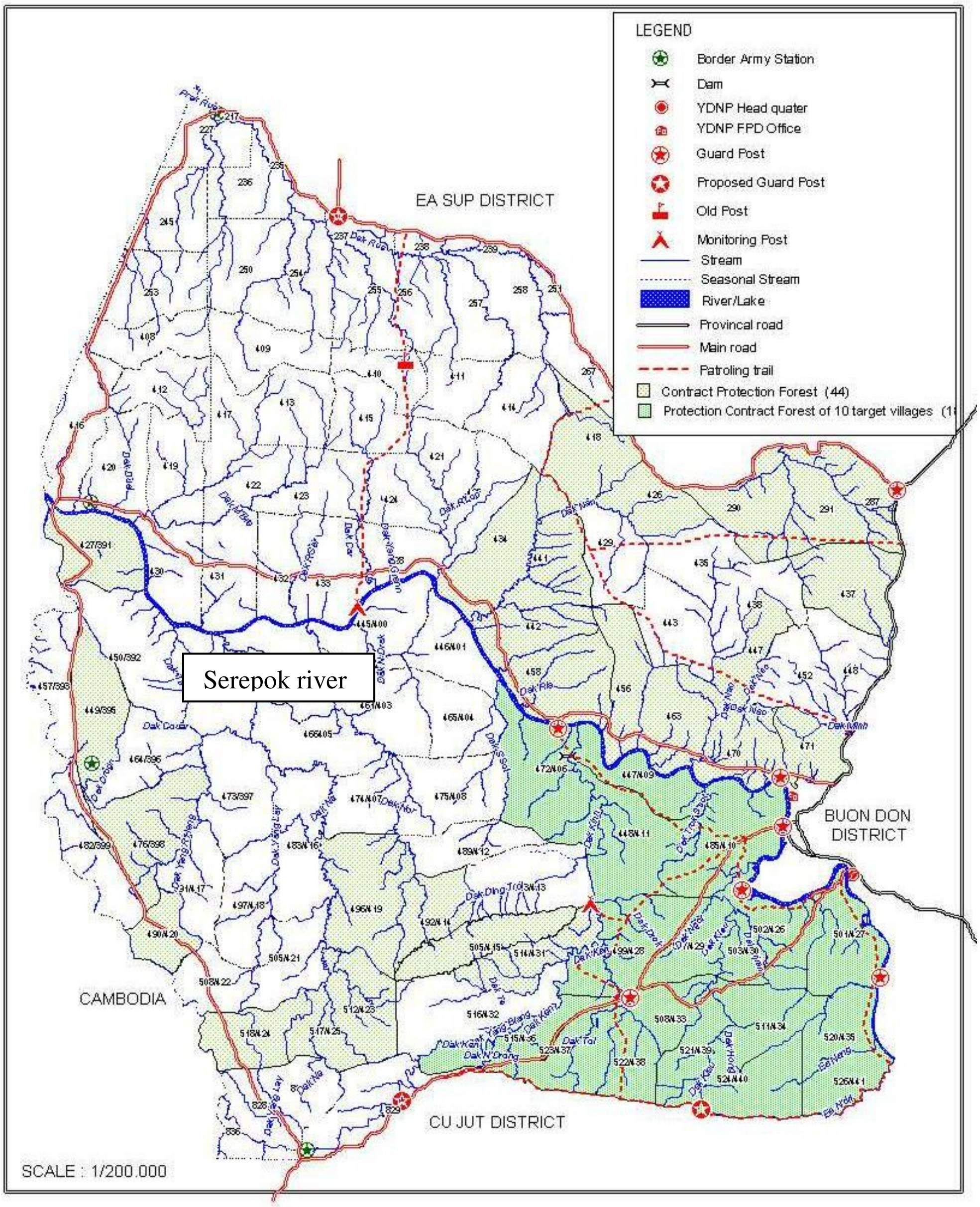

Fig. 3.2 Hydrography system in the YokDon National Park.

The Dipterocarp forests and the whole Serepok river valley spread over the Park together with the villages of ethnic minority in the highlands, who have lived here for a long time. Altogether, we find a lot of spectacular natural landscapes, creating a high ecotourism potential for the National Park.

3.1.4 Climate

The Park belongs to the tropical monsoon zone. Thus each year there is a distinct dry and rainy season. The rainy season concentrates between April and October, accounting for 93.5% of the annual rainfall. According to data from the hydrography and meteorology station of the Dak Lak province in the period of 2001-2006, the average annual rainfall is 1520 mm, while the average annual evaporation is 1,470 mm. The dry season is between November and March with very low rainfall, often accompanied with drought and high wildfire risk.

The average values about air temperature, rainfall and humidity in the period of 2001-2006 is illustrated in the diagrams below (Fig. 3.3, 3.4, 3.5).

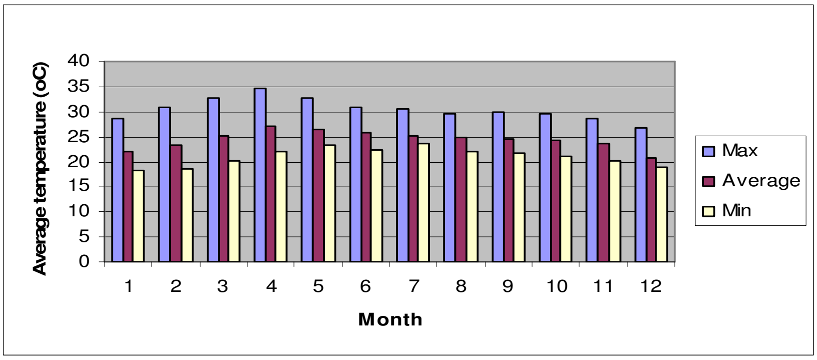

Fig. 3.3 Average air temperature in the period 2001-2006 in the study area. Data from the Hydrography and Meteorology Station of the Dak Lak province (Dak Lak Hydrography and Meteorology Station, 2007).

Compared to rainfall and humidity, the change of air temperature between months in a year is not very high. April and May are months whose highest average air temperature, about 27^0C, while the average temperature in December and January is lowest, about 22^0C (Fig. 3.3).

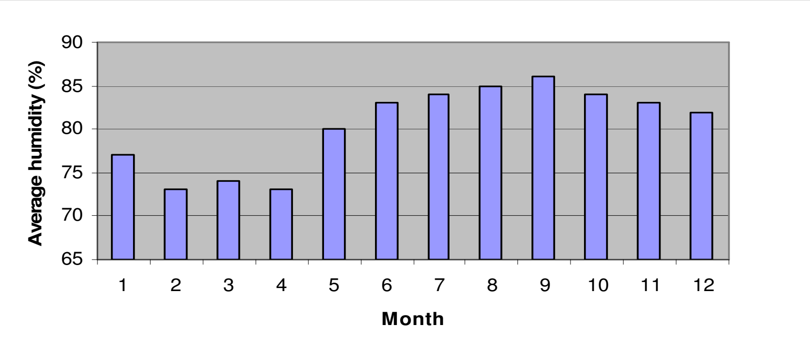

Fig. 3.4 Average atmosphere humidity in the period 2001-2006 in the study area. Data from the Hydrography and Meteorology Station of the Dak Lak province (Dak Lak Hydrography and Meteorology Station, 2007).

The average atmosphere humidity is different between the months in a year. It is lowest in the period between February to April in the dry season, about 73%. The highest atmosphere humidity falls in August and September in the middle of the rainy season, about 85% (Fig. 3.4).

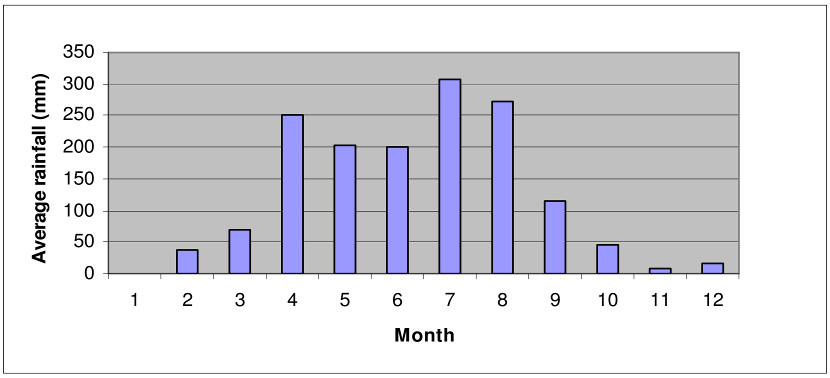

Fig. 3.5 Average rainfall in the period 2001-2006 in the study area. Data from the Hydrography and Meteorology Station of the Dak Lak province (Dak Lak Hydrography and Meteorology Station, 2007).

As shown in Fig. 3.5 the average rainfall obviously changes among months of the rainy season and the dry season. It is very low in the dry season from November to March, the average value is less than 50 mm. In contrast, it is very high from April to August and then quickly decreases in September and October at the end of rainy season. The average annual rainfall in the period 2001-2006 is 1,530 mm.

3.1.5 Flora and Fauna Resources

The flora

Forested land inside the Park accounts for 111,295.8 ha (96.3% of the total area, Table 3.1). The most important forest types are:

- Dry dipterocarp forests: this is the typical forest type in the Park and it is study objective in this research, covering an area of 106,685.5 ha accounting 95.8% the total forested area. They grow at heights about 200-400 m a.s.l., on slopes less than 20^{o}, dominated by Dipterocarpaceae species. This area provides a suitable habitat for wild elephants, wild cow, deer and a lot of birds such as peacocks and several species of birds of prey and large water birds.

- Evergreen broad-leaved closed moist forests: mainly seen in the low hills of the Yokdon mountains.

- Heavily disturbed forests: in this forest type, there are bamboo patches with small areas forming mainly along the streams and in the uplands. In addition, shrub layers often occur in this forest type providing good places for hoof mammals, peacocks and large water birds to come for food.

In addition, there are small areas of semi-deciduous closed forest scattered in the Park. They often have a typical five-layer structure with many various types of plants, such as Lythracea with specific species as *Lagerstrocmia calyculata*, under the forest canopy, there are many kinds of bamboo: *oxytenanthera sp, bambosa balcoa*. These places provide a food source and appropriate shelter for many animals and birds.

Botanic surveys up to the year 1998 recorded 474 species of vascular plants, 328 branches and 101 families, including many economically and ecologically valuable species. According to Diep (1993), the number of well-known botanic species in YokDon National Park amounts to 571 species, 345 branches and 106 families. Among the total species mentioned above, 20 rare and precious threatened species are recorded in the Viet Nam Red Data book.

The fauna

Recent fauna surveys reported 66 species of mammals, 241 species of birds, 46 species of reptiles, 16 species of amphibians, 30 species of fish (Investment plan of the National Park, 2001), and 437 species of butterflies (Subsection of FIPI in the south of the central and the highlands, 2001).

Among them, there are many endemic species and subspecies, which are threatened at various levels, recorded in the Viet Nam Red Data Book, Asia and the world. Many species were recorded in the CITES commitment and in the Decree of wildlife protection of the Vietnamese government. They included 38 species of mammals, 31 species of birds and 10 species of reptiles.

In addition, the aquatic product source in the Mekong river valley is very diverse. Especially fish are adapted to the special features of Yokdon and Mekong river. However, up to now the understanding of the aquatic diversity is still limited. It is necessary to conduct further research in order to explore the diversity and propose methods of suitable management and protection and appropriate exploitation of these resources.

3.1.6 Socio-economic Conditions

In the seven buffer zone communes, there are 53 villages with a total population of about 31,000, and an average density of 13 people per km^2. Accounting for the highest population fraction are the Kinh people (61.7%), the E De (6.5%), the Gia rai (6.5%), the Nung (6.6%), the Tay (6.4%), the M'nong (1.8%), and the Muong (0.2%) (data in 6/2001).

The average natural population growth rate is 4.6% per year (in 1997). The ethnic minority people often live near stable water sources, except the Kinh, who mostly live along traffic roads and in towns. Their income source is mainly from upland rice, cultivation, grazing, forest products, resin, elephant taming, animal hunting and fishing. Coffee, pepper, cashew, and cotton are unstable income sources. The National Program 661 "forest allocation for management and protection" helped them to increase the income and improve their daily lives.

The establishment of new economic zones in the Dak Lak province and free immigration from other provinces increase the population density and create greater pressure on the National Park (Easup district had the highest annual population growth rate of 17% from 1996-1997). In addition, on the expanded park area, there is the Drang Phok village (displayed in Fig. 3.6), with an area of 369.2 ha, including a residential area of only 4.5 ha, the remaining upland rice cultivation accounting for 310.1 ha. The total households amount to 43, comprising of 255 people, accounting for 8.5% of the commune population. Most of them are the M'nong, and their number has considerably increased. Because of low income, some of them often go to the forests to cut trees illegally. This is a challenge to the forest management and protection in the park. The traffic system is limited and unequally distributed in the National Park. In the area, there is a lake of 10.6 ha for rearing aquatic products, and another lake of 276.6 ha for irrigation and several other water dams.

3.2 Establishment of Research Plots as an Empirical Data Base for Modelling Growth and Yield in Dipterocarp Forests

One of the first steps in constructing a growth and yield model for management purposes is to obtain suitable calibration and validation data. The data requirements of many modelling approaches are similar and allow a set of minimum procedures to be established. Stem analysis does not provide reliable growth data for many tree species in the tropical forest. There are several anomalies of growth rings in tropical tree species. Evergreen trees, e.g. *Swietenia* spp. may form annual rings, while deciduous trees (e.g. *Ficus* spp.) may not. Several species like *Hevea Braziliensis* often form several growth rings each year, while other species as *Shorea robusta* form only one ring in the same year, but not necessarily in the same month (Kramer and Kozlowski, 1979). So, data must be obtained from re-measurements on permanent sample plots (PSPs). Permanent plots can never be completely replaced by temporary plots even for species amenable to stem analysis, because only PSPs allow satisfactory statistical comparisons within and between plots to check the adequacy of models (Strand, 1970), and only PSPs can provide reliable and consistent data on mortality, crown dynamics and stand level variables (Mcquillan, 1984)

The study area was determined by the availability of 12 plots with two measurements (plot group A; plots A1 to A12) and 21 new plots established by the author at the end of 2007 (plot group B; plots B1 to B21) covering a total area of approximately 17.2 hectares of dry deciduous Dipterocarp forest in YokDon National Park.

The permanent plots of group A are maintained by the Forest Inventory and Planning Institute of Vietnam (FIPI). In 1991 FIPI started to carry out a program of inventory, monitoring and assessment of forest resources dynamics all over the country. The program has been completed in three stages, stage 1 from 1991 to 1995, stage 2 from 1996 to 2000 and stage 3 from 2001 to 2005 and currently the stage 4 from 2006 to 2010 has been implemented. The results of each stage have contributed to decision making of the government in forest resources management as well as to set up projects for developing the forestry sector. The information and data base of the first stage lead to the government program 327 in 1992 on re-greening bare lands and degraded hills, and plant five million hectares of forest. The results of the second stage helped the government regulate several forestry policies advised for establishing forest plantation areas. The third and fourth stages provide complete and detailed information about quantity, quality as well as dynamics of forests in relation to socio-economic activities in order to create a scientific base for proposing sensible forest resources use, protection, and development strategies all over the country.

In order to meet the above purposes, FIPI has established a network of permanent plots. In the network, there are in total 4,200 primary plots evenly on forested areas all over the country with an area of 100 ha each. The contents of data investigation and collection in the primary plots include:

- describe natural conditions in general, especially factors affecting the vegetation cover,
- measure area of forest resources, states and types of soil, detail topography,
- use camera witch attached GPS to take photographs covering whole plot in order compare to satellite images,
- measure and collect special characteristics of vegetation cover including woody plants, bamboo, regeneration, valuable species, etc.
- collect data about human population, socio-economic features close to the plots, and

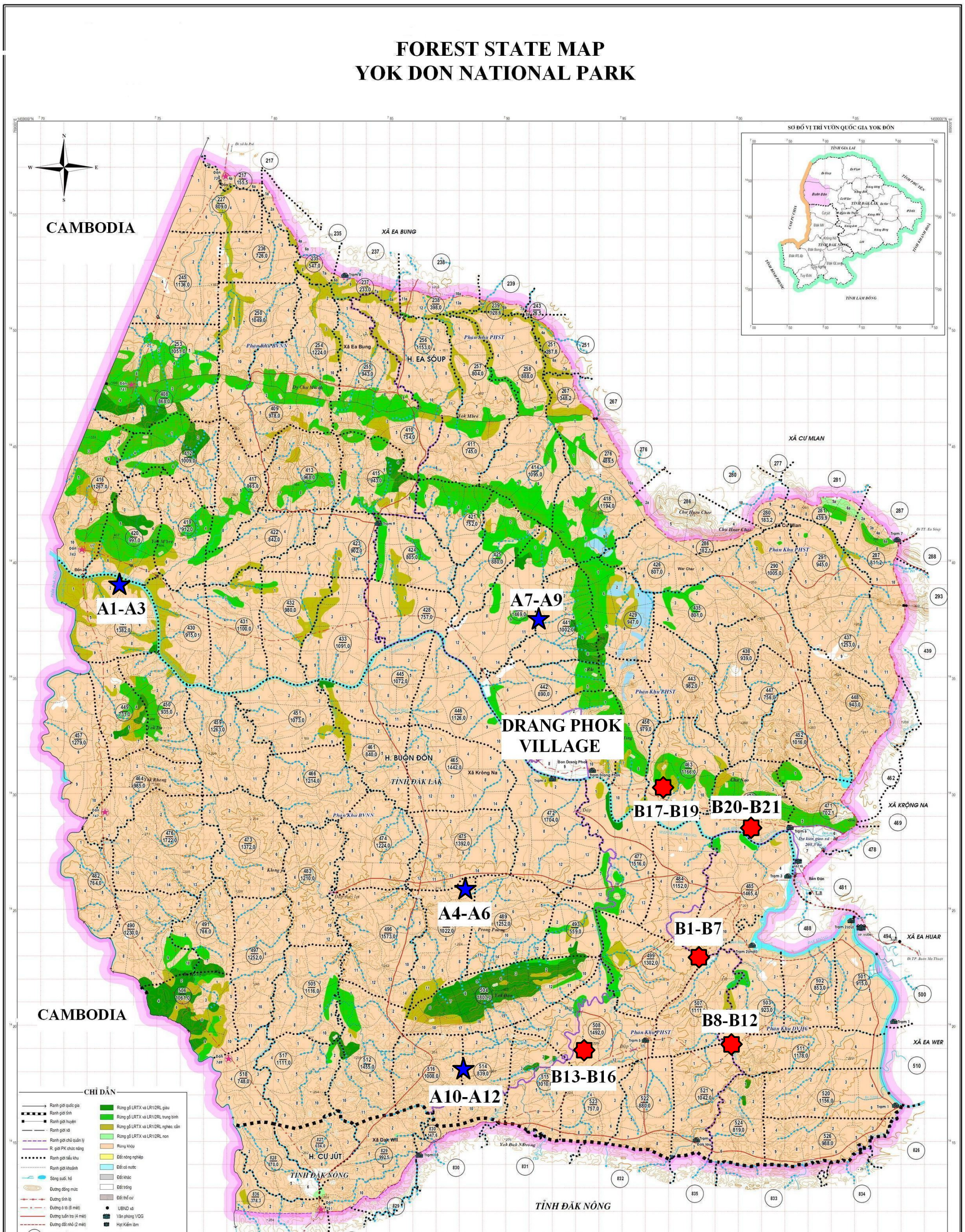

Fig. 3.6 Forest state map of YokDon National Park. There are two main forest types in the Park. The evergreen forest displayed in green color and the Dipterocarp displayed in light brown. The white-colored areas are non-forested. Positions of the research plots used/established in this thesis. Group A: ⬢ ; group B: ★

- collect information and data about the fauna.

From these primary plots, 100 have been selected as permanent ecological research plots in order to represent various forest states, types and ecological areas. Data collection and research on the permanent ecological research plots include:

- determine species associations and their dynamics,
- collect information about wood and biomass production (e.g. standing volume, basal area, volume, basal area and volume increment, mean diameters, diameter distribution, etc.),
- evaluate changes of natural regeneration according to each species or dominant species groups,
- assess tendencies of forest rehabilitation and development, and
- evaluate the dynamics of wildlife and its rehabilitation ability.

In these ecological research plots, three permanent plots on each stand state with an area of one hectare each were established to obtain the data for calculating standing volume, basal area increment and monitoring reactions of various forest states.

Plot group A in this study consists of twelve such permanent one-hectare plots. Plots A1 to A9 were established in 2002, and A10, A11 and A12 were established in 1999. These twelve plots belong to four clusters of plots, where each cluster has three plots which are located closely to each other (see Fig. 3.6 for the positions of the clusters). Each plot is quadratic (100m x 100m). The corners were marked by four concrete stakes and the edges were oriented to the cardinal direction of north-south. In order to be convenient for managing and collecting data, each plot was subdivided into 25 quadratic sub-plots (20m x 20m). On the plots, all trees equal to or larger than 6 cm dbh were identified to species, numbered permanently with metal tags fastened with a nail. The plots have been re-measured once up to now, five years after establishment. Both measurements were carried out in the dry season in order to avoid seasonal fluctuations in girth due to changes in xylem water tension. The data within the main plot were recorded on sub-plot level. At each measurement, trees of at least 6 cm in diameter at breast height (dbh) were recorded in terms of species, diameter, stem quality and subset of total tree height. Mortality was defined by individual tree histories: as plots were re-measured, field crews recorded whether a tree that was previously sampled as "live" had died or was still alive. The number of recruits entering into the smallest size class of 6 cm was also recorded.

The data from these twelve plots already give important insights from the point of view of this thesis. On the other hand, they do not cover extremes of site conditions and stand density. Thus, in order to assess special characteristics of the Dipterocarp forests effectively, it is necessary to include additional data from other sources. According to Vanclay (1991), permanent sample plots should sample the geographic range of the forest, and encompass a broad range of forest types, site quality and topography. A broad range of stand basal area and tree sizes should be sampled for each tree species. Plots should include stands which have been subjected to a range of silvicultural management, including extremes of logging and treatment.

Correspondingly, at the end of 2007 during a measurement campaign in Vietnam, the author established the 21 new permanent plots of group B (B1-B21), (the positions of the plot cluster are shown in Fig. 3.6). Each plot is 2,500 m² large, quadratic (50 x 50 m), and was subdivided into four quadratic subplots. Measurement included all trees with a dbh larger than 6 cm. The information recorded on each plot for the first inventory comprises:

- tree species,
- tree diameter at 1.3 m above ground (dbh), tree height,
- plot location, dimensions and area,
- topography (altitude, aspect, slope, relative position on slope),
- forest type,
- floristics (all plant species on plot and their relative abundance), and
- physical soil characteristics (depth, texture, color, parent material)

These plots will be observed for a long time in the future to obtain more reliable data for recalibration and validation of the model. Besides the modelling task of this work these plots will form a solid empirical source of knowledge about the dynamics of the Dipterocarp forests in the Central Highlands. In order to support a sufficient model flexibility, the plots were established in stands which cover different site qualities from poor to good site quality, and also an as broad as possible range of stand densities.

The data from these plots will be used in this study as an additional data source for calculating special characteristics of Dipterocarp forests in the next chapter.

Chapter 4

Data and Description of Stand Characteristics

4.1 Ecological Classification of the Research Plots by Species Composition

Dipterocarp forests have a species composition and crown layer structure different from other forest types. The association of tree species in Dry Dipterocarp forests differs from site to site. To study the Dipterocarp forests systematically, it is necessary to classify them into different forest types in order to apply appropriate silviculture regimes in forest production and management. Several classification schemes have been developed for Dipterocarp forests in the Central Highland of Vietnam (e.g. Linh, 1988; Con, 1991; Diep, 1993). In reality, the research plots used in this study show a significant difference in terms of the species composition. In order to clear this difference, we used the main dominant species for stratification and developed five association types based on the method of Con as mentioned in Chapter 2 and obtained the results given in Table 4.1 below.

The five association types were based on the main dominant species in which the dominant species account for at least 30% of the total tree number. Among 33 research plots of both group A and B, there are nine plots belonging to association type 1 in which only the species *Dipterocarpus tuberculatus* is dominant, accounting from 49.2 to 93.7 %. In general, in the research plots *Dipterocarpus tuberculatus* is the dominant species that occurs in all plots. Fig. 4.1 illustrates this association type. The four remaining association types have two dominant species each. Fig. 4.2 shows an example of the association type with *Shorea obtusa* as dominant species.

Table 4.1 Species association on the research plots (group A: twelve one ha-plots; group B: 21 0.25 ha-plots).

Association type	Species association	Plot
1	*Dipterocarpus tuberculatus*	B2, B3, B8, B12, B13, B14, B15, B17, B18.
2	*Dipterocarpus tuberculatus, Shorea obtusa*	A2, A5, A6, A7, A8, A9 B5, B9, B10, B11.
3	*Dipterocarpus tuberculatus, Dipterocarpus obtusifolius*	A1, A3,B19, B20, B21
4	*Dipterocarpus tuberculatus, Terminalia alata*	A4, A10, A11,B4, B6, B7
5	*Dipterocarpus tuberculatus, Shorea siamensis*	A12,B1, B16

Fig. 4.1 Association type 1: *Dipterocarpus tuberculatus* as dominating species (plot B18).

Fig. 4.2 Association type 2: *Dipterocarpus tuberculatus* forest with *Shorea obtusa* (plot B10).

As already pointed out, Dipterocarp forests are floristically simpler than evergreen forests. There are about 98 tree species which can be found (Con, 1991), most of them belong to the family of Dipterocarpaceae and Combvetacae. For group A, the number of species per plot recorded for all trees ≥ 6 cm dbh ranged between 17 and 43 (Table 4.2). In total, we found 64 species ≥ 6 cm dbh on all group A plots (see Table 01 in the appendix for a complete species list). Although there are several species recorded in each plot, most of them occurred with very low frequencies, their number less than ten, some species with only one to four trees in each plot. They include: *Careya sphaerica, Mangifera longipetiolata, Wrightia tomentosa, Diospyros sp, Vatica odorata, Ziziphus oenoplia, Hopea odorata, Diospyros pilosella, Phyllanthus emblica, Sindora siamensis, Peltophorum tonkinensis, Paulownia fortunei, Bauhinia purpurea, Butea frondosa, and Litsea lancilimba.* Most of these species are more important in evergreen forests.

However, for both plot groups, in average, one to four species on each plot are dominant as they contributed over two thirds of the number of stems and they were considered to be most important from the timber utilization point of view. These species include *Shorea obtusa* with an overall average percentage of 19.1% of the stem number, *Dipterocarpus tuberculatus* (22.4%), *Dipterocarpus obtusifolius* (11.7%), *Terminalia alata* (11.8%), *Shorea siamensis* (6.6%), and *Xylia dolabriformis* (5.8%). Except for *Terminalia* *alata* which belongs to the Combretaceae family and *Xylia dolabriformis* belonging to the mimosaceae family, the four remaining species belong to the family of Diptorocapaceae. They are all commercial species that provide very valuable timber.

To illustrate the species diversity of the Dipterocarp forests, we use the Shannon diversity index. This index, developed by Shannon and Weaver for use in information theory, was successfully transferred to the description of species diversity in biological systems (Shannon, 1948):

$$H = -\sum_{i=1}^{s} p_i \times \ln p_i \tag{4.1}$$

where:

H: the Shannon diversity index,

p_i : the proportion of a species in the population ($p_i = n_i / N$), n_i the number of individuals of a species i, and N the total number of individuals,

S: numbers of species present,

$\sum$: sum from species 1 to species S,

ln: natural logarithm.

The results of calculation of Shannon diversity index in plot group A and B are presented in Table 4.2 and Table 4.3, respectively.

Table 4.2 Diversity of species composition for plot group A. N1- number of trees per ha, N2- number of species, N3- number of species with frequency >10 trees per ha, N4- number of species accounting for more than 70% total trees, H- Shannon diversity index.

Plot	**N1** (treesha^{-1})	**N2** (species ha^{-1})	**N3** (species ha^{-1})	**N4** (species ha^{-1})	**H**
A1	456	26	7	3	1.793
A2	380	23	4	3	1.847
A3	440	43	10	8	2.707
A4	268	17	4	3	1.796
A5	539	30	6	3	1.928
A6	409	17	6	3	1.865
A7	656	17	5	2	1.662
A8	303	24	7	4	2.311
A9	381	22	7	4	2.313
A10	275	17	5	3	1.912
A11	298	24	7	5	2.219
A12	570	22	6	3	1.866

The Shannon diversity index when applied to the tree species for the group A plots has high values compared to the group B plots. The species diversity in the twelve plots of group A (Table 4.2), ranges from 1.662 to 2.707. In plot A7 with the lowest index there are 23 species recorded in total 656 trees while in plot A3 with the highest index there are 43 species recorded in total 440 trees. The average index is approximately 2. Several species from evergreen and semi-deciduous forests often occur in the plots, and although their quantity is low they increase stand diversity. According to Diep (1993), there are some areas of evergreen forest in YokDon National Park, but these areas decrease more and more because of wildfires. In contrast, the dipterocarpaceae species can usually survive wildfires because of their thick bark.

Table 4.3 Diversity of species composition of group B.

Plot	**N1** (trees/plot)	**N2** (species/plot)	**N3** (species/plot)	**N4** (species/plot)	**H**
B1	125	10	3	2	1.534
B2	193	10	4	2	1,485
B3	98	11	1	2	1,197
B4	168	11	3	3	1,671
B5	145	11	3	3	1,744
B6	281	12	5	3	1,698
B7	178	8	3	2	1,408
B8	82	10	2	3	1,596
B9	105	9	3	3	1,665
B10	154	9	3	2	1,485
B11	180	12	4	3	1,634
B12	160	10	2	2	1,324
B13	174	10	2	2	1,356
B14	118	9	2	2	1,479
B15	206	5	1	1	0,303
B16	225	10	2	1	1,099
B17	129	11	3	2	1,515
B18	88	7	1	1	0,586
B19	126	11	5	3	1,770
B20	289	9	2	2	1,190
B21	244	8	2	2	1,173

For the stands of group B, it is evident that the numbers of species per plot recorded for all trees ≥ 6cm dbh are much lower than those of plot group A. The number of species on the plots is quite similar, ranging from eight to twelve. As an exception, in plot B15 only five species are recorded. Overall, there are in average ten species found per plot. This results in low values of the Shannon index compared to group A, ranging from 1 to 1.74 (Table 4.3). Particularly, in plot B15 and B18 the index values are only 0.3037 and 0.586, respectively. The average value of the index on group B is 1.377. The occurrence of such low index values can be explained as follows: these plots have an area equal to one fourth of the plots belonging to group A, reducing the probability to include rare species. In addition, and more important, these plots were placed in stands which are even more typical deciduous forests, so the number of species belonging to evergreen forests is necessarily lower. The number of evergreen species is strongly limited by the occurrence of wildfires. In these plots, one to three species account for more than 70% of the total tree number, while almost all other species occur with frequency less than 10%. For example, in plot B15 the stand is almost pure, as *Dipterocarpus tuberculatus* represents 94% of all trees. However, the dominant species composition is similar to the stands of group A, including the same species with following percentages: *Shorea obtusa* (12.6%*), Dipterocarpus tuberculatus* (42.1%), *Dipterocarpus obtusifolius* (9.1%), *Terminalia alata* (12.3%), *Shorea siamensis* (9.6%).

4.2 Establishment of Stand Height Curves and Site Quality Classification

4.2.1 Selecting Height Curve Functions

The relationship between tree height and diameter is an important basis for site quality classification in this study. Several functions have been successfully used to establish this relationship. To establish the height curves for the research plots, data were analyzed with the standard research plot evaluation software of the Chair for Forest Growth and Yield Science at Technische Universität München. This package can fit the following six functions:

Parabola (Assmann, 1943):

$$h = a_0 + a_1 \times d + a_2 \times d^2 \tag{4.2}$$

Prodan (Prodan, 1951):

$$h - 1.3 = \frac{d^2}{a_0 + a_1 \times d + a_2 \times d^2} \tag{4.3}$$

Petterson (Petterson, 1955):

$$h = 1.3 + \left(\frac{d}{a_0 + a_1 \times d} \right)^3 \tag{4.4}$$

Korsun (Korsun, 1935):

$$h = e^{(a_0 + a_1 \times \ln d + a_2 \times \ln^2 d)} \tag{4.5}$$

Logarithm:

$$h = a_0 + a_1 \times \ln d \tag{4.6}$$

Freese (Freese, 1964):

$$h = e^{(a_0 + a_1 \times \ln d + a_2 \times d)} \tag{4.7}$$

where:

h: total tree height,

d: diameter at breast height,

a_0, a_1, a_2: regression coefficients,

e: basis of the natural logarithm with the value of 2.7182818…, and

ln: natural logarithm.

The program gives the fitting results in terms of parameters and goodness-of-fit information for each function. Based on these results, the best function for the species (or species group) of interest can be selected. The criteria to select the height curve function are:

- the function should have a high R^2 coefficient and small standard error.

- the function should display truly biological characteristics of the species, give an s-shaped curve and does not decline when diameter increases.

A comparison between the height curves of two inventories in the plots of group A indicates that there is no clear difference between them, so to gain more stable fits, height data of two inventories were pooled to build the height curves of different species groups.

The results show that for the research plots, all the functions above give good fits with the R^2 coefficient ranging from 0.75 to 0.95. Because the amount of height data for some species is not high and only concentrates on small diameter classes, so the extrapolation to large diameter classes is often required. Plausibility in these terms is a very important criterion to select the function. E.g. for the Parabola, the high curve is good for the range of data, however for extrapolated data it gives decreasing values in large diameter classes, which cannot be true according to biological characteristic of trees. Similarly, the Logarithm function gives negative values at small diameters. The functions of Petterson, Prodan, Korsun and Freese all have also high R^2 values, and they are more plausible from the biological point of view. Of all functions the Petterson function turned out to be best, with high R^2 coefficients and suitability for extrapolating data. So in this study, the Petterson function will be used for establishing the plot's height curves.

4.2.2 Categorizing Species Groups

There are many species represented in Dipterocarp forest (total 93 species found in the Dipterocarp forest in the research area and 64 species recorded in the plots), and these species show different potential height levels. Some species have potential heights up to 30 – 40 m while others show a maximum of only 10 – 15 m. To study tropical forests, woody species are usually categorized into different groups based on biological characteristics. In Vietnam, several authors have used height curves before studying Dipterocarp forests. For example, Con (1991) established one height curve function for all species together for four site quality levels. Dong (2002) used the Parabola function to establish height curves for *Shorea obtusa,* one of the most dominant species in Dipterocarp forests, for five site quality levels. Huy (1993) established height curves for four species: *Lagerstroemia calyculata, Xylia dolabriformis, Terminalia alata,* and *Phoebe cuneata* in some areas in the Dak Lak province. However, those results can not be well applied to this research because for the research focus of this work it is not appropriate to use only one curve for all species. So in this study the height curves were parameterized for different species groups.

After grouping and testing data with several criteria, based on biological characteristics, tree species were categorized into three species groups giving good results. Although the Dipterocarpaceae family includes a large number of species, they share common ecological behavior that allows for their categorization in the same guild of regeneration and they are homogeneous enough to be considered as a guild of species (Sac, 1984; Con, 1991; Sist *et al.*, 2003). Therefore we gathered all species belonging to Dipterocarpaceae family and several other species with similar biological characteristic to the first group. This group makes up a high proportion (60 – 80% of the stem number). The most common species in this group are *Dipterocarpus tuberculatus, Dipterocarpus obtusifolius, Terminalia alata, Shorea siamensis, Shorea obtusa*. The second group comprises of evergreen tall species, whose number of trees accounts for a lower proportion (20 – 30% of the total stem number). Its most important species are: *Vitex sumatrana, Dalbergia mimosa, Xylia dolabriformis, Lithocarpus ducampii, Adina cordifolia, Bombax anceps.* The third group includes all small-sized, lower species combined with non-commercial species. The potential height of these species is maximum 10 to 15m and they usually are evergreen, being the minority of the stand. Although these species are noncommercial, they are important from the biodiversity point of view. Most common in this group are *Garcinia oblongifolia, Terminalia bellirica, Lumnitzera coccinea, Phyllanthus emblica, etc.* (Find the full species list of the classification in Table 01 in the appendix).

For the stands of group B, where the data set indicates that the association of tree species is much simpler than that of group A, almost all species belong to the Dipterocarpceae family and account for up to 80 – 90% total trees. In addition, not enough height data were measured to establish height curves for each species group separately. So, the Petterson function was used to establish a height curve for all species together on each plot.

4.2.3 The Results of Height Curve Fitting

The results of height curve fitting are given in Tables 02 and 03 in the appendix.

It is evident that the Petterson function is well suitable for the available data. When data were categorized in to three groups, the R^2 coefficients of the height curves are quite high for species group 1 and 2, ranging from 0.80 to 0.93. For species group 3, because there are not many trees, number of observations range between 10 and 50, the values of R^2 coefficient are slightly smaller than those of group 1 and 2, ranging from 0.70 to 0.91.

To illustrate the different levels of the height curves between different species groups, height curves of selected plots are shown in Fig. 4.3 below. The height curve of group 1 is always in upper position and the height curve of group 3 is always in the bottom for all diameter classes. Thus, the Petterson function seems to be highly suitable for biological characteristics of Dipterocarp forests even though the height curves are supported only by small tree numbers for large diameter classes, especially for species group 2 and 3.

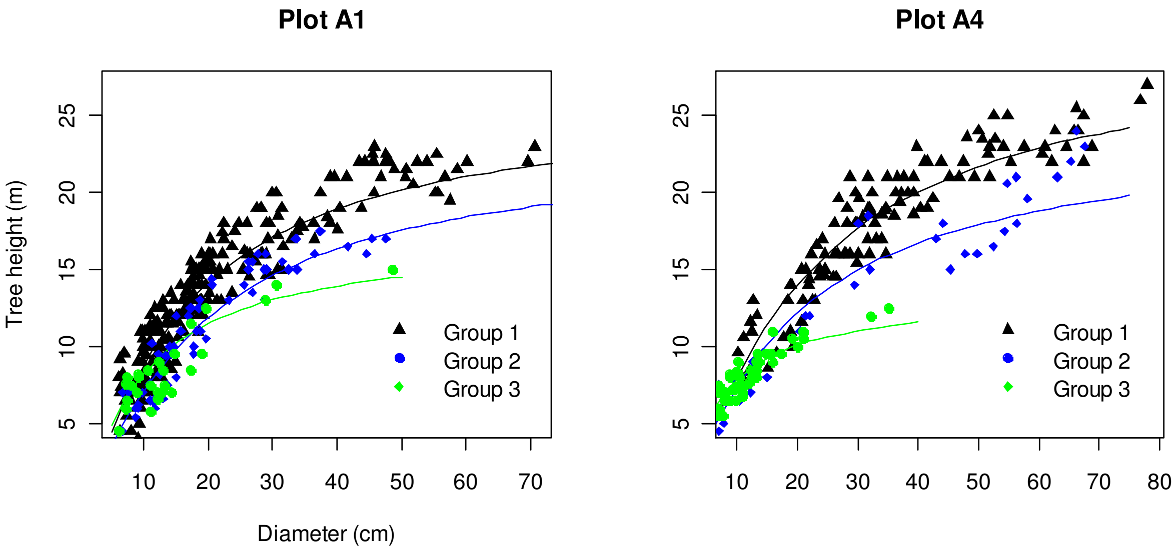

Fig. 4.3 Diameter-height curves of plot A1 and plot A4 for three species groups.

However, the values of height in the same group and diameter classes are considerably different from plot to plot. The graphs in Fig. 4.4 illustrate the difference of high curves among the plots.

The twelve plots are on different site qualities, so the height curves of these plots are very different. The height curves of plots belonging to good site quality are generally higher than those of plots on poorer site qualities. This characteristic will be the basis for classification of the site quality in this study.

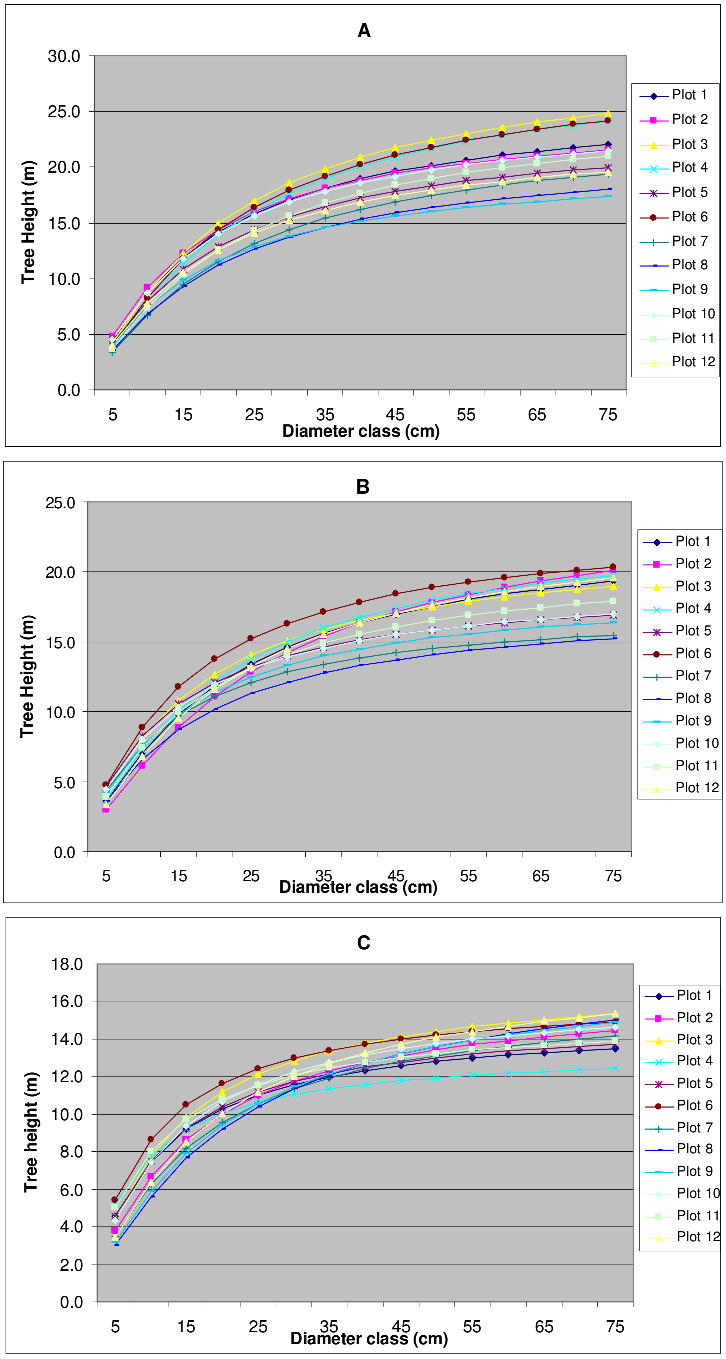

Fig. 4.4 Diameter-height curves for three species groups of the twelve group A plots. A- Species group A. B- Species group B. C- Species group C.

4.2.4. Site Quality Classification

The classification of site quality is an indispensable issue when studying forest growth and yield. As mentioned in Chapter 2, the research results about the height growth were carried out by several scientists (Huy, 1993; Con, 1991; Sac, 1984). They showed that when the age of the tree is very high, the increment of the height reduces. Thus, the relationship between height and age for big trees is less important. They suggested to use the relationship between height and diameter classify site quality. Following the method of site quality classification of the scientists above, in this study site quality was defined based on the average height of the 20 biggest trees in each plot to divide into three levels: good, medium and poor site quality corresponding to site quality 1 (SQ1), site quality 2 (SQ2) and site quality 3 (SQ3), respectively. Because there is a difference about the area of the plot between group A and group B, it is impractical to apply this method for both group plots. In this study, there is no issue in relation to site quality for group B plots. In addition, the area of the group B plots is 2,500 m^2 so it is impossible to apply this method for these plots. Therefore, the classification of site quality was done only for group A plots. The result of site quality classification is as follows:

- Site quality 1 includes three plots: A3, A4 and A6.
- Site quality 2 includes four plots: A1, A2, A10 and A11.
- Site quality 3 includes five plots: A5, A7, A8, A9 and A12.

4.3 Data Sets

The data sets obtained from the research plots were used to calculate stand characteristics and calibrate the growth model. For each purpose, different data sets are required. This section describes the data sets used in the study.

4.3.1 Data for Calculating Stand Characteristics

A detailed description of selected stand characteristics has been shown plot-wise in the previous section including an ecological classification of the research plots by species composition, establishment of stand height curves and site quality classification. The datasets used for these calculations include data obtained from both plot group A and plot group B. For the calculation of stand variables including stand basal area, standing volume, mean basal area diameter, mean height, periodic mean annual basal area and volume increment in the next section, data of both groups is also used.

The number of trees per ha between the two plot groups shows a significant difference. Fig. 4.5 compares the diameter distributions of plot group A and B in terms of average tree numbers per hectare by diameter class. The plots of group B mainly come from poorer sites than those of the group A, so the tree numbers in small diameter classes are higher than those of group A, but in the bigger diameter classes they are lower.

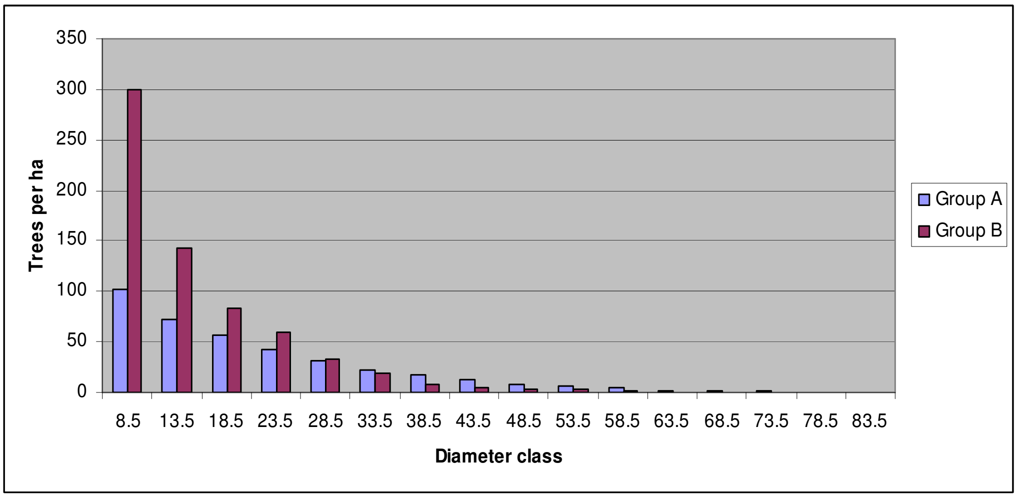

Fig. 4.5 Average tree number by diameter class distribution per hectare of the two groups. In the case of group A, the stem number represents the average of two inventories excluding mortality.

4.3.2 Data Used to Calibrate the Growth Model

Data for calibrating the main components of the growth model including diameter increment, recruitment and mortality functions only came from the group A plots, because they were already re-measured once. A total of 4,975 trees belonging to 64 species were measured, monitored and recorded in the plots.

Data used to develop diameter increment model

Table 4.4 presents the summary statistics of individual tree variables including average, maximum, minimum values of diameter increment, tree volume, tree diameter for each species group over two inventories. The diameter growth level of species group 1 is highest. For calibrating the diameter increment models, only re-measured trees alive during both inventories were used to calibrate. Due to errors in measuring accurately diameter, about 3% of growth diameter values were removed from the process of fitting model as outliers, and this procedure produces better results.

Table 4.4 Summary statistics for individual trees data on 12 plots. Diameter was taken the values at the beginning of the growth interval.

	Diameter growth (cmyr^{-1})			**Tree volume** (m^{3}tree^{-1})			**Diameter** (cm)		
	Group 1	Group 2	Group 3	Group 1	Group 2	Group 3	Group 1	Group 2	Group 3
Mean	0.382	0.323	0.331	0.373	0.387	0.113	21.4	23.5	15.4
S.E	0.002	0.004	0.008	0.102	0.022	0.011	0.3	0.5	0.5
Max	0.781	0.693	0.682	12.041	6.184	1.673	6.0	6.0	6.1
Min	0	0	0	0.005	0.004	0.007	120.4	98.6	60.2
N	3,100	802	302	3,100	802	302	3,100	802	302

Fig. 4.6 illustrates the distribution of number of trees by diameter class for three species groups. Trees were grouped into 16 5-cm diameter classes, from diameter class 8.5 cm (trees 6.0 to 11.9 cm in diameter) to diameter class 83.5 cm (trees 81.0 cm in diameter and above). The average number of trees per ha over all the plots decreased exponentially as tree diameter increased for all three species groups. Tree number of species group 1 in all classes is highest while those of species group 3 is lowest.

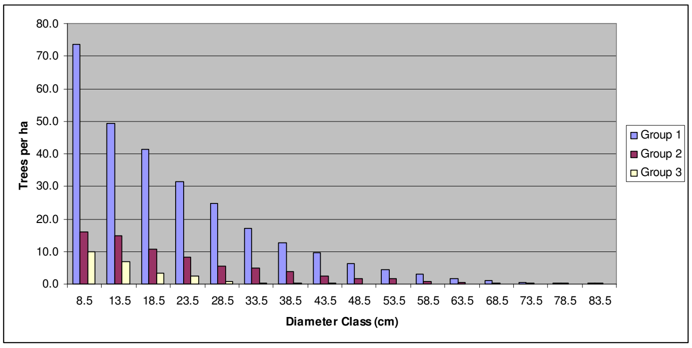

Fig. 4.6 Average number of trees per hectare for three species groups over twelve plots of group plot A, between the two inventories.

Data for recruitment

In this study, recruitment models were developed to estimate the number of recruits exceeding the threshold diameter of 6 cm dbh each year for each species group. The number of recruits that entered the diameter class 6 cm dbh for each species group in one interval of 5 years was recorded in the second inventory. The annual number of recruits was obtained by converting 5-year-periodic recruitment by linear interpolation. Table 4.5 below presents the data for recruitment model development

Table 4.5 Data for developing the recruitment function. The tree number was trees from 6 cm taken at the beginning of the growth interval of 5 years. Recruitment is number of recruits for a growth interval of 5 years.

	Tree number (treesha^{-1})				**Recruitment (treesha^{-1})**			
Plot	Group 1	Group 2	Group 3	total	Group 1	Group 2	Group 3	total
A1	295	74	30	399	34	8	15	57
A2	267	57	18	342	14	9	15	38
A3	211	136	44	391	26	12	11	49
A4	145	40	40	225	19	3	21	43
A5	407	63	27	497	32	8	2	42
A6	270	65	17	352	44	11	2	57
A7	509	67	29	605	43	6	2	51
A8	175	55	35	265	32	4	2	38
A9	231	78	33	342	24	11	4	39
A10	151	80	9	240	19	13	3	35
A11	145	89	22	256	19	15	8	42
A12	450	51	22	523	35	11	1	47
Total	3,256	855	326	4,437	341	111	86	538

Mortality data

As described in the previous section, the data for developing mortality function came from data set of twelve one-ha permanent sample plots, collected between two inventories of an interval of five years. Trees from 6 cm dbh were included into the model. Mortality was defined as a tree that was previously sampled as "live" had died until the second inventory.

Table 4.6 shows the number of dead trees and the live trees for each species group in twelve plots. There are plenty of observations in species group1 but very few in species group 3. Altogether, there are 233 dead trees in these plots including 156, 53 and 24 dead trees recorded during the growth period of five years in species group 1, 2 and 3, respectively.

Table 4.6 Summary of the data of mortality status in the plots used to develop mortality functions. Dead trees are the trees died for the growth period of five years.

Plot	Tree number (treesha^{-1})				Dead trees (treesha^{-1})			
	Group 1	Group 2	Group 3	total	Group 1	Group 2	Group 3	total
A1	295	74	30	399	16	3	2	21
A2	267	57	18	342	11	3	2	16
A3	211	136	44	391	15	14	5	34
A4	145	40	40	225	5	7	3	15
A5	407	63	27	497	23	3	1	27
A6	270	65	17	352	24	0	0	24
A7	509	67	29	605	23	0	2	25
A8	175	55	35	265	6	5	2	13
A9	231	78	33	342	9	3	4	16
A10	151	80	9	240	4	7	0	11
A11	145	89	22	256	2	7	3	12
A12	450	51	22	523	18	1	0	19
Total	3,256	855	326	4,437	156	53	24	233

Table 4.7 below presents the summary statistics of the diameter data of living trees and dead trees of three species groups used to develop mortality models. The dead trees mainly concentrate on the small diameter classes, therefore the mean diameter of dead trees is lower than that of live trees.

Table 4.7 Summary statistics of the mortality data used for the model development. The living trees were taken the values of diameter at the beginning of growth interval.

	Diameter of living trees (cm)			Diameter of dead trees (cm)		
	Group 1	Group 2	Group 3	Group 1	Group 2	Group 3
Mean	21.4	23.5	15.4	12.7	13.8	13.7
S.E	0.3	0.5	0.5	0.5	1.1	1.0
Min	6.0	6.0	6.1	6.0	6.1	8.0
Max	120.4	98.6	60.2	44.0	37.6	23.6
N	3,100	802	302	156	53	24

4.4 Stand Variables

This section presents the calculation results of stand variables including stand basal area and volume, mean basal area diameter and height, basal area and volume increment and establishment of the relationship between variables.

4.4.1 The Method of Calculating Stand Variables

Standing volume:

$$\mathbf{V} = \sum_{i=1}^{n} v_i \qquad (4.8)$$

Where:

V: standing volume per ha (m^3ha^{-1}),

v_i: individual tree volume (m^3tree^{-1})

As there were no volume functions available for each species we applied the volume function of Dong (2002) to calculate the individual tree volume for all species.

$$V_i = -0.08069 + 0.31144 \times D_i^2 \times H_i \qquad (4.9)$$

Where:

D_i: diameter at breast height (m), and

H_i: total tree height (m).

Mean basal area diameter:

$$d_g = \sqrt{\frac{4 \times BA}{\pi \times N}} \times 100 \qquad (4.10)$$

Where: dg: mean basal area diameter (cm)

BA: stand basal area per hectare (m^2ha^{-1})

N: number of trees per hectare ($trees.ha^{-1}$)

Mean basal area height (hg)

It is calculated from the fitted height curves shown above by inserting dg.

4.4.2 Calculation of Stand Variables

Table 4.8 presents the summary results of calculation of key stand variables including stand basal area, standing volume, mean basal area diameter and mean height for the group A plots in initial time and five years later. Detailed calculation results of stand variables at the first and the second measurement as well as the dead trees between two measurements for each species group can be found in Table 04 in the appendix.

Table 4.8 Growth and yield characteristics of plot group A. iBA- Mean periodic annual increment of basal area; iV- Mean periodic annual increment of standing volume. N*- number of trees per ha including recruit trees between two measurements.

	First measurement					Second measurement					Increment	
Plot	**N*** (trees ha^{-1})	**BA** (m^{2}ha^{-1} yr^{-1})	**V** (m^3 ha^{-1})	**dg** (cm)	**hg** (m)	**N** (trees ha^{-1})	**BA** (m^{2}ha^{-1} yr^{-1})	**V** (m^3 ha^{-1})	**dg** (cm)	**hg** (m)	**iBA** (m^{2}ha^{-1} yr^{-1})	**iV** (m^{3}ha^{-1} yr^{-1})
A1	456	18.35	120.54	22.6	15.1	435	20.74	138.3	24.6	15.7	0.478	3.554
A2	380	20.74	138.31	26.4	16.3	364	23.16	157.61	28.5	16.8	0.484	3.86
A3	440	25.05	192.44	26.9	17.6	406	26.90	208.76	29.0	18.3	0.372	3.264
A4	268	20.77	165.86	31.4	18.1	253	22.66	182.73	33.8	18.7	0.378	3.374
A5	539	19.62	119.98	21.5	13.3	512	21.80	134.77	23.3	13.9	0.434	2.958
A6	409	18.63	130.94	24.1	16.0	385	20.85	149.89	26.3	16.8	0.444	3.788
A7	656	19.36	99.32	19.4	11.3	631	22.14	116.33	21.1	11.9	0.556	3.402
A8	303	10.15	53.83	20.7	11.4	290	11.49	61.34	22.5	12.0	0.266	1.502
A9	381	14.35	77.68	21.9	12.1	365	16.04	87.68	23.7	12.6	0.338	2.002
A10	275	17.60	118.97	28.5	16.5	264	19.56	134.03	30.7	17.0	0.392	3.012
A11	298	15.36	96.47	25.6	14.5	286	17.15	109.13	27.6	15.1	0.358	2.532
A12	570	18.26	103.83	20.2	12.7	551	20.92	121.31	22.0	13.2	0.534	3.496

The data set of group A plots includes two measurements. Because in the first measurement only trees from 6 cm dbh and above were recorded and measured, there was a missing of the recruitment trees entering a diameter of 6 cm between the two measurements. In order to be able to calculate the amount of stand basal area and volume increment of the plots, the dbh of these recruitment trees was assumed to have been 5 cm in the beginning of the period.

The calculation results in Table 4.8 show that, in initial time basal areas range from 10.15 m^2 in plot A8 to 25.05 m^2 per ha in plot A3, the mean basal area in initial time is 18.18 m^2 per ha. These plots have been harvested in the past decades and now they are recovering, thus, resulting the increment of the stand basal area and volume. The mean periodic annual basal area increment ranges between 0.266 $m^2ha^{-1}yr^{-1}$ in plot A8 to 0.556 $m^2ha^{-1}yr^{-1}$ in plot A7, the average annual basal area increment is 0.42 m^2 per ha. After five years because no harvesting in the plots was carried out, only natural mortality occurred and the amount of natural mortality is much less than that of increment, so the basal area per ha at the second measurement increases ranging from 11.49 m^2 in plot A8 to 26.91 m^2 in plot A3, the average basal area is 20.28 m^2 per ha.

Volume is closely related to the basal area, so similar to basal area, the standing volumes of the plots are also different, in initial time, volumes range from 53.83 m^3 in plot A8 to 192.44 m^3 per ha in plot A3. The mean volume is 118.18 m^3 per ha. After 5 years, the volumes per ha increase ranging from 61.34 m^3 in plot A8 to 208.76 m^3 in plot A3. The average volume is 133.49 m^3 per ha. The mean periodic annual volume increment ranges between 1.50 $m^3ha^{-1}yr^{-1}$ in plot A8 to 3.86 $m^3ha^{-1}yr^{-1}$ in plot A2, the average amount of volume increment is 3.06 $m^3ha^{-1}yr^{-1}$.

Mean basal area diameters are proportional to tree number per ha and stand basal area and mean basal area height is closely related to diameter. At initial time, the average basal area diameter and height are 24.1 cm and 14.6 cm, respectively. After a growth interval of five years, the mean basal area diameter and height increase reaching the values of 26.09 cm and 15.1 m, respectively.

For the stands of group B, the first survey was made at the end of 2007, so there is only dataset of one measurement existing. The main stand variables including tree number per ha, stand basal area, standing volume, mean basal area diameter and mean height are presented in Table 4.9. Details of calculation results of the stand variables for three species groups can be found in Table 05 in the appendix.

As mentioned in Chapter 3 In order to obtain long-term growth data that include different competition effects, group B plots were established in the stands with a different range of basal area. These stand basal areas range from 10.23 m^2 per ha in plot B10 to 22.36 m^2 per ha in plot B4. The average basal area in these plots is 15.34 m^2 per ha. The standing volumes range from 47.05 m^3 per ha in plot B10 to 138.09m^3 per ha in plot B4. The average volume in these plots is 85.66 m^3 per ha.

Table 4.9 Growth and yield characteristics of plot group B.

Plot	**N** (trees ha^{-1})	**BA** (m^2ha^{-1})	**V** (m^3ha^{-1})	**dg** (cm)	**hg** (m)
B1	500	19.50	129.31	22.3	14.6
B2	772	17.35	91.26	16.9	11.5
B3	392	17.09	109.44	23.6	12.3
B4	672	22.36	138.09	20.6	13.5
B5	580	13.76	70.78	17.4	11.0
B6	1,124	16.28	81.08	13.6	10.7
B7	712	11.69	48.21	14.5	9.1
B8	328	14.06	88.67	23.4	13.1
B9	420	11.74	62.47	18.9	11.1
B10	616	10.23	47.05	14.5	9.7
B11	720	12.36	59.32	14.8	9.7
B12	640	15.37	81.86	17.5	11.6
B13	696	14.18	69.95	16.1	10.9
B14	472	14.08	82.81	19.5	13.4
B15	824	14.58	74.07	15.0	11.1
B16	900	14.29	65.29	14.2	9.9
B17	516	13.75	82.63	18.4	12.7
B18	352	16.50	102.83	24.4	14.6
B19	504	15.65	92.59	19.9	13.4
B20	1,156	19.86	121.85	14.8	12.8
B21	976	17.41	99.34	15.1	12.9

A preliminary assessment about the relationship between diameter and height in group B plots in order to roughly define site quality shows they are mainly placed on poorer site quality compared to group A plots. In general, the tree number per ha is higher than that of group A plots ranging from 328 in plot B8 to 1124 in plot B6, the average is 660 tree number per ha while the average tree number per ha in group A plots is 395. The average basal area and standing volume of group B plots are lower than those of group A plots.

From the calculation results of stand variables given in Tables 4.8, 4.9 and Tables 04, 05 in the appendix, the values of mean diameter and mean height are summarized in Tables 4.10 and 4.11 below.

Table 4.10 Range of mean diameter and mean height in the stands of group A.

Species group	Range of values of mean diameter (cm)			Range of values of mean height (m)		
	Minimum	Maximum	Average	Minimum	Maximum	Average
1	20.5	37.9	26.9	11.7	19.6	15.3
2	22.5	38.2	27.9	12.5	16.5	13.6
3	11.8	28.0	17.9	8.4	12.0	8.6

Table 4.11 Range of mean diameter and mean height in the stands of group B.

Species group	Range of values of mean diameter (cm)			Range of values of mean height (m)		
	Minimum	Maximum	Average	Minimum	Maximum	Average
1	12.9	25.6	18.2	8.7	14.7	11.9
2	7.2	41.2	21.3	4.3	17.2	12.2
3	9.7	31.7	14.9	6.2	17.3	10.1

The values presented in Table 4.10 show, that the values of mean diameter and mean height of the stand of group A are considerably different between species groups in the same plot. However, in general, mean diameter and height of species group 1 and 2 are similar and usually considerably higher than those of species group 3. In the stands of group B very few trees belong to species group 2 and 3, so the range of values of diameter and height of these two species groups in the plots are high (see Table 4.11).

4.4.3 Relationships between Stand Variables

Fig. 4.7A presents the relationship between standing volume increment and basal area in the twelve plots of group A. As expected, the volume increment seems to strongly relate to the basal area. For plot A8 with the lowest value of basal area (10.15 m^2ha^{-1}), the volume increment is also low. The volume increment increases with increasing basal area and gains a maximum value of 3.86 $m^3ha^{-1}yr^{-1}$ with a basal area of 20.74 m^2. From there, it has a tendency to decrease when basal area continues increasing. This is illustrated by plot A3 with a basal area of 25.05 m^2ha^{-1} but a quite low volume increment of 3.26 $m^3ha^{-1}yr^{-1}$. This is because of the effect of competition on the stand growth at high densities. Seemingly, the tree numbers at highest density cannot compensate the competition-induced growth reduction of the individual trees. This relationship will also be very valuable in the context of modelling because it allows deriving maximum stand densities as guidelines for simulating mortality. Fig. 4.7A also illustrates that the plots cover a wide range of stand densities with a corresponding wide range of growth reactions. Fitting the growth model with data from these plots will make it flexible in terms of growth reactions to different treatment concepts.

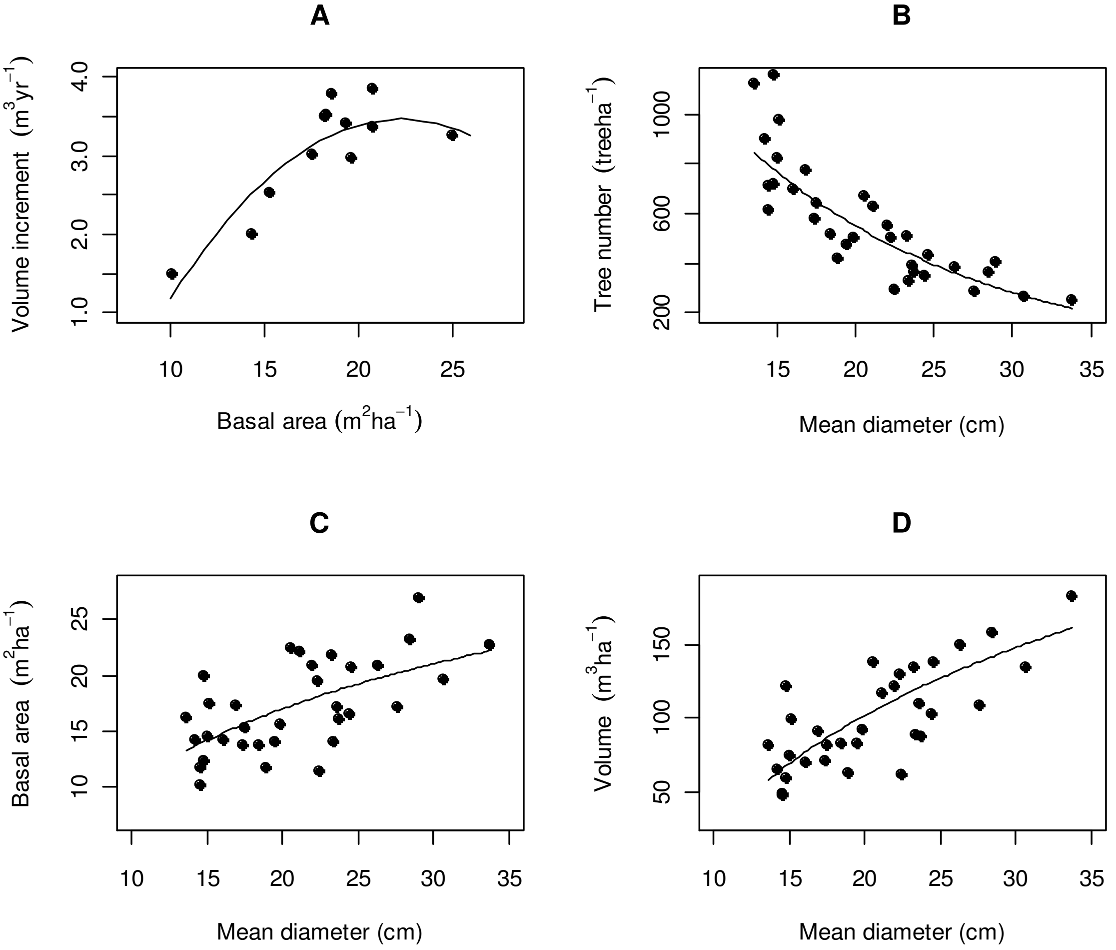

Fig. 4.7 Relationships between important stand variables; A- relationship between basal area and volume increment for the group A plots; B - relationship between mean diameter and tree number for both group plots; C - relationship between mean diameter and basal area for both group plots; D- relationship between mean diameter and standing volume for both group plots.

To formulate the relationship shown in Fig. 4.7A mathematically, a parabola function was fitted:

$$y = -0.015 \times BA^2 + 0.674 \times BA - 4.055 \qquad R^2 = 0.79 \qquad (4.11)$$

where:

y: mean periodic annual volume increment (m^{3}ha^{-1}yr^{-1})

BA: stand basal area (m^{2}ha^{-1}).

Fig. 4.7B highlights the relationship between mean diameter and number of trees over the plots A and B, it indicates that the number of trees per ha is negatively proportional to mean diameter, the number of trees very high in the stands with small trees and low in the stands with big trees. Such relationships will be very valuable in the context of modelling because they allow to derive maximum stand densities as guidelines for simulating mortality. The plots B6, B20, B21 have very small mean diameters: 13.6; 14.8; 15.1cm and very high tree numbers: 1,124; 1,156; 976 per ha respectively, while the plots A4 and A10 have big mean diameters: 33.8; 30.7 cm and low tree numbers: 223; 264, respectively.

To formulate this relationship mathematically, a negative exponential function was used and successfully fitted:

$$N = 2090.4 \times e^{-0.0667 \times dg} \qquad R^2 = 0.758 \qquad 4.12)$$

where:

N: number of trees per ha, and

dg: mean basal area diameter (cm).

Fig. 4.7C and 4.7D illustrate the relationships between basal area, standing volume per hectare and mean diameter. It is evident that the bigger the mean diameter, the higher the basal area and standing volume. For the plots B7 and B10 whose mean diameter are 14.5 cm, the basal areas are 11.69 and 10.23 m^2 per ha, the volumes are 48.21 and 47.05 m^3 per ha, respectively. In the plots with large mean diameters, basal area and standing volume are also high. For example, in the plots A2, A3 and A4 with mean diameters of 28.5, 29 and 33.8cm, the basal areas are 23.76, 26.9 and 22.6 m^2 per ha, the volumes in these plots are 157.61, 208.76 and 182.73 m^3 per ha, respectively.

Mean diameter clearly affects the basal area and standing volume, but it is not their only determining variable. The plots with similar mean diameters but different numbers of trees have very different basal areas and standing volumes. For example, in the plots A8 and A11 whose quite big mean diameters: 22.5 and 27.6 cm, but the basal areas and standing volumes are low: 11.49 and 17.15 m^2, 61.34 and 109.13 m^3, respectively. That is because the number of trees in these plots is very low, only 276 and 271 trees, respectively.

The data sets obtained from the research plots and the calculation results of stand characteristics in this chapter are the base for developing the forest growth model. The growth model will be calibrated based on different site quality levels and species groups and depend on stand density. Once the model was developed, an evaluation of the model will be partly done based on the comparisons between the simulating results and the calculation results of this chapter. In the next chapter, we present how the growth model will be constructed, the working principle of the model as well as how to parameterize the main components of the model.

Chapter 5

Model Conception and Parameterization

In this study we develop a size class, multi-species model based on differential equation systems for modelling the growth and yield of the Dipterocarp forests in Central Highlands of Vietnam and name it DIPGROW. Typical models of this type are, as shown in paragraph 2.3, those developed by Stephens and Waggoner (1970), Brunner and Moser (1973), Leak and Graber (1976), Campbell (1981), Howard and Valerio (1992), Lin *et al.* (1998). This chapter focuses on describing the structure and principle of the model approach and developing the model.

5.1 Model Conception

5.1.1 The Concept of System Dynamics Diagrams

The so-called System Dynamics Diagrams (Forrester, 1961) explained shortly in this paragraph are an ideal notation for representing differential-equation based models graphically. As time step in the presented model is not assumed to be infinitesimally small, but is set to a discrete step of one year, these equations are difference equations, not differential equations in the strict sense of the word. However, the more common term "differential equation" is used throughout this text.

Conveniently, the simulation software Vensim DSS 5.7a which will be used for model implementation supports graphical model design with System Dynamics Diagrams. The method is based on the conventions of System Dynamics, a field of science initiated by the works by Jay Forrester (Forrester, 1961, 1968, 1969). For an overview of the field see Sterman (2000). System Dynamics emphasizes the role of feedback as a key to understanding the behaviour of systems. As forests are profoundly feedback-driven systems –the change of a forests state is highly dependent on the current state itself- such software offers itself as an ideal tool for the purpose of this study.

A System Dynamics Diagram (SD-Diagram, Stock and Flow Diagram) has four key elements (see Sterman (2000) for detailed explanations):

1) State variables of a system are noted as rectangles (usually called stocks or levels).

2) Flows are the processes that change state variables (by draining or filling stocks). They are noted as pipes with an arrowhead and are at least connected to one stock. Often, they connect two stocks.

3) Auxiliary variables can be all kinds of constants or auxiliary calculations. They are denoted just by their name.

4) Arrows denote all kinds of dependencies between variables, except the influence from flows to stocks.

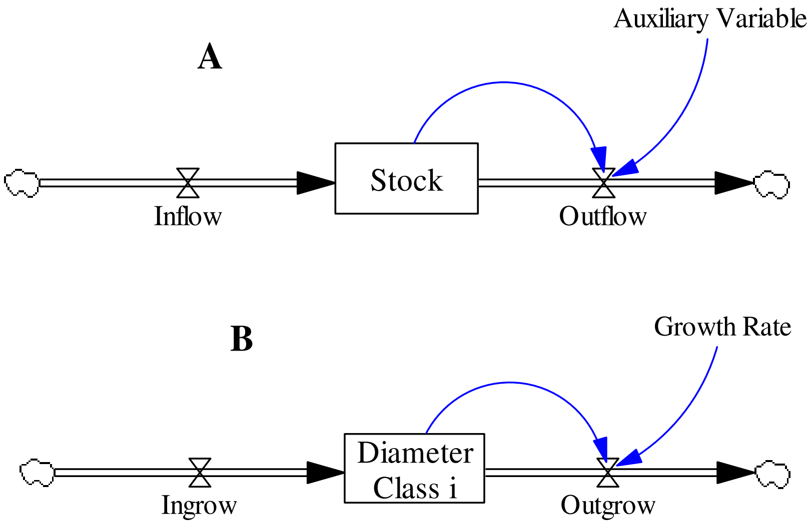

Fig. 5.1 System Dynamics Diagram notation.

Fig. 5.1 shows the key elements of a SD Diagram. 5.1A denotes an abstract system, where a Stock is incremented by an Inflow and drained by an outflow which is dependent on an auxiliary variable and the current value of the stock itself. 5.1B shows the same structure as it can be found in the growth model represented here. The stock represents the number of trees in a given diameter class, while there is ingrowth from lower classes and outgrowth in higher classes. The outgrowth in this example is dependent on a transition rate and the quantitative accumulated in the stock itself. If a flow is directly or indirectly dependent on a stock that it is changing, this constitutes a feedback mechanism. Sometimes it is convenient to note the so-called link-polarity at an arrowhead in an SD diagram. A + sign denotes a positive polarity, meaning that cause and effect change in the same direction when everything else stays constant. A – sign denotes a negative polarity, meaning that cause and effect change in opposite directions.

Mathematical representation of stocks and flows:

The quantity of material in any stock is the accumulation of the flows of material in less the flows of material out. Thus, a stock and flow diagram has a precise and unambiguous mathematical meaning. Stocks accumulate or integrate their flows; the net flow into the stock is the rate of change of the stock. Therefore, the structure represented in Fig. 5.1A above corresponds to the following integral equation:

$$Stock(t) = \int_{to}^{t} [Inflow(s) - Outflow(s)]ds + Stock(t_0) \tag{5.1}$$

where: Inflow(s) represents the value of the inflow at any time s between the initial time to and the current time t. Stock(to) is the material at the initial time to. Equivalently, the net rate of change of any stock is the inflow less the outflow, defining the differential equation:

$$\frac{\Delta(Stock)}{\Delta t} = \frac{\Delta(Inflow)}{\Delta t} - \frac{\Delta(Outflow)}{\Delta t} \tag{5.2}$$

5.1.2 Model structure and Implementation

This section describes the structure as well as working principle of the primary components of the DIPGROW model. The basic structure of the model is formed by a large number of narrow diameter classes that are represented as stocks and subsequently connected by flows representing in- and outgrowth from the respective classes. Such a chain is implemented for each species group. The main components of the growth model changing the tree number in each diameter class are ingrowth, outgrowth, mortality and harvesting (Fig. 5.2).

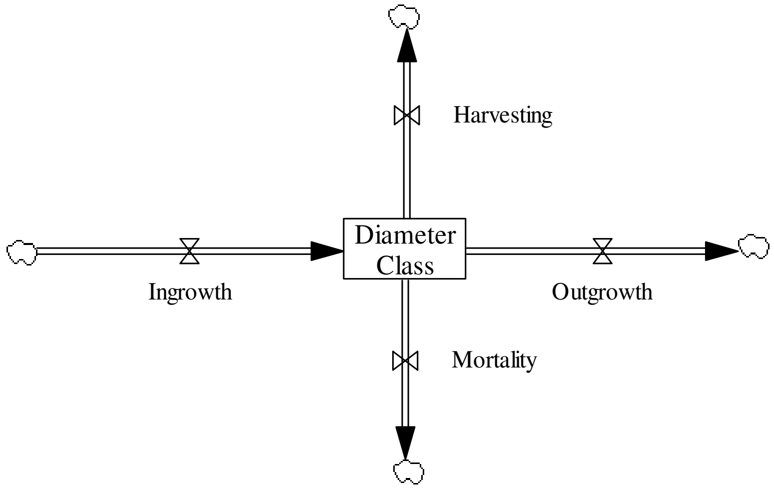

Fig. 5.2 Stock- and Flow-structure of a diameter class.

At first, it is necessary to explain the meaning of the variable names in the diagram above.

- Diameter Class: number of trees per ha in the diameter class,
- Mortality: number of trees in the class dying in a simulation interval (one year),
- Harvesting: number of trees in the class being harvested in a simulation interval,
- Ingrowth: number of trees growing into the class from the next lower class in a simulation interval,
- Outgrowth: number of trees growing out of the class into the next higher class in a simulation interval, where the ingrowth into the lowest diameter class is constituted by recruitment. The highest class serves as a container for very large trees and therefore has no outgrowth.

Each of the flows connected with a diameter class can be expressed as a function of the current stand characteristics, and is thus formulated as a differential equation. This set of differential equations (base functions) altogether describes the net changes in the tree number, Δ(Diameter Class$_i$) / Δt in the diameter class i:

$$\frac{\Delta(Diameter\ Class_i)}{\Delta t} = \frac{\Delta(Ingrowth)}{\Delta t} - \frac{\Delta(Outgrowth)}{\Delta t} - \frac{\Delta(Mortality)}{\Delta t} - \frac{\Delta(Harvesting)}{\Delta t} \qquad (5.3)$$

The time step Δt presented in the model is set to a discrete step of one year. In order to avoid a confusing model formulation, the dependencies of in-, and outgrowth, mortality and harvesting on stand characteristics are mathematically disaggregated into convenient sub-functions (control functions). Thus, the actual differential equations can be kept reasonably simple.

The distributions of tree number at time t_0 taken from inventories provide initial values for the simulation run. The tree numbers in the different diameter classes from t_0 to t_n are obtained by stepwise numerical integration of the differential equations over the time intervals t_0-t_1, t_1-t_2, ..., t_{n-1}-t_n. Based on the tree numbers per diameter class, the control functions calculate the relevant stand and size-class attributes and other intermediate variables in each time step. Hereupon, the base functions change the stem number in each size class for the current time step. The new stem numbers in each size class are used as input variables for the control functions in the subsequent time step.

The major components of the DIPGROW model as implemented in the Vensim software are shown in the following text:

Outgrowth

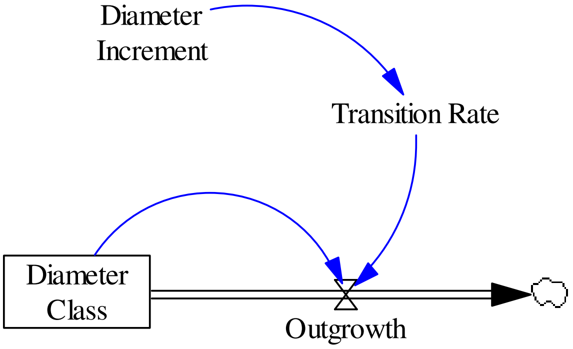

Fig. 5.3 Principle of tree transition from one class to the successive higher class.

Fig. 5.3 explains the principle of trees from diameter class i moving up to diameter class i +1. For each time step, Outgrowth, the number of trees in a class moving to next higher class can be defined as follows:

$$Outgrowth = Diameter\ Class \times Transition\ Rate \qquad (5.4)$$

Transition Rate (1/year) is understood as a relative rate. It can be interpreted as the probability that a survival tree moves from one diameter class to the next in one time step. According to Schütz (2006) it is defined as:

$$Transition\ Rate = \frac{1}{a} I_d \qquad (5.5)$$

where *a* is the width of each diameter class, defined as 1 cm in this study. And I_d is the estimated annual diameter increment of an average tree in the diameter class. It is a function dependent on tree size and conditions of the stand, especially its density. This is a key function of the model; it will be shown in detail in 5.3.1.

Recruitment

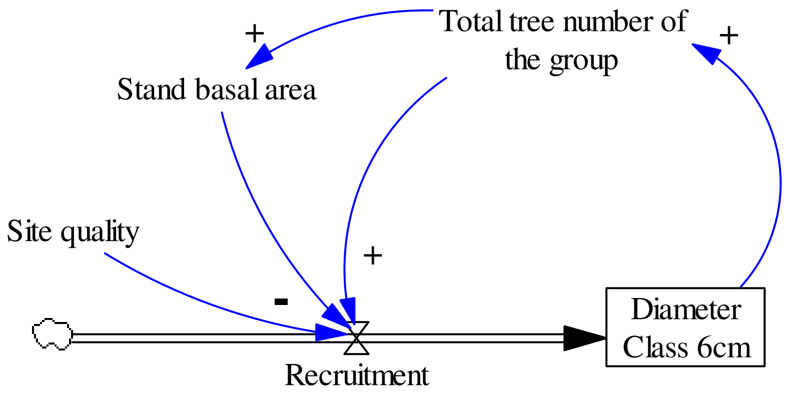

Fig. 5.4 Diagram of recruitment to the smallest diameter class of 6cm.

Recruitment is expressed by the number of trees entering the smallest diameter class of 6 cm each year. Fig. 5.4 presents a description of the relationship between the recruitment and relevant variables. The number of recruits per year for each species group is a function accounting for variables including site quality, total stand basal area and the total tree number of the respective species group (summed up over all diameter classes). In detail, the recruitment function will be shown in 5.3.3.

Recruitment has a positive relation to tree number of the species group and negative relation to stand basal area. Therefore, there are two feedback loops in this diagram. The negative feedback loop shows that higher recruitment leads to higher total number of trees in the stand and, thus, higher stand basal area. However, when stand basal area increases, the recruitment will decrease. On the other hand, the positive feedback shows that more trees generate more recruitment, thus generating more trees. Thus, the positive feedback loop keeps recruitment going, the negative one regulates it down.

Mortality

The number of dead trees in each year is defined by the following formula:

$$Mortality = Diameter\ Class \times Mortality\ Rate \tag{5.6}$$

where: Mortality Rate is probability of a tree dying in a year, it is a function which incorporates variables such as diameter midpoint of the class, stand basal area and basal area of larger trees. It will be presented in detail in 5.3.2.

The structure of the mortality model (Fig. 5.5) illustrates two negative feedbacks. Higher tree number increases the stand basal area and basal area of larger trees, thus leading to a higher mortality rate and higher mortality. However, higher mortality in turn will cause the tree number to decrease. This feedback is controlled the competition among trees in the stand and can –together with tree growth- self-regulate the stand density and lead naturally to stabilization state of the stand. In this figure, basal area of larger trees is related to the tree number of the stand; however, it is generated by only a half of the trees which are counted as larger.

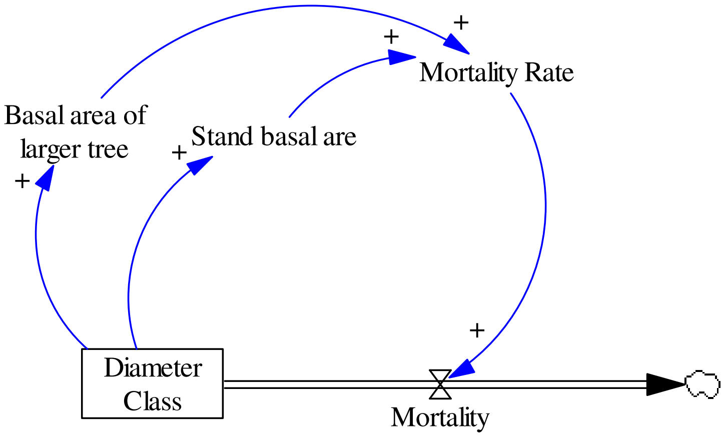

Fig. 5.5 Structure of the mortality model for each diameter class.

Harvesting

Harvesting is represented by the number of living trees harvested per ha in each cutting cycle. The model was constructed to allow harvest to be able to take place in cycles with any desired intervals. Several harvesting schemes may be applied (see Lin *et al.*, 1998; Kammesheidt *et al.*, 2002; Liang *et al.*, 2005; Tietjen and Huth, 2006). The following management guides were considered:

1) Diameter-limit cut: removal of all trees larger than a given diameter class. The maximum diameter of trees to be left depends on species group and site quality as well as on the management purpose.

2) Proportion harvesting rule: in each diameter class, a certain proportion of trees α_h may be harvested during a cycle. A special case is for example:

$\alpha_i = 1$ for $h \geq i$, and

$\alpha_i = 0$ otherwise

in this case all trees in diameter class i and above would be harvested, but none of the others (it becomes the method of diameter-limit cut). Another special case is that all $\alpha_h = 0$ representing an undisturbed forest. (Lin *et al.*, 1998)

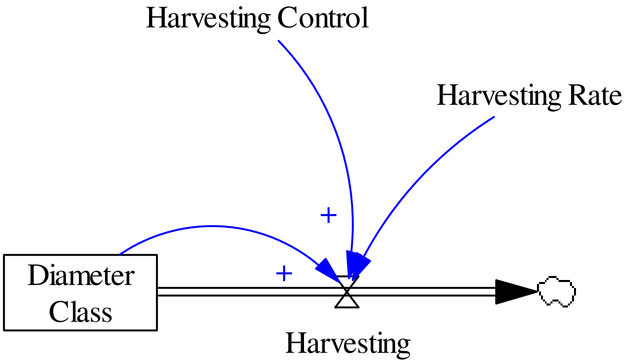

Fig. 5.6 Structure of the harvesting model for diameter limit cut and proportion harvesting rule.

The harvesting methods 1 and 2 are illustrated by Fig. 5.6 and the number of trees harvested in each diameter class each cycle was defined as follows:

$$\textit{Harvesting} = \textit{Diameter Class} \times \textit{Harvesting Rate} \times \textit{Harvesting Control} \quad (5.7)$$

where:

Harvesting Rate: the proportion of trees to be cut in each diameter class.

Harvesting Control allows harvest to occur only in the time interval specified as harvesting cycle by the way that it takes only the values of zero and one. Harvesting Control equals one if harvest takes place and zero otherwise.

$$\textit{Harvesting Control} = \textit{IF THEN ELSE(MODULO(Time, Harvesting Cycle)=0, 1, 0)} \quad (5.8)$$

Where:

Time is years from the beginning of the simulation.

This formula is Vensim code in which *MODULO (Time, Harvesting Cycle)* is a function that takes the value of remainder of the division of Time with Harvesting Cycle. At the time of each harvesting cycle, the value of the remainder is equal to zero so the value of *MODULO(Time, Harvesting Cycle)* is equal to zero resulting Harvesting Control is equal to 1.

3) q-factor guide: as suggested by Williston (1978), the desired stand state is determined by the remaining basal area, the q ratio (the slope of the stem number-diameter distribution), and the largest diameter class.

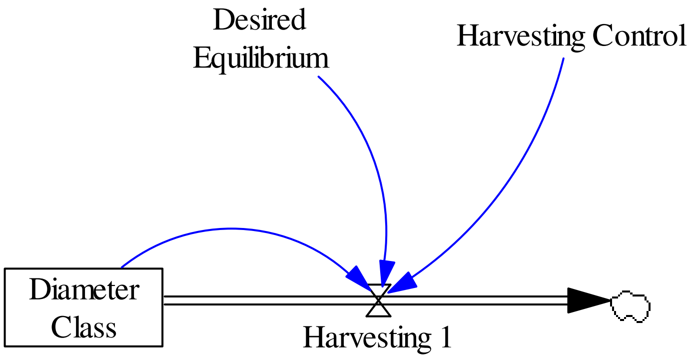

Fig. 5.7 Structure of the harvesting model for q-factor guide.

After defining the forest distribution goals, the amount of trees to be harvested can be calculated during simulation by comparing the number of trees in each diameter class between the goal distribution and actual distribution, any excess of trees over the target number in any class would be cut.

$$\text{Harvesting} = \max(0, \text{Diameter Class} - \text{Desired Equilibrium}) \times \text{Harvesting Control} \quad (5.9)$$

where: Desired Equilibrium is the tree number in the class of the desired stand state in the respective diameter class. The cutting could take place in cycles with user- defined length, but a harvest would occur only if Harvesting Control was not zero, according to equation (5.8).

As the definition of a target state by the q-factor method will play an important role in the model applications presented later, it deserves a short explanation: the quotient q between the number of trees in successive diameter classes is a widely accepted means of calculating the desired distribution (Alexander and Edminster, 1977). Accordingly, the ratio of the tree numbers N in adjacent size classes remains constant:

$$\frac{N_1}{N_2} = \frac{N_2}{N_3} = \cdots = \frac{N_{i-1}}{N_i} = q \quad (5.10)$$

The diameter distribution of uneven-aged forests in equilibrium typically tends towards an inverse J-shaped curve, as described by the negative exponential function:

$$N_i = k \times e^{-a \times Di} \quad (5.11)$$

Where: N_i and D_i are number of trees per ha and midpoint of the i^{th} diameter class, respectively. Parameters a and k determine slope and scale of the distribution. The constant a controls the the rate at which number of trees change between successive diameter classes. The value of a can be calculated according to quotient q from the following equations:

$$N_i = k \times e^{-a \times Di} \tag{5.12}$$

$$\rightarrow \quad N_{i+1} = k \times e^{-a \times (Di + h)} \tag{5.13}$$

where h is the width of the diameter classes.

From (5.10), take (5.12) divided by (5.13), it is given:

$$q = \mathrm{e}^{\mathrm{a \times h}} \tag{5.14}$$

$$\rightarrow \quad a = (ln\ q) / h \tag{5.15}$$

The value of q can be estimated for a given set of stand inventory data by using the linear regression (by taking the logarithm of both sides of equation (5.11)):

$$Ln\ N_i = b_0 + b_1 \times D_i \tag{5.16}$$

where b_0 and b_1 are parameters to be estimated ($b_0 = \ln k$, $b_1 = -a$).

And from that equation, we can deduce the value of q by the formula:

$$q = e^{-b_1 \times h} \tag{5.17}$$

The stand basal area can be calculated by the follwing formula:

$$BA = \sum \tfrac{\pi}{4} \times D_i^{\,2} \times N_i \tag{5.18}$$

substituting equation (5.11) to equation (5.18), the parameter k may be expressed as:

$$k = \frac{BA}{\sum_i \frac{\pi}{4} \times D_i^2 \times e^{-D_i \times (\ln q)/h}} \tag{5.19}$$

Finally, the number of trees in each diameter class can be estimated with equation (5.11) by substituting the values of a and k defined above.

System dynamics diagram of the simulation model

Fig. 5.8 shows the complete SD Diagram for the DIPGROW model, however in a condensed notation that includes all diameter classes with the connected flows in one. This notation allows to give an impression of the overall model complexity without leading into confusion. Actually, the relationships shown in Fig. 5.8 are in effect for each diameter class in each species group. While the text in this chapter presents the essential equations and variables only, the complete set of model equations and variables as shown in Fig. 5.8 will be listed in the appendix.

A growth model of the chosen type only performs correctly when the diameter classes are adequately narrow. Thus, a class width of 1 cm was chosen. The model was set up to simulate in discrete time steps of one year. These settings also ensure for the investigated dipterocarp forests, that no tree can be expected to move more than one diameter class in a single time step. Therefore, the resulting model consists of 76 one-cm diameter classes ranging from 6 to 81 cm dbh for the three species groups, the last class gathering all trees with diameters above 80.5 cm. As described above, each diameter class stores its number of trees which can change by ingrowth from lower diameter classes, outgrowth into higher classes, mortality, and harvest. From the number of trees in each diameter class and each species group, the aggregated stem numbers such as total stem number by species group, stem number across species for diameter classes with a given width of 5 or 10 cm, etc. can be easily calculated, just by summation of the corresponding values of the diameter classes. And similarly, from the stem number and the values of diameter classes, it is easy to calculate the values of various basal areas such as basal area of different diameter classes, stand basal area by species group, total stand basal area, cumulative basal area or basal area of larger trees than subject tree. These are very important indices and they are used as an approved measure of competition for calibrating ingrowth, outgrowth and mortality functions of the model. The values of volume such as standing volume and harvesting volume are also defined similarly by incorporating the height functions established according to each species group and site quality level which were presented in the previous chapter.

From a feedback view, the model includes four processes that change the number of trees in a diameter class: ingrowth (for the smallest diameter class of 6 cm, it is the recruitment), outgrowth, mortality and harvesting. All of these four processes are influenced by the condition of the stand, being derived from the tree numbers in the diameter classes such as stand basal area, basal area of larger trees (or cumulative basal area denoted as in the model). Vice versa these processes in turn are changing the stand condition. This feedback is the most important driver for stand dynamics and must be covered adequately by a simulation model. In particular, ingrowth and outgrowth decrease as basal area increases and mortality increases when basal area increases. This self-correcting mechanism has the potential to lead naturally to stabilization of the stand, although, as will be shown later, the time path towards stability may be slow and oscillatory.

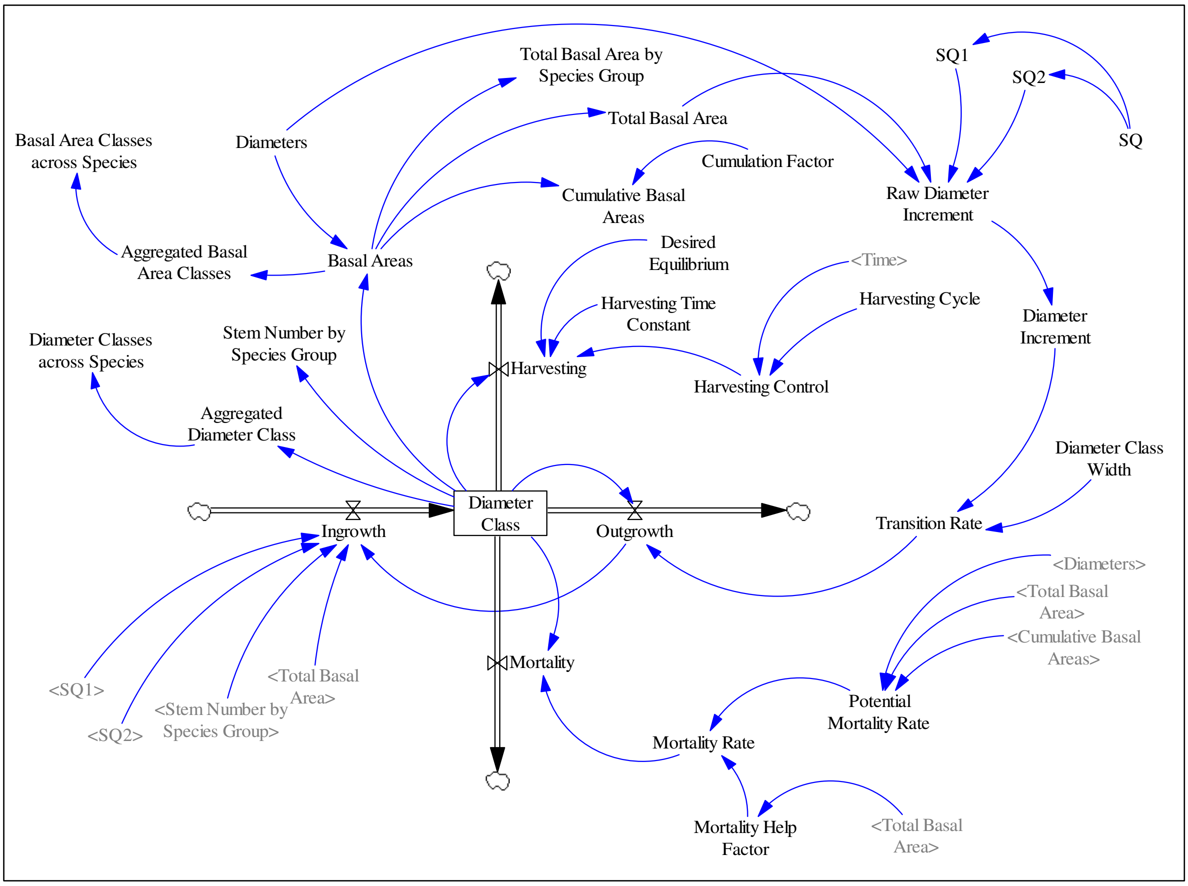

Fig. 5.8 Complete SD Diagram of the simulation model DIPGROW. Variables and equations that are not in the text can be found in the appendix.

As presented before, the four key processes affecting each diameter class are determined through following component models: recruitment, diameter increment, mortality and harvesting. The first three component models are developed with the empirical data from the permanent plots as will be explained in detail in the next paragraph.

5.2 Development of the Major Components of the Growth Model

5.2.1 Diameter Increment Model

For estimating the outgrowth of a diameter class, an estimation of the annual diameter increment of an average tree in the class is needed. For expected annual diameter growth, most models suitable for mixed forests predict individual tree growth explicitly, often with equations to estimate diameter increment from tree diameter and other variables

(Vanclay, 1994; Kolbe, 1999; Palahí, 2003; Schütz, 2006). According to Vanclay, these equations are usually fitted with data from re-measured permanent plots on which trees have been individually identified. Some alternatives such as stem analysis exist where such data are not available, but these approaches are generally less accurate.

It is often convenient to model diameter increment directly, but this is not the only alternative. Individual tree growth may be simulated as basal area increment or as diameter increment (Ong *et al.*, 1996; Liang, 2005). Tree diameter increment and basal area increment are related mathematically, and any apparent differences in the goodness-of-fit may be due to differences in the error structure and implied functional relationship, rather than the superiority of one model than the other (Vanclay, 1994).

The increase in tree diameter can be also expressed as a yield function that predicts the future diameter, or as a growth function which estimates the increment over a specified period. Yield equations can be differentiated to form growth equations and thus to provide compatible growth and yield estimates.

In this study, a growth rather than a yield model was chosen for predicting diameter increment because the implications regarding serial correlation of errors are minimized.

Based on the available dataset and biological processes associated with tree growth, the following variables at the tree-level and stand-level are considered as potential predictor variables in the diameter increment models developed later.

Diameter at breast height (D), diameter squared (D^2)

Many variables such as age, top height and site quality used in plantation growth models have little relevance in mixed-species stands. In uneven-aged forest, tree size (usually diameter) might be a better variable than tree age for growth models, and thus, has been widely used in modelling individual-tree growth (Monserud and Sterba, 1999; Vanclay, 1995; Zhao *et al.*, 2004).

The shape of a typical diameter increment curve relative to diameter is unimodal with a maximum at a level of diameter depending on the species. That is, diameter increment increases to a maximum point and then slowly decreases, approaching zero when tree matures (Wykoff *et al.*,1982). The variables diameter and diameter squared were included in the growth model to capture this trend.

Other transformation variables of diameter: 1/D, $D/\bar{D}$

Some transformations of diameter such as reciprocal of diameter (D^{-1}) and relative diameter ($D/\bar{D}$) can be used to develop the diameter increment model. Relative diameter ($D/\bar{D}$) is ratio of tree diameter (D) to mean stand diameter ($\bar{D}$). These two above variables were included in the growth model to test the hypothesis that the increment of small trees in one stand is more strongly affected by relative size than that for large trees in a different stand, even though both of small trees and large trees are at the same relative position in the diameter distribution within their stands (Wykoff, 1990).

Competition measure

The degree of competition among individual trees in forests greatly influences their growth. In this study, spatial information from mapped tree locations is not available, so only distance-independent competition indices were used to develop diameter increment functions, thus results the distance-independent model. Competition can be expressed by several stand density indices.

Competition amongst trees can be one-sided or two-sided. In one-sided competition, larger trees are at a competitive advantage over small trees, but smaller neighbors do not affect the growth of larger trees (Cannell *et al.*, 1984; Ford and Diggle, 1984). In this case, light rather than other environmental resources is the major limiting resource and competition for light is expressed as the primary cause of size inequality and self-thinning in crowded populations. The basal area of larger trees has been found to be a useful predictor and is commonly used to capture one-sided competition in modelling tree growth (Wykoff *et al.*, 1982). In two-sided competition, all trees exhibit some competition on their neighbors, regardless of their sizes (Cannell *et al.*, 1984). This type of competition is usually for below ground resources such as moisture and nutrients. In addition, larger trees have an intrinsic disadvantage because tree growth is sigmoidal, even without competition. The relative growth rate of trees decreases with size and the competitive advantage of larger trees are reduced by their intrinsic growth disadvantage (Schwinning and Weiner, 1997).

Stand basal area is a good measure for stand density and competition since it combines both tree size and number. At the same stand development stage, trees in a stand with larger basal area are likely to experience more competition than trees in another stand with smaller basal are given a regular spacing pattern. Therefore, stand basal area was used as a predictor variable to capture two-sided competition.

Site effects

Diameter increment is also considerably affected by site quality. The two following dummy variables were set to identify the effects of three site quality levels on diameter increment and they are coded as follows:

SQ1	SQ2	
Poor	0	1
Medium	1	0
Good	0	0

5.2.2 Mortality Model

Tree mortality is a very complicated process and is generally the result of complex interactions among multiple factors such as environmental, physiological, pathological and entomological factors, as well as some random events. Tree death is often a gradual process, although it can be abrupt sometimes (Waring, 1987).

There are several factors which affect on mortality, the causes of mortality can be differentiated to two major categories of mortality: natural mortality and human-related mortality. Natural mortality includes regular and catastrophic mortality. Regular mortality refers principally to ageing, suppression and competition, but also from normal incidence of pests, diseases, and weather phenomena. Catastrophic mortality includes wildfire, severe weather conditions and major pest and disease outbreaks.

Human-related mortality includes planned harvesting, silvicultural treatment, and any deaths which may arise indirectly from these activities.

This study evaluated only regular mortality involving the factors such as ageing, suppression and competition because only these factors are included in the dataset. It was not considered to catastrophic and human-related mortality.

Theoretically, both probability of survival and probability of mortality can be modeled. In this study, probability of mortality rather than survival was modeled.

Many methods for predicting mortality have been developed. The simplest stand-level of accounting for mortality is to apply an annual fixed percentage reduction in the population, resulting in a negative exponential survival function. This is used for modelling mortality in very young stands where stand information is restricted to stem stocking and stand height (Burgman *et al.*, 1994). Stand density approaches (Yoda *et al.*, 1963) indicate only the residual stocking and give no indication of survival of individuals. Hamilton (1986, 1990) proposed the use of logistic functions to predict survival rather than mortality. Hamilton and Edwards (1976) presented a robust function which predicts survival from tree size and stand density. Liang *et al.* (2005), Lin *et al.* (1998) estimated the mortality rate using linear functions. Of the methods mentioned above, logistic regression appears to be the best method for individual tree mortality modelling and has been widely applied (Monserud, 1976; Vanclay, 1991; Burgman *et al.*, 1994; Yang *et al.*, 2003; Zhao *et al.*, 2004).

Mortality can be modeled either annually or every n years with n equal to the measurement interval. For data with unequal measurement intervals, annual mortality rate is generally modeled. The data used in this study have an equal measurement interval of 5 years. However, in order to embed to the model in this study, mortality rates were discounted to obtain annual rates. The procedure to transform mortality rates for n years to annual mortality rates is as follows:

The probabilities of survival (P_s) and mortality (P_m) are mathematically connected by the standard identity:

$$P_s = 1 - P_m \tag{5.20}$$

We use the compound interest formula to convert survival to other period lengths:

1-year: $$P_{s1} = 1 - P_{m1} \tag{5.21}$$

n-year: $$P_{sn} = P_{s1} \times P_{s1} \times .... \times P_{s1} = (P_{s1})^n = (1 - P_{m1})^n \tag{5.22}$$

1-year: $$P_{m1} = 1 - P_{sn}^{1/n} = 1 - (1 - P_{m\,n})^{1/n} \tag{5.23}$$

When establishing the mortality model the following variables at the tree-level and stand-level are evaluated as potential predictors:

Diameter at breast height (D), diameter squared (D^2), and the reciprocal of diameter (D^{-1})

Like in growth models as mentioned before, tree size is often used as a predictor in mortality functions instead of tree age due to the lack of information of individual tree age. This variable has been widely used in modelling individual tree mortality (e.g. Buchman *et al.*, 1983; Wykoff, 1990; Vanclay, 1995; Monserud and Sterba, 1999; Yao e*t al.,* 2001).

Mortality rates are often high for small trees because of the competition of larger trees, decreasing with increasing tree size. However, as trees continue to grow larger, the probability of mortality starts to increase again. Larger trees normally associated with the senescence, they are easy vulnerable to disease, wind and other mortality factors (Silvertown, 1982; Harcombe, 1987). This U-shaped mortality trend could be captured by diameter (D) and diameter squared (D^2). In addition, for most species, the mortality rate for the smallest trees is quite high, and declines quickly as trees become larger, a hyperbolic D^{-1} transformation of diameter should capture this nonlinear effect. Therefore, in this study variables diameter (D), diameter squared (D^2) and reciprocal of diameter (D^{-1}) were selected as predictor variables.

Competition factors

Similar to tree growth, the competition influencing mortality can be expressed by stand density measures as both one-sided and two-sided competition which are expressed by basal area of larger trees and stand basal area.

Site quality

Site quality may affect on the mortality rate. So it is also considered as a potential predictor in this study.

Diameter increment

Diameter increment has been used to develop the individual tree mortality model in several studies (e.g. Buchman e*t al*., 1983; Hamilton, 1986, 1990; Palahí e*t al*., 2003). According to Hamilton (1986), average annual diameter growth rate for the preceding measurement period should be one of the best predictors of probability of mortality. Some studies (Hamilton, 1986; Dobbertin and Biging, 1998) reported that mortality rates were higher for trees with reduced growth rates. Although diameter increment was indeed an important variable in describing tree mortality, it was not considered as a predictor variable in this study because the data of preceding increment of the dead trees was not available.

5.2.3 Recruitment Model

In natural forests, regeneration is an essential component of selection harvesting systems. Thus, the amount of this regeneration should be taken into account (Vanclay, 1992). According to Vanclay, there are two approaches to predicting regeneration and recruitment. Regeneration models predict the development of trees from seed or seedlings, and recruitment models predict the number of stems reaching or exceeding some specified size limit (e.g. 1.3 m height or 10 cm dbh, etc.). As suitable data for modelling regeneration are often difficult to obtain, recruitment rather than regeneration models is mostly used in growth and yield models.

For recruitment models, it is convenient to differentiate two approaches:

- Static approaches which take relatively little account of stand condition and thus predict a fairly constant amount of recruitment indicating the long-term average expectation under typical conditions. One common assumption is that the number of trees in the smallest class remains unchanged, irrespective of outgrowth to the next class, and of the total stand density (e.g. Buongiorno and Michie, 1980).
- Dynamic approaches which respond to stand condition, predicting recruitment as a function of stand density, composition, and other parameters.

Variables used in recruitment models are commonly site productivity, stand density (e.g. stand basal area, stem number, competition factors).

As indicated by Vanclay (1992), one of the difficulties in modelling recruitment is the great variability in regeneration. Much of the variability associated with regeneration is due to the fact that during any period some regeneration may or may not occur, and that if the data are portioned in to a two-stage system, the ability to predict the amount of regeneration is greatly enhanced. With this approach, the first equation predicts the probability that some recruitment will occur, usually with a logistic function with presence (or absence) of recruitment as the response variable. The second stage is a conditional function which can be used to estimate the number of recruits, given that some is known to occur. This conditional function can be estimated using ordinary linear regression (Ferguson *et al.,* 1986, Stage and Ferguson, 1982) .

For natural uneven-aged mixed forests, the two-stage approach is more practical for predicting the recruitment. However, the data required for applying this method is not available.

For this study, based on available data, a linear regression model of recruitment is used with the incorporation of the potential variables including stand density and site quality.

5.3 Results of Model Parameterization

When selecting the equations of diameter increment, mortality and recruitment, the following criteria were applied:

- Any relationship that violates accepted biological principles should be rejected, even if it results in efficient predictions for a particular data set.
- goodness of fit, statistical significance of the parameters and unbiased distribution of residuals, and
- simplicity and parsimony.

All statistical computations reported in this chapter were done with the free statistic software R (R Development Core Team, 2008)

5.3.1 Diameter Increment Model

A preliminary examination of the data set suggested that there were differences between the patterns and the rates of diameter increment of the species groups. The pattern of diameter growth for species group 3 was clearly different from those of species group 1 and 2, and the growth rate between species groups was also different. Due to these differences, the data were separated in order to establish the same function with separate parameter estimates for each species group.

When fitting different forms of growth functions, the variables distinguishing inter-specific and intra-specific competition, transformations of diameter such as 1/D, $D/\bar{D}$, and basal area of larger trees did not show obvious trends. So they were not included into the final growth model. The predictor variables determined above were tested with various forms of functions using the empirical single tree increment data described in Chapter 4 and the results of fitting different functions were compared to select the best function. Finally, the follwing form turned out to be best:

$$I_d = a_1 \times D^b + a_2 \times D + a_3 \times BA + a_4 \times SQ1 + a_5 \times SQ2 \qquad 5.24)$$

where:

I_d: estimated annual diameter increment (cm $year^{-1}$),
D: diameter at breast height (cm),
BA: stand basal area (m^2 ha^{-1}),
SQ1: dummy variable, takes the value 1 with site quality 2 (medium site quality) and 0 otherwise,
SQ2: dummy variable, takes the value 1 with site quality 3 (bad site quality) and 0 otherwise, and
a_j, b : parameters to be estimated.

Table 5.1 The estimated parameters and fit statistics of the tree diameter increment models by species group. Standard errors are given in parentheses, R^2 = coefficent of determination, df = degrees of freedom. Significant level: '***' 0.001; ' ** ' 0.01; ' * ' 0.05 ; ' . ' 0.1

Parameter		Species group		
		1	2	3
D^b	a_1	0.1726 (0.0057)***	0.1758 (0.0114)***	0.2178 (0.0161)***
b	b	0.5587 (0.0173)***	0.4729 (0.0281)***	0.5254 (0.0459)***
D	a_2	-0.0215 (0.0014)***	-0.0144 (0.0014)***	-0.0296 (0.0045)***
BA	a_3	-0.0020 (0.0004)***	-0.0015 (0.0006)*	-0.0025 (0.0009)**
SQ1	a_4	-0.0534 (0.0034)***	-0.0401 (0.0054)***	-0.0088 (0.0086)$^{.}$
SQ2	a_5	-0.0855 (0.0033)***	-0.0854 (0.0057)***	-0.0405 (0.0088)***
R^2		0.544	0.524	0.489
df		2831	740	283

The ordinary least squares (OLS) technique was applied to fit a non-linear model. The parameter estimates and related statistics are listed in Table 5.1. All variables had the expected signs and were statistically significant at the 0.05 level. The values of coefficient of determination (R^2) are 0.544; 0.524; 0.489 for species group 1 to 3, respectively, and the estimates of standard errors of parameters range from 0.0004 to 0.0459 in the final models.

Fig. 5.9 displays the partial effect of each explanatory variable such as diameter, basal area and site quality on the predicted diameter increment, holding the others constant at their sample mean.

The relationship between diameter and tree growth was illustrated on Fig. 5.9A. The positive parameters for variable D^b and negative parameters for variable D 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. For species group 1 and 2, the patterns of diameter increment curve are quite similar, trees grow slowly at small diameter of 5 cm with an increment level of 0.22 cm per year. The growth rate increases with tree diameter up to about 35 cm, and then gradually declines. However, the growth rate of species group 1 is larger than that of species group 2 in general and the difference of growth rate is relatively clear for intermediate diameter classes. For species group 3, it grows quite fast at the beginning diameter classes, increases with the slower level compared to group 1 and 2, reaching maximum increment level at diameter of about 20 cm, and then declines with a quite fast level. This trend agrees with biological characteristics of the species in the group, that is, trees in species group 3 include small trees with maximum diameter of about 50 cm recorded in practice. For diameter classes larger than 30 cm, trees in species group 1 and 2 grow significantly faster than those of species group 1. The sign of the parameters of the basal area for three species groups is all negative, it implies that the diameter increment is significantly and negatively related to stand basal area for all species groups.

Fig. 5.9B indicates the effect of stand basal area on diameter increment. As expected, for a given diameter and site, the growth rate was higher for stands with lower basal area. Higher stand basal area reduces significantly the growth rate of all species group. In particular, this effect is clearer for species group 3 than two other groups.

The growth on various site quality levels is also significantly different. Fig. 5.9C, 5.9D and 5.9E highlight the effect of site quality on diameter increment. The growth rates of the same species group on different site quality levels shown in these figures indicate 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.

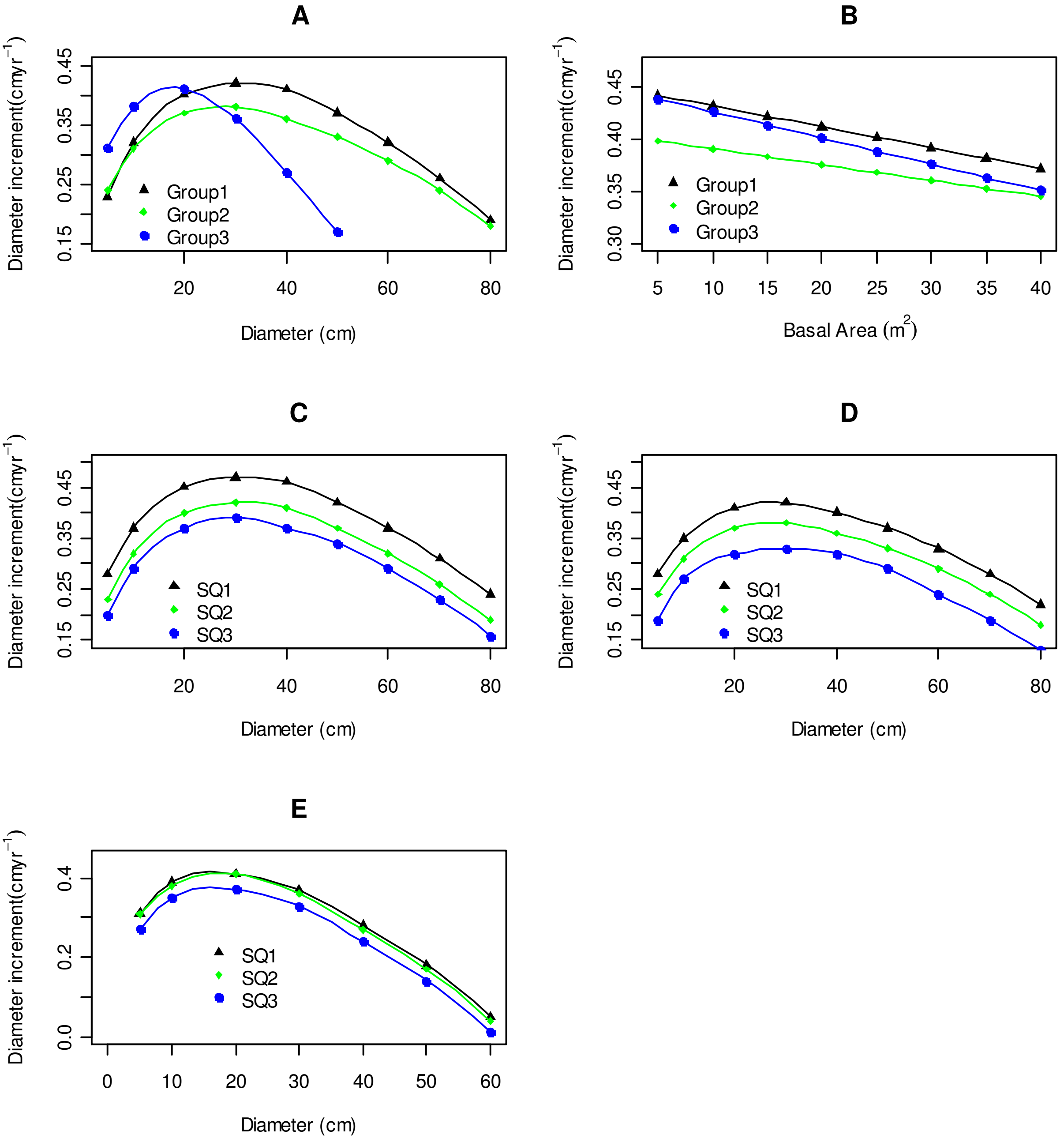

Fig. 5.9 Partial effect of variables on diameter increment. A - The effect of diameter on diameter increment. B - The effect of basal area on diameter increment. C, D, E – The effect of site quality on diameter increment of species group 1, 2 and 3, respectively.

Through these parameters, we can see that the effect of different site quality levels on diameter increment for species group 1 and 2 is very clear. Trees grow fastest on site quality 1 and slowest on site quality 3. However, for species group 3, the difference of growth level between site quality 1 and site quality 2 is not clear. This is indicated by a very small parameter of the dummy variable SQ1 (-0.0088). This suggested that the approach of site quality classification was conformable to the species group 1 and 2, but not for species group 3. However, this classification approach was acceptable because trees in species group 3 account only for a very low proportion in the stands, so that it did not affect significantly the results of the overall model.

The residual plots of the final individual-tree diameter increment models for each species group are given in Fig. 5.10. They proved that there were no obviously observable patterns on these residual plots.

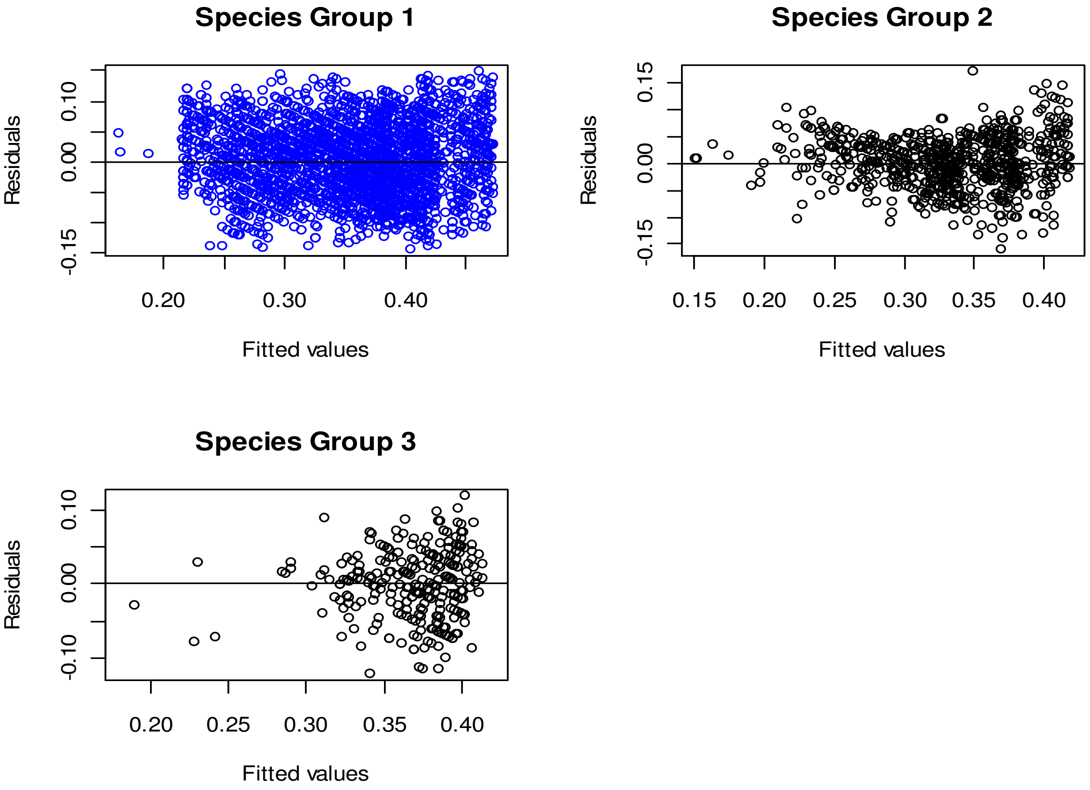

Fig. 5.10 Plots of residuals against the fitted values of individual-tree diameter increment model for three species groups.

5.3.2 Mortality Model

The general mortality model for each species group was formulated as the following logistic function:

$$P_m = \left[1 + e^{-(a_0 + a_1 / D + a_2 \times D + a_3 \times D^2 + a_4 \times BA + a_5 \times Bcum)}\right]^{-1} \qquad (5.25)$$

where:

P_m: annual mortality rate of a tree in each diameter class,

D: the middle values of the diameter classes (cm),

BA: stand basal area ($m^2 ha^{-1}$),

B_{cum} : basal area of larger trees than the subject tree ($m^2 ha^{-1}$), and

a_j: parameters to be estimated.

For this analysis, because the number of trees in the diameter class of one cm is very low; therefore, the data were classified into 4-cm diameter classes and denote them to the middle values of each class. The smallest class is from 6 to 10 cm dbh and the largest diameter class gathering all trees larger than 80 cm dbh.

Three methods were used to estimate the parameters of the mortality function: linear, non-linear and logistic regression using the respective data transformations. When fitting the mortality function, we tried to incorporate the factor of site quality levels (good, medium, and poor) for the data in the plots. However, the results did not show any obvious trend of effect of different site quality. The estimated coefficients have different signs for the three species groups. Thus, we decided not to include this index as a predictor variable.

Although the trends of mortality rate the three methods are conformable to the hypotheses that mortality rate is high when trees are small and decreases when trees become larger, the estimated coefficients have different signs for the three species groups. The non-linear regression method gave parameters with overall plausible signs. Therefore, it was applied in this study. The parameter estimates and related statistics of the mortality equations for three species groups are shown in Table 5.2. Variables whose associated parameter estimates were not statistically significantly different from zero are excluded from the model. Therefore, the resultant models are reduced forms of the general mortality model shown above. The mortality rates for three species groups were independent of site productivity. All parameters listed in Table 5.2 are highly significant ($P = 0.05$) with the exception of the coefficients of species group 3. As the number of observations for species group 3 is not sufficient, only 24 dead trees were recorded, so this explained the low R^2 coefficient of species group 3 (0.136). However, the signs of parameters were plausible, thus we decided to keep the form of that function for the mortality model.

The fitting results for species group 1 and 2 are better as the amount of data was sufficient. The values of R^2 are 0.47; 0.527; 0.136 for species group 1 to 3, respectively, and the estimates of standard errors of parameters range from 0.0007 to 0.875 in the final models. All the signs of parameters are plausible. For species group 1, the parameter of D was negative, the parameter of D^2 was positive so it can capture the U-shaped mortality trend. For species group 2 and 3, the negative parameter of reciprocal of diameter captures the hyperbolic trend of mortality rates. The signs of variables of basal area and basal area of larger trees in three species groups are all positive indicating that mortality rate increases when stand density increases.

Table 5.2 The estimated parameters and fit statistics of mortality rate models by species group.

Parameter		Species group		
		1	2	3
Intercept	a_o	-4.0527 (0.4817)***	-7.7813 (0.3526)***	-7.1774 (0.6351)***
1/D	a_1		15.5840 (2.1428)***	0.1906 (0.8749)$^{.}$
D	a_2	-0.1582 (0.0329)***		
D^2	a_3	0.0011 (0.0007)$^{.}$		
BA	a_4	0.0951 (0.0199)***		
B_{cum}	a_5		0.1389 (0.0161)***	0.1493 (0.3666)***
R^2		0.470	0.527	0.136
df		224	225	225

Fig. 5.11 shows the partial effect of each variable on predicted annual mortality rate while other variables were held at their sample mean. Fig. 5.11A indicates the mortality rates against diameter of three species groups are relatively different. For species group 1, with the data set quite abundant, the mortality rate curve can capture the U-shape. Mortality rate is highest in the smallest diameter class, it rapidly decreases as diameter increases and then increases again for very large trees. For species group 2, mortality rate is high in small diameter classes, and then decreases when diameter increases. In general, mortality rates of species group 2 are higher than those of species group 1 for diameter classes above 20 cm. For the range of data set, the mortality rates of species group 3 showed a small change among diameter classes with an average rate of about 1%, because there are few trees of species group 3 and their distribution range of diameter classes is narrow, mainly concentrated on diameters less than 30 cm.

Fig. 5.11B and 5.11C illustrate the effect of stand basal area and basal area of larger trees on expected mortality rates. Higher stand basal area or basal area in larger trees significantly increases mortality rates.

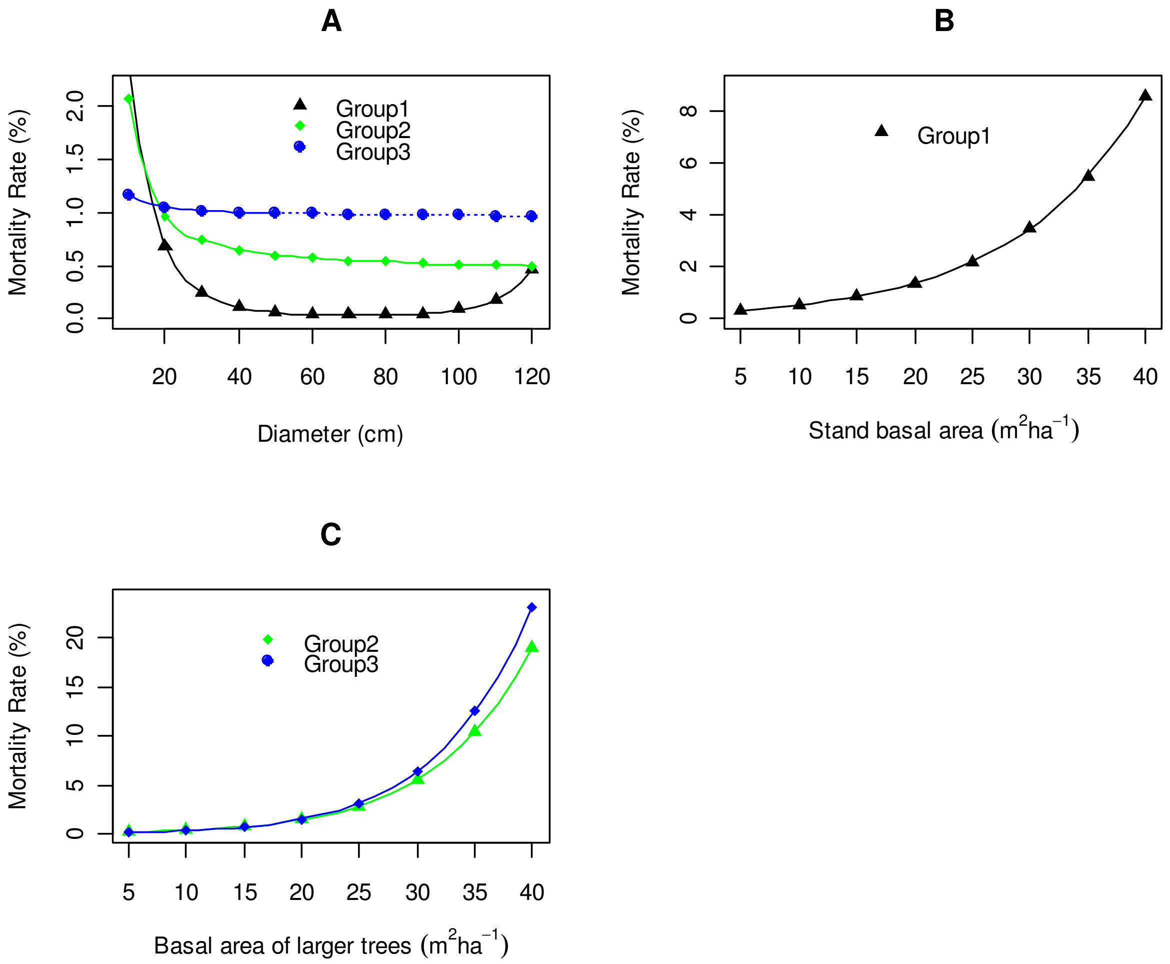

Fig. 5.11 Partial effect of variables on mortality rate of three species groups. A – effect of diameter on mortality rate, dashed line of group 3 is for extrapolation of diameter. B - effect of stand basal area on mortality rate for species group 1. C - effect of basal area of larger trees on mortality rate for species group 2 and 3.

5.3.3 Recruitment Model

A data set comprising 538 recruits in total 12 plots of group A for a growth interval of 5 years provided estimates of the amount of recruitment (data shown in Table 4.6, Chapter 4). Preliminary analysis of the data set indicated that stand basal area and the abundance of the species in the stand explained most of the variation. In addition, the site quality also affected on recruitment, this suggested that a following linear model may be used to develop recruitment model for three species groups. The response variable is number of recruits entering the smallest diameter class of 6 cm dbh per year per hectare for each species group obtained by dividing the five-year-values of recruits by 5. The explanatory variables include stand basal area, number of trees of the species group, and site quality. The site quality was incorporated to the model to account for the effect of site quality on recruitment, it was coded as dummy variable like diameter increment models. The form of the model is as follows:

$$Nr(i) = a_0 + a_1 \times N_i + a_2 \times BA + a_3 \times SQ1 + a_4 \times SQ2 \tag{5.26}$$

where:

$Nr(i)$: number of recruits of species group i per year (trees ha^{-1}),

N_i: number of trees of the species group i per ha (trees ha^{-1}),

BA: stand basal area ($m^2\,ha^{-1}$),

a_i: parameters to be estimated,

SQ1: dummy variable, take the value 1 with site quality 2 and 0 otherwise, and

SQ2: dummy variable, take the value 1 with site quality 3 and 0 otherwise,

The ordinary linear regression method was used to estimate the parameters of the function, the results are given in Table 5.3 below.

The model fit results in a high coefficient of determination, R^2 = 0.788; all parameters in the model are statistically significant at the 0.05 level with the exception of the parameter SQ1 indicating that the effect between site quality 1 and site quality 2 on recruitment is not clear. The sign and magnitude of the parameter estimates were plausible.

Table 5.3 The estimated parameters and fit statistics of recruitment models.

	Parameter	Estimation result
Intercept	a_o	4.202(1.611)*
N_i	a_1	0.017 (0.002)***
BA	a_2	-0.126 (0.033)*
SQ1	a_3	-0.807 (0.575)$^{\cdot}$
SQ2	a_4	-1.731 (0.621)**
R^2		0.788
df		31

The result of recruitment model confirmed the negative effect of stand basal area on ingrowth found by several authors (Lin *et al.*, 1998; Kolbe *et al.*, 1999; Zhao *et al.*, 2004; Liang *et al.*, 2005), the effect was highly significant indicated that ingrowth was lower at higher stand densities. When other conditions were held constant, recruitment of a species group was affected positively by the number of trees of the same species group in the stand.

The negative sign of the dummy variables indicated that the number of recruits was higher on a good site than on a poor site, for stands with equal basal area and number of trees.

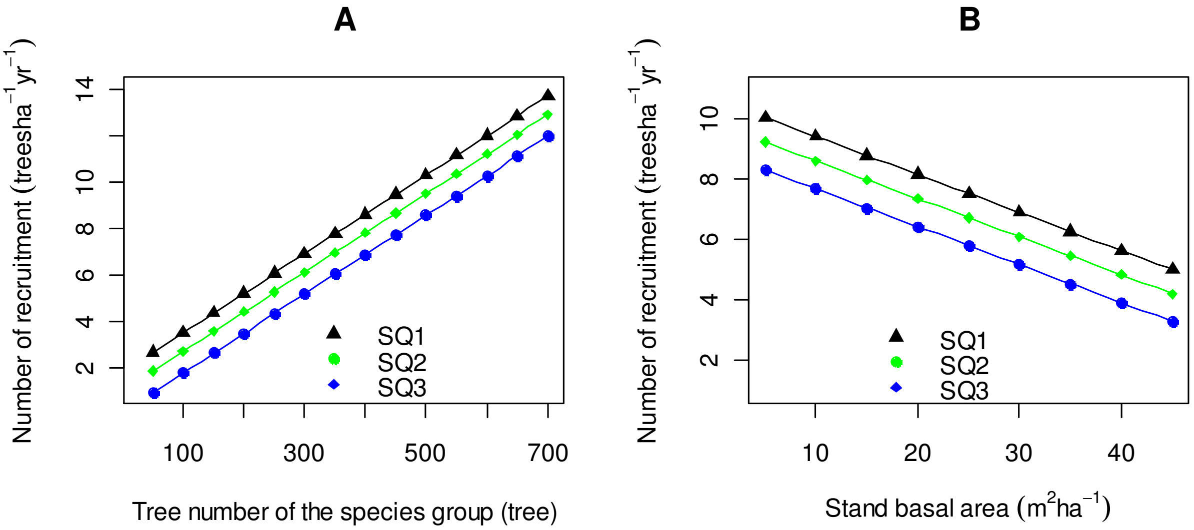

Fig. 5.12 Partial effect of variables on recruitment, with other variables being held constant at their sample mean. A- Effect of tree number per ha on the expected annual number of recruits; B- Effect of stand basal area on the expected annual number of recruits.

Fig. 5.12 shows the effect of variations in the stand basal area and number of trees on the predicted recruitment with other variables were held constant at their sample mean. The number of recruits is clearly affected by the number of trees and stand density for all three species group. Because the tree number in species group 1 is always dominant its recruitment is much higher than that of species group 2 and 3.

The results of fitting the recruitment function are presented in Fig. 5.13 showing the annual predicted versus observed values of recruitment of the 12 plots for the three species groups. The best accordance is found for species group 1, when the number of trees of the species group is high, and the worst fitting is for species group 3, when the number of trees is very low.

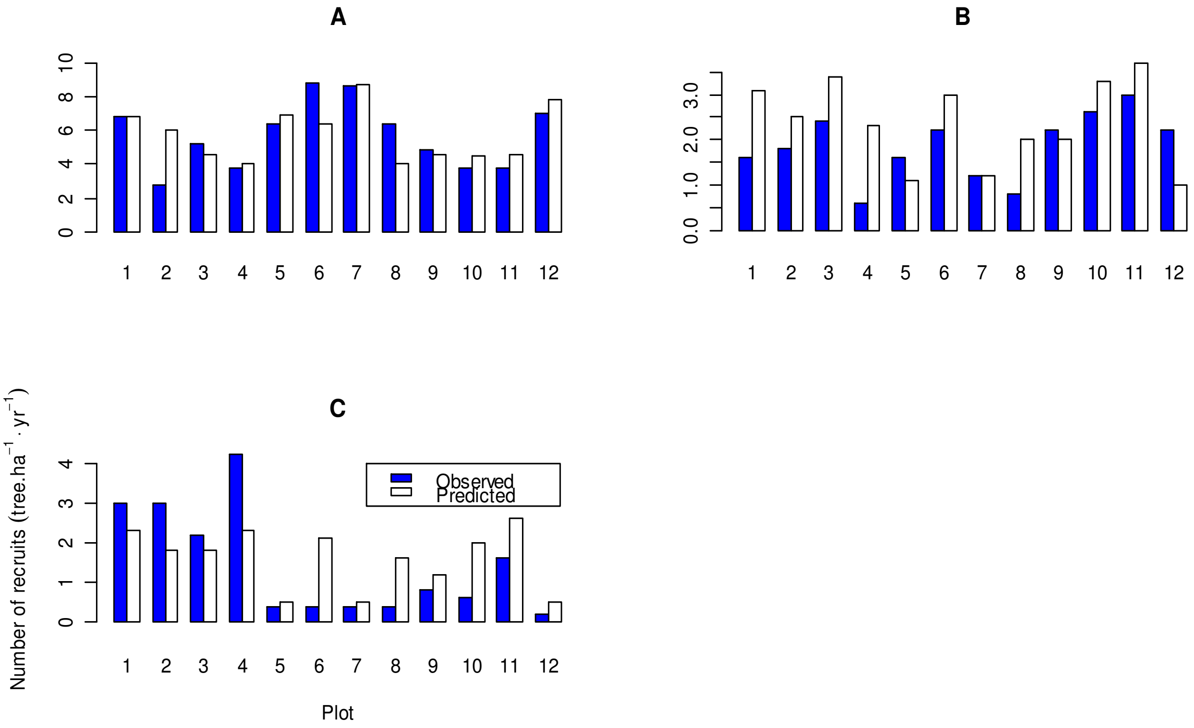

Fig. 5.13 Annual predicted (white) vs. observed recruitment (blue) of the 12 parameterisation plots for the three species groups. A- Species group 1; B – Species group 2; C – Species group 3.

The fitted model equations for diameter increment, recruitment and mortality were embedded into DIPGROW. Before the growth model is applied in forest management practice, a thorough evaluation is necessary. This will be the content of the next chapter.

Chapter 6

Model Evaluation

Model evaluation is an important part of model building, and it should take place at every stage of model design, fitting and implementation. Effective model evaluation is not a single, simple procedure, but comprises several interrelated steps that cannot be separated from each other or from the purpose and process of model construction (Vanclay and Skovsgaard, 1997). The criteria for model evaluation should be related to suitability of the selected model approach for given objectives and purposes, to the validity and logic of the developed biometric model and the suitability of the software developed from the biometric model (Pretzsch *et al.*, 2002). According to Vanclay and Skovsgaard (1997), thorough model evaluation consists of a number of interrelated steps, including examination of the structure and properties of a model, with or without supplementary data, to confirm that it has no internal inconsistencies and is biologically realistic. Others require comparisons with empirical data to quantify the performance of the model, and have become known in forestry literature as benchmarking (Buchman and Shifley, 1983). Ideally, benchmark tests should involve data which are in some sense unlike the data used to fit the model, but useful insights can be obtained with the calibration data.

In this chapter a thorough evaluation involving qualitative and quantitative aspects will be presented. When the growth model is used to simulate stand dynamics, it is applied iteratively, each iteration simulating one year's growth.

6.1 Evaluation of the Model Approach

The selected model approach should be checked for suitability regarding the user's objectives and purposes. According to Pretzsch *et al.* (2002), the following criteria are considered essential:

- Does the model approach make full use of existing information from forestry practice to meet the user's need?

- Does the model approach fulfill the user' information requirements?

- Does the model approach make the best possible use of existing data and the state of knowledge on biology to solve user problems?

- Does the selected degree of complexity correspond to the model objectives?

The questions defined above involve the model approach, the model objectives, the available data, the information to build the model, and the information requirement of the forest managers. These issues have been stated in the previous chapters and will be considered in detail in this section for convenience.

The model approach chosen in this study is a compromise resolution between whole stand models and individual-tree models. When the class size is infinitely large and only one class exists, then the method is a whole stand approach. When the class width is infinitely small and each tree is considered a single class, then the method is the individual-tree approach. However, the model approach in this study has a narrow class size of only one cm, thus it breaks down the forests into many small diameter classes and therefore, it permits to simulate the growth and yield of the forests with very detailed information about stand structure. The determination of the model approach was based on existing data sets obtained from permanent plots in the Dipterocarp forests that were established just a few years ago. The information collected in these plots includes site conditions, species composition, and measurement on individual trees such as diameter, subset of height. Additional data required to construct a high resolution model such as a individual-tree model (e.g. Wykoff *et al.*, 1982; Wensel and Koehler, 1985; Pretzsch, 1995; Nagel, 1996; Pretzsch *et al.*, 2002) or a process model (e.g. Amateis, 1994; Mohren *et al.*, 1994; Matala *et al.,* 2003) including crown dimension, tree position, disturbance factors, etc. is up to now not available. Therefore, with such existing data sets, development of a size class distribution for the forests in question was well suited in practice.

One important objective of this study was to keep the model conceptually and operationally simple. Nevertheless, the information it provides, should be sufficient to answer key questions of importance to forest managers. Forest managers, planners and policy makers can use the model to predict the outcomes of different types of forest use in order to make wise decisions for sustainable management. The applications of the growth model in the following chapter show that the growth model provides a reliable way to examine silvicultural and harvesting options, to determine the sustainable timber yield, and examine the impacts of disturbance factors on long-term dynamics of the Dipterocarp forest. Therefore, the growth model in this study should be an effective tool in practice of sustainable Dipterocarp forest management.

In this study, the process of development of the model components was based on the state of knowledge about different aspects on forest and especially biology that has been continuously developed. According to Pretzsch *et al.* (2002), in the past decades a vast amount of information has been gathered on the dimensions, structure and growth characteristics of individual stand components. A number of growth laws such as the law of optimum basal area (Assmann, 1953, 1956), self-thinning rule (Reineke, 1933; Yoda *et al.*, 1963), law of crown efficiency (Assmann, 1979) have been derived, may be used to evaluate growth models. The growth laws on individual tree and stand level have been taken into account when developing the diameter increment, mortality and recruitment model in this study. As the component functions of the model were developed based on biologic knowledge about competition factors, and they have well proved to be parsimonious, biologically realistic, and consistent with existing theories of forest growth, the growth model can be used to predict realistic responses to management actions and analyze the effects of different policies for forest management. The results from the scenario analysis of the model provide important information that is useful for the forest managers in decision making.

6.2 Validation of the Growth Model

Once the growth model has been calibrated, its forecasting accuracy must be assessed. The most important aspect of model validation is the comparison of prognosis and empirically observed growth. In the ideal case, there is enough independent data to test the model with. A common technique is to calibrate the model just on a random subsample of the data and compare its performance to the other subsample. However, due to the deficiency of data in this study all available data sets have been used to calibrate the model. As stated by Buongiorno (1996), to be useful in management, a growth model must be realistic over several decades, and even centuries. One test consists in comparing the asymptotic stand state predicted by the model, as time increases to infinity, with data from stands that are believed to be close to a climax state.

In this study, two types of quantitative validation were conducted. First, the short-term forecasts on the calibration plots for a growth interval of five years to test the goodness-of-fit of the calibrated model using data set of group A. Second, long-term steady states predicted by the model were checked for quantitative plausibility.

6.2.1 Short-Term Prediction of a 5-Year Period

For short-term prediction, the growth model was used to predict the state of each plot at the second measurement in term of basal area and tree number by diameter class, after five years, given its initial state. The results were then compared to the observation values to assess the accuracy of projections of the model.

Table 6.1 below shows the results of the actual basal areas for each species group of the twelve plots of group A at two measurements as well as the predicted basal areas at the second measurement. The difference between actual and predicted basal areas of twelve plots is very small. The range of difference percentage related to the observed values is from -1.92% in plot A7 to 1.94% in plot A6. The average difference percentage of twelve plots is 0.79%.

Table 6.1 Predicted vs. observed basal areas for each plot of group A for the three species groups, after five simulation years. BA1- Basal area at the first measurement. BA2- Basal area at the second measurement.

Plot	Species group	BA1 (m^2ha^{-1})	BA2 (m^2ha^{-1})		Difference percentage
			Observed	Predicted	(%)
	1	13.07	14.96	14.70	
A1	2	4.40	4.75	4.80	
	3	0.87	1.02	1.00	
total		**18.34**	**20.73**	**20.52**	**-1.05**
	1	16.09	18.14	17.98	
A2	2	4.07	4.37	4.47	
	3	0.57	0.64	0.65	
total		**20.74**	**23.15**	**23.09**	**-0.29**
	1	17.37	18.70	18.68	
A3	2	6.56	7.01	7.00	
	3	1.10	1.19	1.20	
total		**25.04**	**26.90**	**26.88**	**-0.09**
	1	16.31	17.89	17.70	
A4	2	3.97	4.13	4.20	
	3	0.48	0.63	0.60	
total		**20.77**	**22.66**	**22.60**	**-0.27**

Table 6.1 (continued)

Plot	**Species group**	**BA1** (m^2ha^{-1})	**BA2** (m^2ha^{-1})		**Difference percentage**
			Observed	Predicted	(%)
	1	15.72	17.55	17.40	
A5	2	3.35	3.61	3.56	
	3	0.56	0.63	0.64	
total		**19.62**	**21.79**	**21.60**	**-0.91**
	1	14.19	15.85	16.22	
A6	2	3.69	4.14	4.17	
	3	0.749	0.85	0.87	
total		**18.62**	**20.84**	**21.26**	**1.94**
	1	15.06	17.49	17.12	
A7	2	3.98	4.28	4.20	
	3	0.32	0.36	0.40	
total		**19.35**	**22.14**	**21.72**	**-1.92**
	1	6.32	7.30	7.14	
A8	2	3.22	3.46	3.53	
	3	0.60	0.72	0.78	
total		**10.15**	**11.48**	**11.44**	**-0.40**
	1	8.97	10.23	10.09	
A9	2	4.77	5.15	5.18	
	3	0.60	0.650	0.75	
total		**14.34**	**16.04**	**16.03**	**-0.05**
	1	12.38	13.91	13.69	
A10	2	4.54	4.91	5.01	
	3	0.66	0.73	0.72	
total		**17.60**	**19.56**	**19.42**	**-0.74**
	1	9.06	10.35	10.18	
A11	2	5.49	5.95	6.02	
	3	0.80	0.85	0.93	
total		**15.36**	**17.15**	**17.13**	**-0.14**
	1	15.55	17.86	17.56	
A12	2	2.17	2.43	2.39	
	3	0.53	0.63	0.63	
total		**18.26**	**20.92**	**20.58**	**-1.68**

Table 6.2 shows the means of the actual and predicted number of trees per hectare across twelve plots, by size, species group and site quality at the time of the second measurement. The predicted and observed tree number by diameter classes at the second measurement was aggregated with diameter class width of 5 cm. Comparisons of the difference between observed and predicted number of trees for each site quality and each

species group done by the method of paired sample t-tests showed that there are no statistically significant difference.

Table 6.2 Predicted (Pred.) vs. observed (Obs.) average number of trees per hectare for each site quality by 5-cm diameter classes for the group A plots after a five year simulation interval. Notes: a- average of the plots: A3, A4, and A6; b- average of the plots: A1, A2, A10, and A11; c- average of the plots: A5, A7, A8, A9, and A12.

Diameter class	Site quality 1[a]		Site quality 2[b]		Site quality 3[c]	
midpoint (cm)	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.
Species group 1						
8.5	29.8	38.8	38.7	38.8	115.3	128.6
13.5	31.8	35.0	33.3	34.8	68.5	68.2
18.5	37.8	37.3	33.1	34.8	47.7	51.6
23.5	25.8	23.7	25.9	24.5	41.3	42.0
28.5	16.3	16.0	27.0	27.0	28.9	29.6
33.5	17.2	16.7	22.7	23.3	17.2	16.8
38.5	13.4	14	14.1	14.0	12.0	12.8
43.5	10.8	10.3	11.1	12.3	9.3	10.0
48.5	8.3	9.7	7.7	8.0	5.1	4.2
53.5	7.8	7.3	4.2	3.8	3.2	3.4
58.5	3.8	3.7	3.6	3.5	2.3	2.2
61+	11.4	11.3	3.0	3.3	2.3	2.4
Species group 2						
8.5	16.0	14.0	16.8	16.3	17.9	19.8
13.5	12.8	13.7	14.8	15.0	13.5	15.2
18.5	14.5	15.3	11.1	11.5	8.8	8.6
23.5	13.0	13.3	9.3	9.0	5.4	5.0
28.5	6.3	5.3	7.2	7.8	4.7	4.8
33.5	6.8	7.3	5.8	5.8	3.6	3.4
38.5	3.1	3.0	6.2	5.5	3.1	3.2
43.5	2.6	2.7	3.5	3.5	2.2	2.0
48.5	1.4	1.0	1.7	2.3	2.3	2.4
53.5	1.9	2.0	1.9	2.0	1.3	1.6
58.5	1.5	1.7	1.1	0.8	1.0	0.8
61+	2.7	2.7	2.0	1.8	1.6	1.6
Species group 3						
8.5	16.3	18.0	9.1	13.0	10.3	11.2
13.5	9.9	11.3	6.3	6.3	11.6	9.6
18.5	6.1	4.0	2.9	2.5	4.8	4.4
23.5	4.7	5.0	3.4	3.3	3.0	2.8
28.5	2.3	2.3	1.3	1.0	1.1	0.8
33.5	0.8	1.0	0.5	0.3	0.3	0.4
38.5	0.0	0.0	0.5	0.5	0.2	0.2
43.5	0.5	0.3	0.3	0.5	0.0	0.0
48.5	0.1	0.3	0.4	0.2	0.1	0.0
53.5	0	0	0.4	0.5	0.1	0.2
58.5	0	0	0.2	0	0	0
61+	0	0	0.1	0.2	0	0

Fig. 6.1 below highlights the difference between predicted and observed values of basal areas and number of trees by diameter class in the plots. For stand basal area, Fig. 6.1A shows that observed values are very close to those of predicted ones. The differences between observed and predicted tree number for each site quality presented in Fig. 6.1B, 6.1C and 6.1D are also very small. This indicated that the growth model provided accurate predictions.

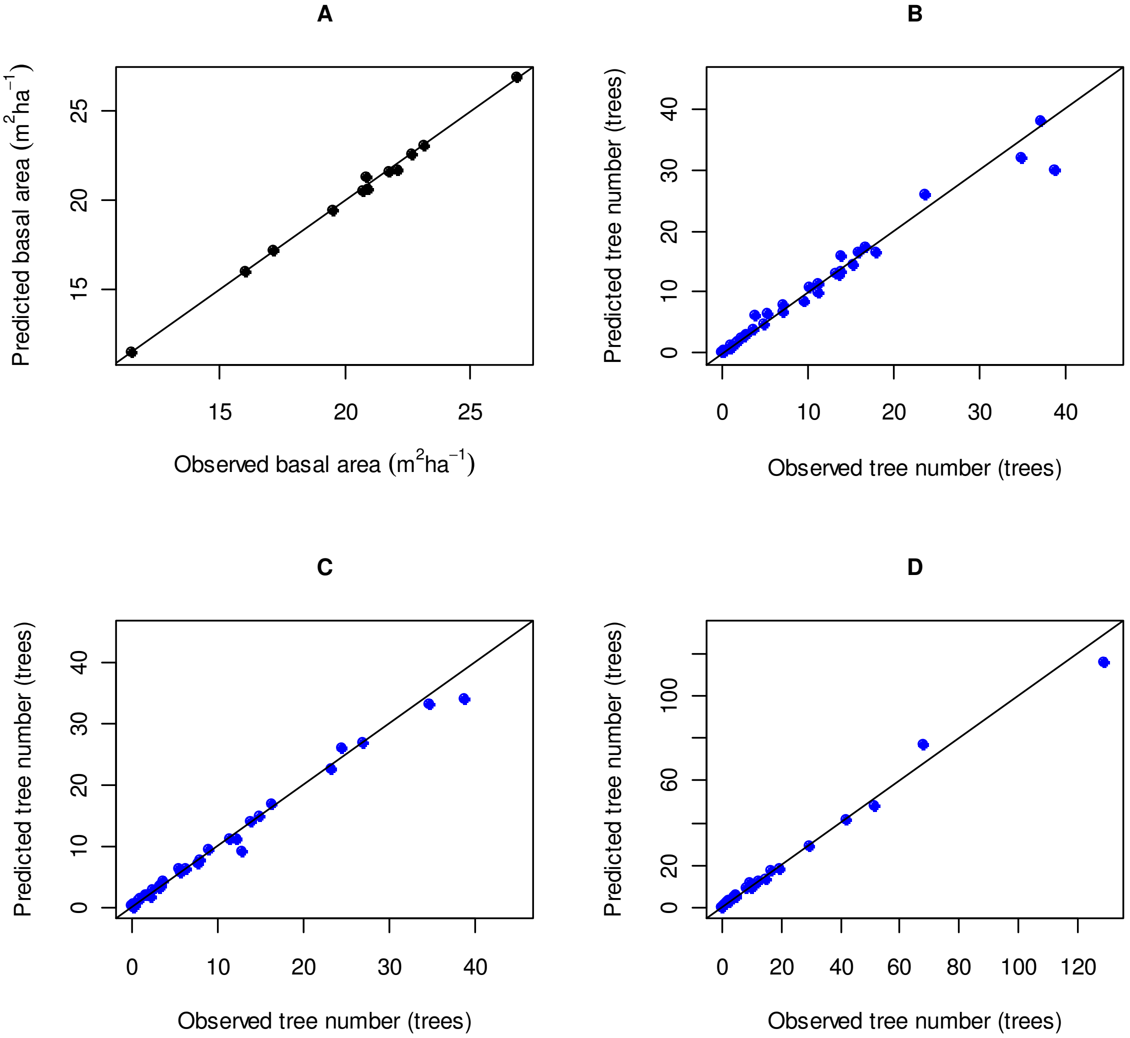

Fig. 6.1 Observed vs. predicted values after a simulation period of five years for all group A plots. A- basal area values of 12 plots; B- tree number by diameter classes of site quality 1; C- tree number by diameter classes of site quality 2; D- tree number by diameter classes of site quality 3. The graphs were constructed using values presented in tables 6.1 and 6.2.

6.2.2 Long-Term Validation of Steady States

The accuracy of a growth model over a single growth period of five years is obviously not sufficient to warrant applicability for management. The model behavior should also be consistent with biological knowledge and practical experience of stand growth over long time in the absence of violent natural or human disturbance. For example, basal area should remain within plausible limits, the number of trees and their distribution by size, and the species composition must change according to a plausible succession pattern (Lin *et al.*, 1998).

To check the plausibility of the model, the model was applied to simulate the development of a stand on three site qualities without harvest over one thousand years. The initial stand for the three simulations was the average state over twelve plots of group A. Each simulation is for a given site quality. The data within each species group reveals the inverse J-shaped distribution of the number of trees by diameter class, typical of uneven-aged forests.

The results of the three simulations are presented in Fig. 6.2 which shows the long-term evolution of stand basal area corresponding to the three site quality levels. The expected total basal area fluctuates over time. Even after one thousand years, a steady state had not been reached. The reason for these oscillations is the big delay in the feedback between basal area and regeneration. The trend of development of basal area over time is in general similar on the three site quality levels. However, there are differences of the growth rates between site qualities and, thus, they cause differences of oscillation periods and amplitudes between different site qualities. The oscillation periods for site quality 1, 2 and 3 are approximately 280, 320 and 380 years, respectively. The average stand basal areas on three site qualities are different, approximately 25, 23 and 21 m^2ha^{-1} for site quality 1, 2 and 3, respectively.

For all site quality levels, species group 1 always remains dominant and species group 2 fluctuates with a tendency of slight decrease over time. Species group 3 shows an oscillation that is countercyclic to the rest of the stand. For this group, its basal area will increase when total basal area of the stand decreases and vice versa. This can be explained as follows: species group 3 consists of small evergreen light-demanding species at the lower layer, which respond quickly to the stand basal area. When stand basal area reduces, the number of recruits of this group increases. In addition, the growth level of this species group at the beginning is higher than that of species group 1 and 2 (see Fig. 5.9A, Chapter 5). As a result, its basal area will increase. When stand basal area increases, because of competition, many of this tree species group will die so that its basal area decreases. The maximum total stand basal area reaches a quite high value of approximately 37 m^2ha^{-1} at the time of 100 years. It seems clear that the diameter distribution that was used as the start situation (Fig. 6.5, distribution T = 0) is not that of a mature undisturbed stand, but rather the result of periodic harvests.

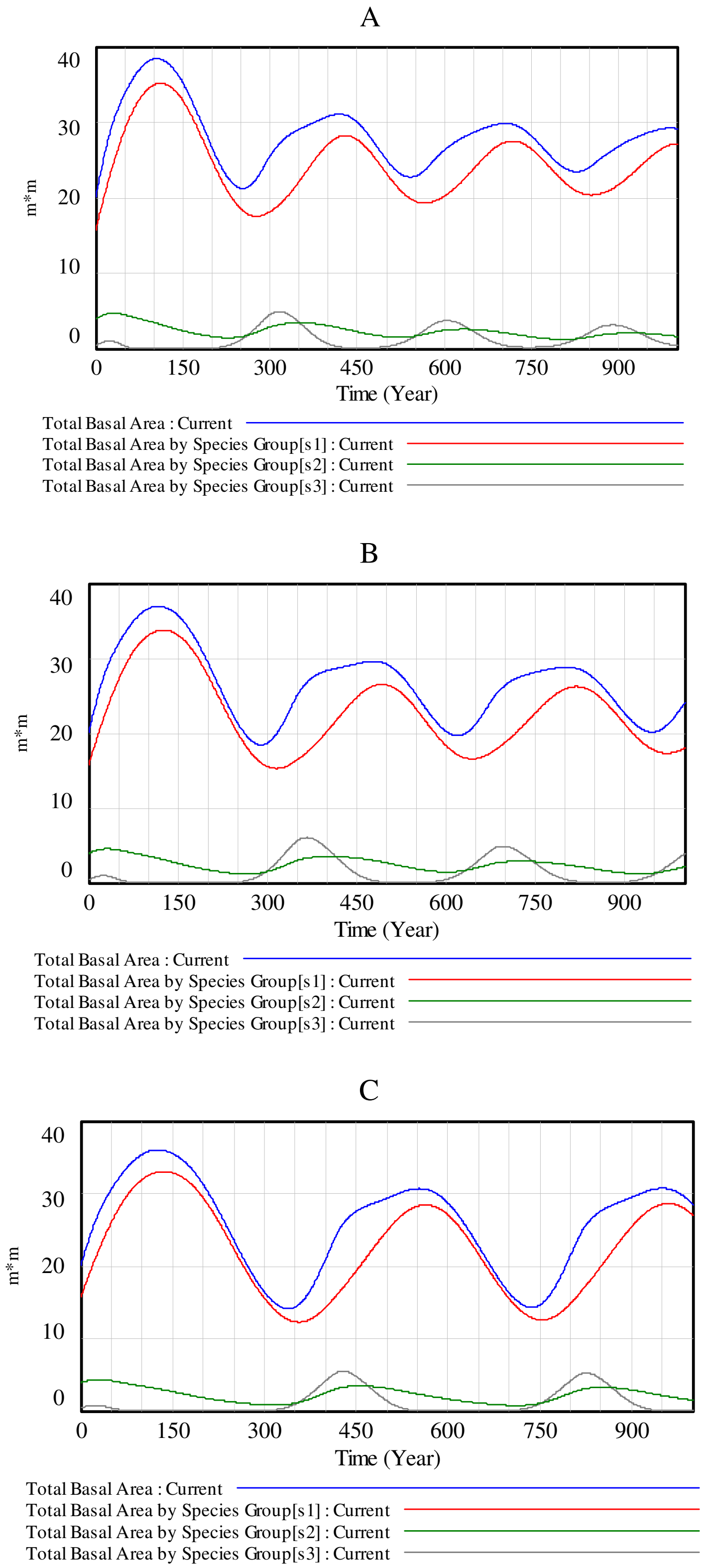

Fig. 6.2 Simulated basal area (m^2ha^{-1}) evolutions over one thousand years in total and separated for species group of an undisturbed stand on three site qualities. A- Site quality 1. B- Site quality 2. C- Site quality 3.

In general, the growth model prediction fits with the structural characteristics of evolution of the natural forests. The maximum existing basal area of Dipterocarp forests in Vietnam is about 30 m^2ha^{-1} (Diep, 1993).

The same simulation runs were also analysed for the development of the diameter distribution. The trends of diameter distribution evolution for three site qualities are similar. However, because of different growth levels between site qualities, the time periods to transform from one distribution to the another are different. Fig. 6.3 presents the summary results of the simulation for three site qualities. The number of trees from these simulation outputs was aggregated according to diameter classes of 5 cm, starting with a threshold of 6 cm. At the initial time diameter distribution had an inverse J-shape reflecting many trees in small diameter classes and few large trees. Over time trees became lager and the stand basal area increased, decreasing the increment and increasing mortality of the trees, especially in the lower diameter classes. Thus, the number of small trees decreased, which is reflected in the distribution T = 30 in the graphs in Fig. 6.3. The increase size of the smaller resulted in a higher number of trees in the middle classes, and yields a unimodal distribution after about 45, 50 and 60 years for site qualities 1, 2 and 3, respectively. During that time interval ingrowth surpassed mortality, resulting in an increase of stand basal area (distribution T= 45, T = 50 and T = 60). The high basal area caused the ingrowth to decline below the mortality rate, resulting in a decline in total number of trees. Decreased ingrowth coupled with continuing transition to higher classes lead to a J-shaped distribution (distribution T = 170, T = 200 and T = 250 in Fig. 6.3A, 6.3B and 6.3C, respectively). At that time the stand had an overweight of large trees, and basal area was also very low. This situation favoured ingrowth and led to an increase in the number of trees in the smaller classes. As a result after some decades the diameter distributions have a U shape that has several trees in the high classes (distribution T = 270, T = 300 and T = 330 in Fig. 6.3A, 6.3B and 6.3C, respectively). During a time period of about 30 to 50 years from that time, large trees will die because of senescence while recruitment is continuous resulting the inverse J-shaped distribution again (distribution T = 300, T = 340 and T = 380 in Fig. 6.3A, 6.3B and 6.3C, respectively). This evolution of dynamics of an undisturbed stand is consistent with the findings of Buongiono and Michie (1980) and Lin *et al.* (1998).

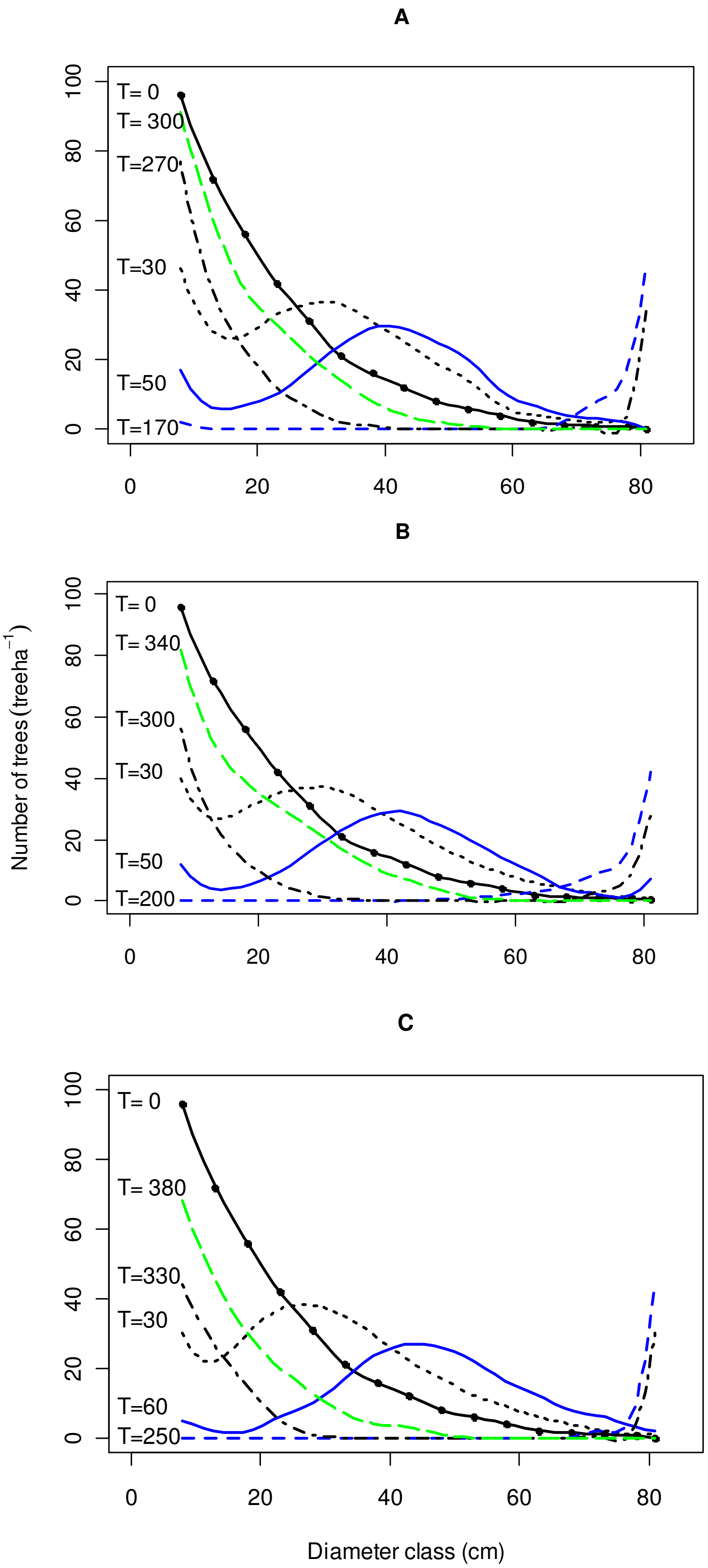

Fig. 6.3 Predited long-term diameter distribution evolutions of an undisburbed forest stand for three site qualities. The numbers T indicate years since start of the simulation run. A- Site quality 1. B- Site quality 2. C- Site quality 3.

6.3 Evaluation of the Growth Simulator

For a better understanding, at first the following strict differentiation is being made between the concepts of forest growth models and growth simulators. The biometric and mathematical representation of growth processes leads to a growth model. The conversion of this growth model into a practicable computer program for prediction and scenario calculations leads to the creation of a growth simulator. A model is therefore always the precondition for the development of a simulator, but the development of a model needs not necessarily result in a simulator (Pretzsch *et al.*, 2002).

Today, with the modern information technology the growth models have been supported by computer software programs and become effective tools for forest management. The growth model in this study has used the simulation software Vensim DSS 5.7a for implementation. It has proven to be a very useful framework as it is a visual modelling tool for conceptualizing, building, simulating, analyzing and optimizing model of complex dynamic systems.

The simulator was constructed to provide a simple way to feed information as an input. To simulate the growth and yield of a stand, the input information including diameter distribution and site quality is required. The initial distribution with the diameter class width of one cm is defined and put in an Excel file, the model has an interface for reading the initial stand data from that file easily. The growth model was calibrated on the basis of classifying the Dipterocarp forests into three site quality levels, represented by notation “SQ” in the simulator. After defining the site quality of the stand, the “SQ” of the simulator was assigned the numerical values of 1, 2 or 3 for the good, medium or poor site quality, respectively. The simple way of feeding the input data allows to apply method of scenario analysis very effectively. There are several applications of the model based on the results of the scenario simulation, for example, determination of the stand structure goals, analysis of stand disturbances, etc. The simulator, thus, allows to implement this easily.

The simulator was designed for a simple mechanism to compare different management regimes. As presented in Chapter 5, it can be used to calculate the yield of a given stand under different harvesting methods.

The simulator provides a really effective and vivid way for the output. The simulation results can be presented under flexible forms such as tables and graphs. It can easily generate these graphs and tables, and it can also converse a graph into a table and vice versa. A table provides detailed data about the simulation results of entire simulation period. In contrast, a graph shows a visualization of the simulation results. These graphs and tables are the most important results of the simulation. In this study, to obtain and illustrate the results of different simulations, a series of graphs accompany with tables was created. These types of graph and table include:

- Graphs of development of stand basal area over time for total stand and each species group.
- Graphs displayed the harvesting volumes each cycle for total stand and for each species group.
- Graphs of dynamics of diameter distribution with a diameter class width of 5 cm for each diameter lass. It is easy to create graphs for different diameter class widths.
- Tables of data about the development of stand basal area over time for total stand and each species group.
- Tables of data about dynamics of tree number over time in each diameter class of 5 cm. It is also easy to create tables for different diameter class widths.
- Tables of harvesting volumes for total stand, each species group and each harvesting cycle.
- Tables of cumulative harvesting volume for the simulation period for total stand and each species group.

These graphs and tables above were used to present the validations and example applications of the growth model in this study. For other applications of the model, the simulator allows to generate different suitable graphs and tables easily.

The simulator that has been designed in this study is very flexible as it can be modified easily to implement other applications. In addition, to develop a growth model for other forest types, the simulator can be used as a working prototype and the model components will be replaced by the new ones which are calibrated with empirical data.

However, at the moment the growth model is still too difficult to be used by forest managers. To make it easy to use, a user interface needs to be created. This work should be executed in the further steps.

Chapter 7

Applications of the Growth Model DIPGROW

Growth models support forest researchers and managers in many ways. Some important uses include the ability to predict future yields and to explore silvicultural options. Growth models provide a reliable way to examine silvicultural and harvesting options, to determine the sustainable timber yield, and examine the impacts of forest management and harvesting on their values of the forest (Vanclay, 1995).

Although the applications of growth models are in many ways, their particular uses will be applied in particular context.

In this chapter, three example applications of the growth model for forest management questions are presented. The first one concerns growth and yield estimations under different management options in order to define the target distributions that produce maximum sustainable yield, the second one estimates the time that a given disturbed stand can become the target state and the third one aims at studying forest dynamics and succession under varying influence of wildfires.

7.1 Estimation of the Growth and Yield of Forest Stands and Determination of the Target Diameter Distributions

One of the most important applications of growth models is their usage for growth and yield prediction. By using the scenario analysis method, the model can be used to calculate the yield corresponding to each given harvest regime. The basic method is to nominate a cutting cycle length, construct a typical stand table and apply a logging rule to predict the loggable volume.

The dipterocarp forests in Vietnam have been overharvested for a long time in the past (Diep, 1993), the actual diameter distribution of forest has been heavily disturbed, not follwing the typical inverse J-shape of an uneven-aged forest. Currently, there are mainly young, poor and degraded forests, just few medium and rich forests. Therefore, the method of proportion harvesting rule described in Chapter 5 is unpractical because it is difficult to regulate a given disturbed stand to a desired state.

For the purpose of sustainable forest management with the actual conditions in Vietnam, of the three methods mentioned in 5.1.2, the harvesting method of q-factor guide seems to be suitable. Using this harvesting method, the regulation of the forest state through cutting is carried out not only in large diameter classes, but also in small classes; thus, it is able to supply an amount of timber as well as fuelwood to the current needs of local people and also to regulate the forest step by step to desired structures. Therefore, in this chapter this method will be applied for the example application.

For this method, as presented in Chapter 5, the growth model can be used to estimate the yield of any stand easily. At first it is necessary to determine the target state of the stand. After some harvesting occurrences, the stand will be regulated to the target state step by step. The model can be used to calculate the harvesting amount and define the time needed to regulate the stand towards the desired state. When the stand reaches the target state, it will supply a stable yield under the harvesting rule. However, the stable yield will be different depending on the target diameter distribution and the harvesting cycle.

In this study, we consider that a target diameter distribution is one that produces maximum long-term sustainable yield. It should be also different depending on site quality.

The scenario analysis method will be applied to define the target diameter distribution. Various diameter distributions defined by the q-factor method as described in Chapter 5 will be used as initial states for the simulation runs.

In order to reduce the number of the scenarios but still determine the desired states that produce maximum long-term sustainable yield, the values of the three factors including basal area, q-value and maximum diameter should be limited in the range close to values of the actual stands. For the twelve plots of group A, the basal area ranges from 10.15 to 25.05 m^2ha^{-1} and the values of q is from 1.4 to 1.6.

Based on their diameter increment levels, the management purpose and the suggestion of several Vietnamese scientists (Sac, 1984; Con, 1991; Diep, 1993) we set the maximum diameters as follows: for site quality 1 maximum diameters are 70 cm for species group 1 and 2; 35 cm for species group 3. The maximum diameters for site quality 2 are 60 cm for species group 1 and 2 and 35 cm for species group 3. For site quality 3, maximum diameter of species group 1 and 2 is 50 cm, species group 3 is 35 cm.

Concerning harvesting cycle, an important aspect needs to be mentioned here. As presented in Chapter 5, the model components including growth, recruitment and mortality models were all constructed incorporating stand basal area. However, the effect of harvest on mortality was not considered in the model. Harvest will reduces the basal area, thus, increases the growth level of the stand and decreases the mortality. So, for a given stand the shorter the harvesting cycle, the higher annual yield it produces. For this reason, harvesting cycle should be chosen suitably with the production practice. In this study, a short harvesting cycle of ten years was applied because it is practical to the community forest management practice in Vietnam (Huy, 2007)

Therefore, the initial states will be defined by two changing factors: basal area and q-quotient. Basal areas change with ten values is set to 7.5, 10.0, …, 30.0 m^2ha^{-1}. The proportion of the basal area between species groups is fixed to that of average basal areas over the sample plots. This proportion is 75%, 20% and 5% for species group1, 2 and 3, respectively. In this study the q-quotient was defined with diameter class with of 5 cm and it changes with five values: 1.3; 1.4; 1.5; 1.6 and 1.7. When applying to the simulation, each site quality will take four of these five values. So, all together 120 scenarios will be simulated for three site qualities.

Simulation time is 100 years. The result of the simulation can provide the information about the amount of each harvest and total harvesting volume of all harvests. The long-term sustainable yield is defined as the average annual harvesting amount during simulation time, that means, total harvesting amount divided by 100.

An example of scenario simulation is presented in Fig. 7.1. The initial stand has the following parameters: basal area = 15 m^2, q = 1.4 and site quality = 1. During the simulation period, the stand was always maintained in the equilibrium state in terms of basal area and diameter distribution by the harvesting method of q-factor guide because it is considered as the target state. The stand produces a sustainable yield of 3.74 $m^3ha^{-1}yr^{-1}$.

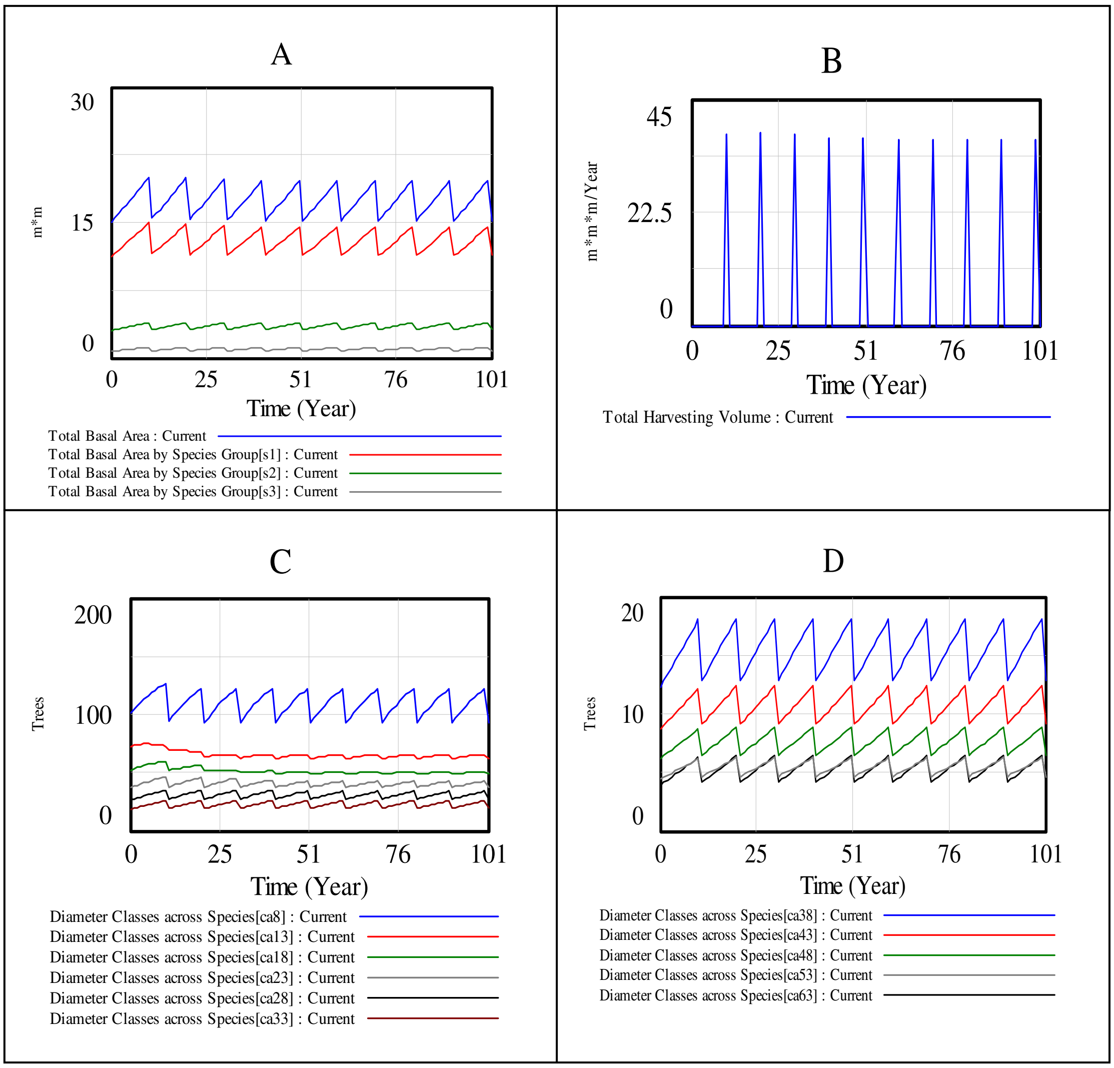

Fig. 7.1 Results of a scenario simulation of a stand. A- Dynamics of stand basal area. B- Harvesting volume. C, D- Dynamics of tree number by diameter class. ca8- mean diameter class 6 to 10, ca13- mean diameter class 11 to 15, etc.

The values of the long-term sustainable yield of all scenarios obtained by simulations are given in table 7.1 below.

Table 7.1 Mean annual volume increments produced by various initial stands.

Basal area (m^{2}ha^{-1})	**Long-term sustainable yield** (m^{3}ha^{-1}yr^{-1})			
Site quality 1	**q = 1.3**	**q = 1.4**	**q = 1.5**	**q = 1.6**
7.5	2.05	2.27	2.47	2.64
10.0	2.58	2.84	3.08	3.28
12.5	3.05	3.34	3.60	3.70
15.0	3.40	3.74	3.8	3.62
17.5	3.59	3.85	3.74	3.40
20.0	3.63	3.91	3.50	3.35
22.5	3.15	3.35	3.04	3.18
25.0	2.75	2.94	2.80	2.91
27.5	2.29	2.45	2.57	2.67
30.0	2.12	2.25	2.36	2.45
Site quality 2	**q = 1.3**	**q = 1.4**	**q = 1.5**	**q = 1.6**
7.5	1.76	1.90	2.03	2.15
10.0	2.20	2.38	2.54	2.67
12.5	2.58	2.75	2.90	2.85
15.0	2.60	2.83	3.05	2.98
17.5	2.70	2.83	3.12	2.93
20.0	2.50	2.78	3.00	2.85
22.5	2.30	2.44	2.54	2.36
25.0	2.16	2.13	2.21	2.17
27.5	2.00	1.89	1.95	1.80
30.0	1.86	1.75	1.80	1.70
Site quality 3	**q = 1.4**	**q = 1.5**	**q = 1.6**	**q = 1.7**
7.5	1.57	1.65	1.72	1.78
10.0	1.97	2.06	2.13	2.18
12.5	2.29	2.38	2.46	2.34
15.0	2.44	2.53	2.66	2.50
17.5	2.41	2.47	2.55	2.32
20.0	2.26	2.31	2.25	2.12
22.5	2.09	2.13	1.95	1.79
25.0	1.75	1.85	1.79	1.65
27.5	1.63	1.64	1.66	1.53
30.0	1.40	1.41	1.54	1.43

The results of sustainable yield obtained from scenario simulations of the growth model presented in table 7.1 show that the long-term annual sustainable yield was strongly affected by factors including stand basal area and q-value of the initial stand. The graphs in Fig. 7.2 are based on the values given in table 7.1 and highlight the effect of initial density, site quality and q-values on the long-term annual sustainable yield. With the same q-value and on the same site quality, the annual sustainable yield changes with different basal area. For all three site qualities, the relationship between annual sustainable yield and stand basal area follows a similar pattern. Stands with lowest basal area of 7.5 m^2ha^{-1} would produce very low yields, stands with higher stand basal area give higher yields. However, the annual sustainable yield will decrease quickly with very high stand basal area. It implies that density and competition cause a reduced growth.

Fig. 7.2A, 7.2B and 7.2C also illustrate the effect of q-value on annual sustainable yield. With the same site quality and basal area, stands with different q-values produce different annual yields. The graphs show that when basal area is lower than 12.5 m^2ha^{-1}, higher q-value is coupled with higher annual yield of the stand. However, this rule is not true with stands of higher stand basal area. This can be explained as follows: with the same stand basal area, the stand with higher q-value has higher tree number at small diameter classes. In addition, with such a lower basal area, the growth competition is still not strong, therefore trees grow quite fast. The growth of the stand is proportional to the tree number. However, with the higher stand basal area, the competition factor affects significantly on tree growth, especially on the growth of the small trees. With the simulation results above, the stand on site quality 1 produces maximum annual yield of 3.91 $m^3ha^{-1}yr^{-1}$ with q-value = 1.4 at basal area = 20 m^2ha^{-1}. For site quality 2, the stand produces maximum annual yield of 3.12 $m^3ha^{-1}yr^{-1}$ with q-value = 1.5 at basal area = 17.5 m^2ha^{-1}. And for site quality 3, the stand produces maximum annual yield of 2.66 $m^3ha^{-1}yr^{-1}$ with q-value = 1.6 at basal area = 15 m^2ha^{-1} (see Table 7.1).

From the above results, in order to define exactly the stand basal areas that produce maximum annual yields on three site qualities, we continue to simulate with the stands whose basal area surrounding to values found out above corresponding to the q-values defined. With these simulation results, finally we achieved the following results: for site quality 1, the maximum annual yield obtained was 3.91 $m^3ha^{-1}yr^{-1}$ at stand basal area of 20 m^2ha^{-1}; 3.22 $m^3ha^{-1}yr^{-1}$ at stand basal area of 18 m^2ha^{-1} for site quality 2 and 2.75 $m^3ha^{-1}yr^{-1}$ at stand basal area of 16 m^2ha^{-1} for site quality 3.

Fig. 7.2D presents the results of simulation of the stands with q-values are 1.4, 1.5, 1.6 for site qualities 1, 2 and 3, respectively that produce maximum yields. The mean annual volume increments are significantly different between site qualities. The yield of site quality 1 (best site quality) was always higher than that of site quality 2 and 3.

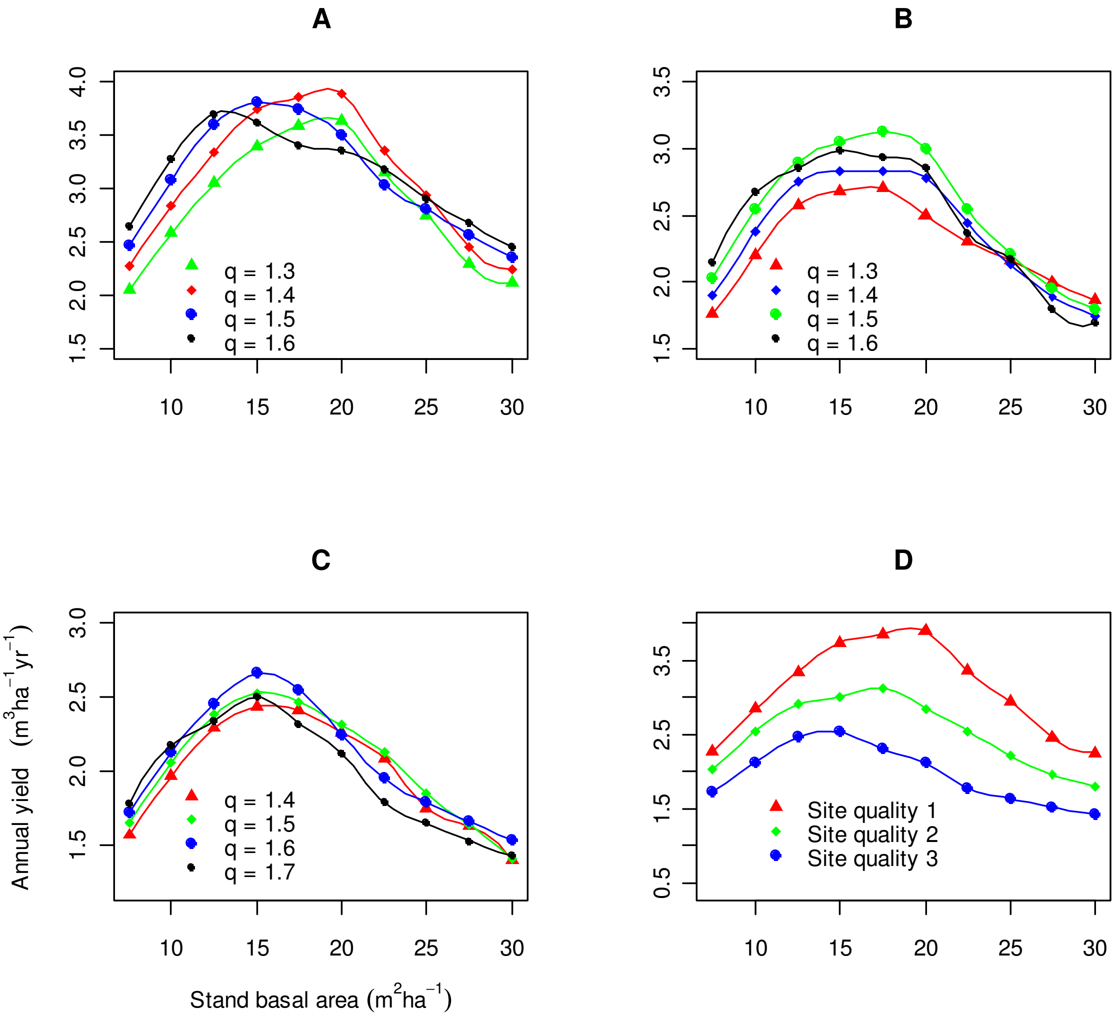

Fig. 7.2 Simulation results of mean annual volume increment (MAI) obtained by the stands with different basal areas and q-values. A- Site quality 1, B- Site quality 2, C- Site quality 3, D- Mean annual volume increment with different site quality and q-values.

Target diameter distributions for each site quality will result with parameters presented in table 7.2. For site quality 1, the target distribution has following parameters: basal area = 20 m^{2}ha^{-1}, q = 1.4, maximum diameter is 70 cm for species group 1 and 2, 35 cm for species group 3. For site quality 2: basal area = 18 m^{2}ha^{-1}, q = 1.5, maximum diameter is 60 cm for species group 1 and 2, 35 cm for species group 3. For site quality 3: basal area = 16 m^{2}ha^{-1}, q = 1.6, maximum diameter is 50 cm for species group 1 and 2, 35 cm for species group 3.

Table 7.2 The target diameter distribution for three site quality levels. G1 – species group 1; G2 – species group 2; G3 – species group 3; N- total number of trees per ha (trees.ha$^{-1)}$; BA- stand basal area (m^{2}ha^{-1}); D_i – Diameter class at mid point (cm). $BA = \pi \sum_{i=1}^{n} D_i^{\,2} N_i / 40000$. N_i – tree number in diameter class i.

D_i	**Site quality 1** BA = 20 m^{2}ha^{-1}, q = 1.4				**Site quality 2** BA = 18 m^{2}ha^{-1}, q = 1.5				**Site quality 3** BA = 16 m^{2}ha^{-1}, q = 1.6			
	G1	G2	G3	Total	G1	G2	G3	Total	G1	G2	G3	Total
8.5	96.9	25.8	12.8	135.5	134.0	35.7	14.0	183.8	170.1	45.4	14.9	230.3
13.5	69.2	18.5	9.1	96.8	89.3	23.8	9.3	122.5	106.3	28.3	9.3	143.9
18.5	49.4	13.2	6.5	69.1	59.5	15.9	6.2	81.6	66.4	17.7	5.8	89.9
23.5	35.3	9.4	4.6	49.3	39.7	10.6	4.2	54.4	41.5	11.1	3.6	56.2
28.5	25.2	6.7	3.3	35.2	26.4	7.1	2.8	36.3	25.9	6.9	2.3	35.1
33.5	18.0	4.8	2.4	25.2	17.6	4.7	1.8	24.2	16.2	4.3	1.4	21.9
38.5	12.9	3.4		16.3	11.7	3.1		14.9	10.1	2.7		12.8
43.5	9.2	2.4		11.6	7.8	2.1		9.9	6.3	1.7		8.0
48.5	6.6	1.7		8.3	5.2	1.4		6.6	4.0	1.1		5.0
53.5	4.7	1.2		5.9	3.5	0.9		4.4				
58.5	3.3	0.9		4.2	2.3	0.6		2.9				
63.5	2.4	0.6		3.0								
68.5	1.7	0.5		2.2								
N	**334.8**	**89.1**	**38.7**	**462.6**	**397**	**105.9**	**38.3**	**541.5**	**446.8**	**119.2**	**37.3**	**603.1**
BA	**15.0**	**4.0**	**1.0**	**20.0**	**13.5**	**3.6**	**0.9**	**18.0**	**12.0**	**3.2**	**0.8**	**16.0**

Fig. 7.3 illustrates the target diameter distributions of three species groups for each site quality. Diameter distribution of three species groups on all site qualities has the form of inverse J-shape. Different values of q-quotient result in different tree numbers in each diameter classes for each site quality. The number of trees in site quality 3 is highest, and then follows site quality 2 and finally site quality 3. This is consistent to the actual state of forest production, and it is in agreement with the suggestion that we should produce large timber on good site quality and small timber on poor site quality areas (Huy, 1993).

The target forest stand defined above was quite similar to the actual state. According to the calculation results of stand variables in Chapter 4, average basal area across 12 plots is 19 m^{2}ha^{-1}, and diameter distribution also follows the form of negative exponential distribution. This implies that the results of simulation of diameter distribution are suitable in practice.

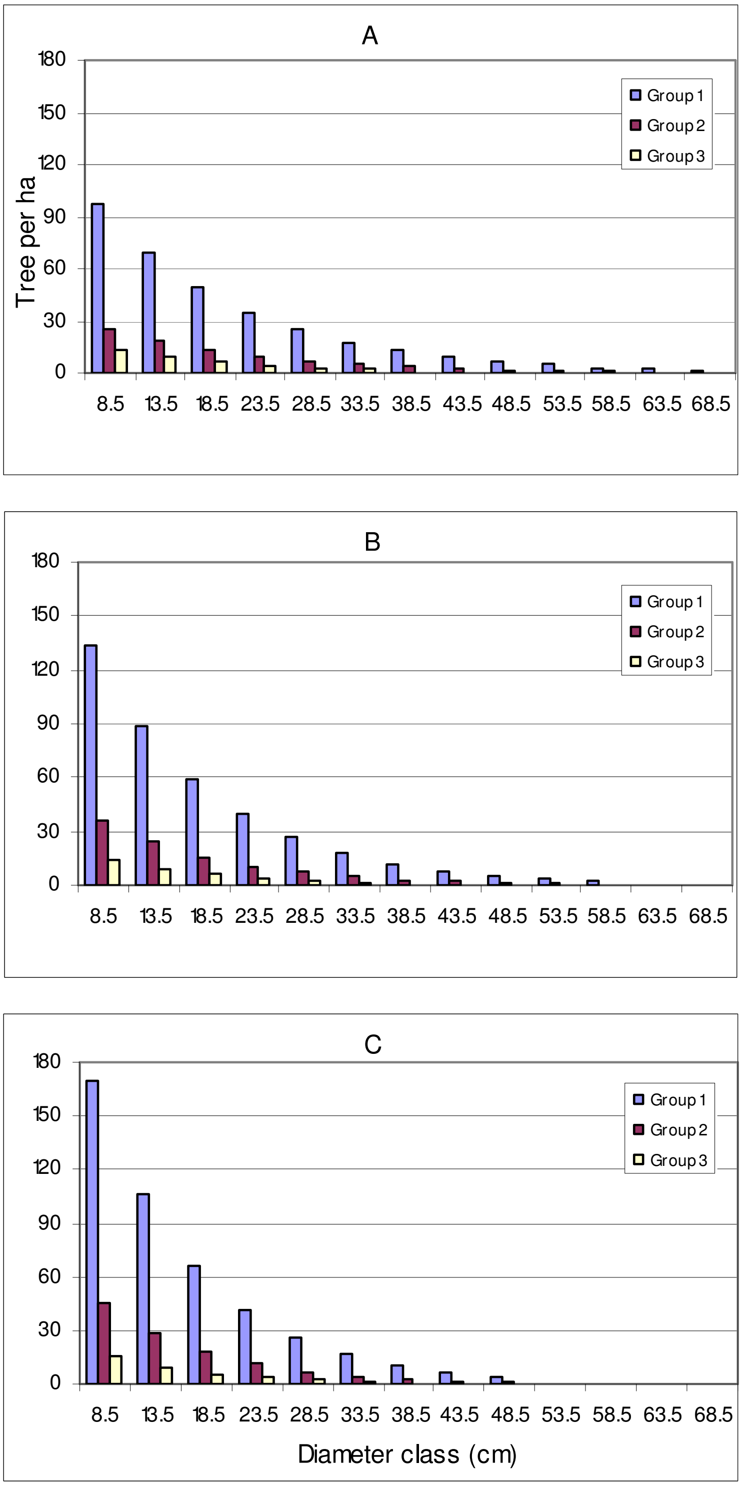

Fig. 7.3 The target diameter distributions of three species groups for three site qualities. A- Site quality 1. B- Site quality 2. C- Site quality 3. The graphs were constructed using the values in table 7.2

7.2 Estimation of Time to Regulate a Given Stand to the Target Stand

The analyzed Dipterocarp forests were destroyed or badly degraded during the time of wars and heavy exploitation in the last decades. At present the majority of the Dipterocarp forests are poor and degraded forests and the diameter distribution of the forests was disordered. It is usually not followed to the natural distribution rule of an uneven-aged forest which is negative exponential distribution. In the previous section, we used the growth model to simulate various scenarios to explore the target distributions that produce maximum sustainable yield for different site qualities. Once the target distributions were determined, the forests should be applied to the harvesting method of q-factor guide in order to regulate the actual state to the desired state step by step.

In this section we use the growth model to estimate the time which is required for regulating a given stand towards the target stand by using the harvesting rule of q-factor. According to Sist *et al.* (2003) this time is called the return time of harvestable stems or volume. The target stand should be required to $\pm 20\%$ of the steady state in terms of tree number, basal area and harvestable volume because the variations of the density become very slow when approaching the stationary value.

Fig. 7.4 below illustrates the simulation results for plot A8 belonging to site quality 3. It was heavily overharvested and its density amounts only to 10 m^2ha^{-1}.

According to the simulation results presented in Fig. 7.4, the steady state of basal area and diameter class was obtained in approximately 50 years, after five cutting occurrences. The stable harvesting volume was gained from the 60th year, after the stand reaches the steady state. However, when applying this method, the cutting occurs in every diameter class causing the lower tree number in small diameter classes. The number of trees in small diameter classes of 8.5, 13.5 and 18.5 cm is very low; thus, it can not reach the target tree number. Fig. 7.4C shows that, the smallest diameter class of 8.5 cm has only about 125 trees compared to 230 trees determined for the target distribution (the results shown in Table 7.2). It implied that there is a shortage of recruitment in the stands belonging to site quality 3. For larger diameter classes, the steady diameter distribution may be obtained more slowly (shown in Fig. 7.4D). For heavily disturbed and overharvested stands like plot 8, there were few large trees so that it takes a long time to have enough trees in the large diameter classes to reach the steady state. However, at this steady state the basal area and harvesting volume are also lower than those of the target stand (see Fig. 7.4A and 7.4B).

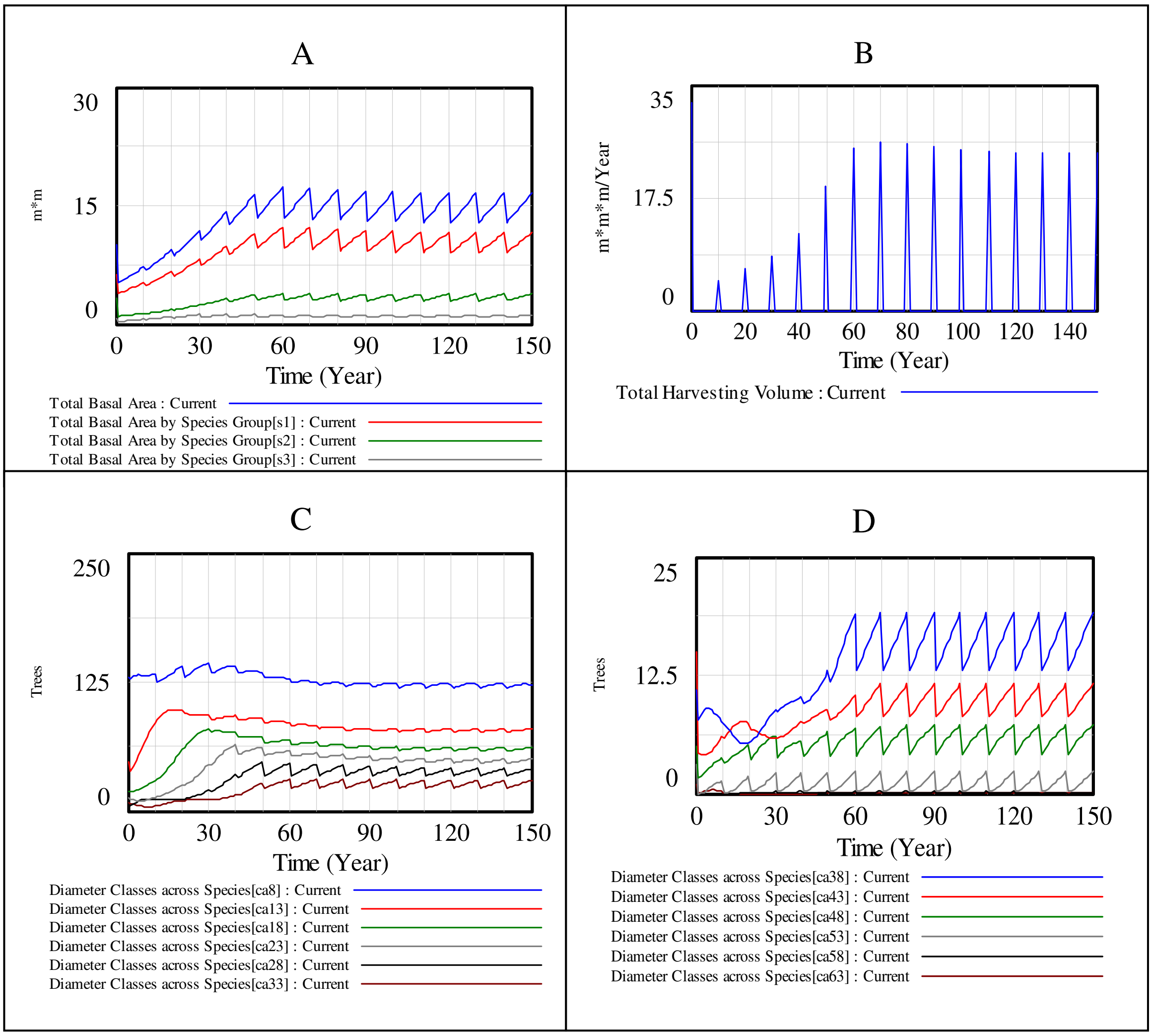

Fig. 7.4 Simulation results of the growth model for plot A8 over 150 years following the harvesting method of q-factor guide. A – Basal area ($m^2 ha^{-1}$) by species group, the stable state obtains after about 50 years. B- Total harvesting volume ($m^3 ha^{-1}$). C, D- Dynamics of tree number by diameter class.

In order to maintain higher number of trees in the small classes, we try to apply this harvesting rule with the slight modification of no cutting occurs in the small diameter classes of 8.5, 13.5 and 18.5 cm.

The simulation results in Fig. 7.5 show that, with the slight modification of the method the time regulating the stand towards the target state does not differ from the simulation results before. However, the number of trees in small diameter class increases considerably. In the smallest diameter class of 8.5 cm, at the equilibrium there are approximately 200 trees per ha (shown in Fig. 7.5C), close to the target state. The basal area and harvesting volume when the stand reaches the equilibrium are also very close to those of the target state.

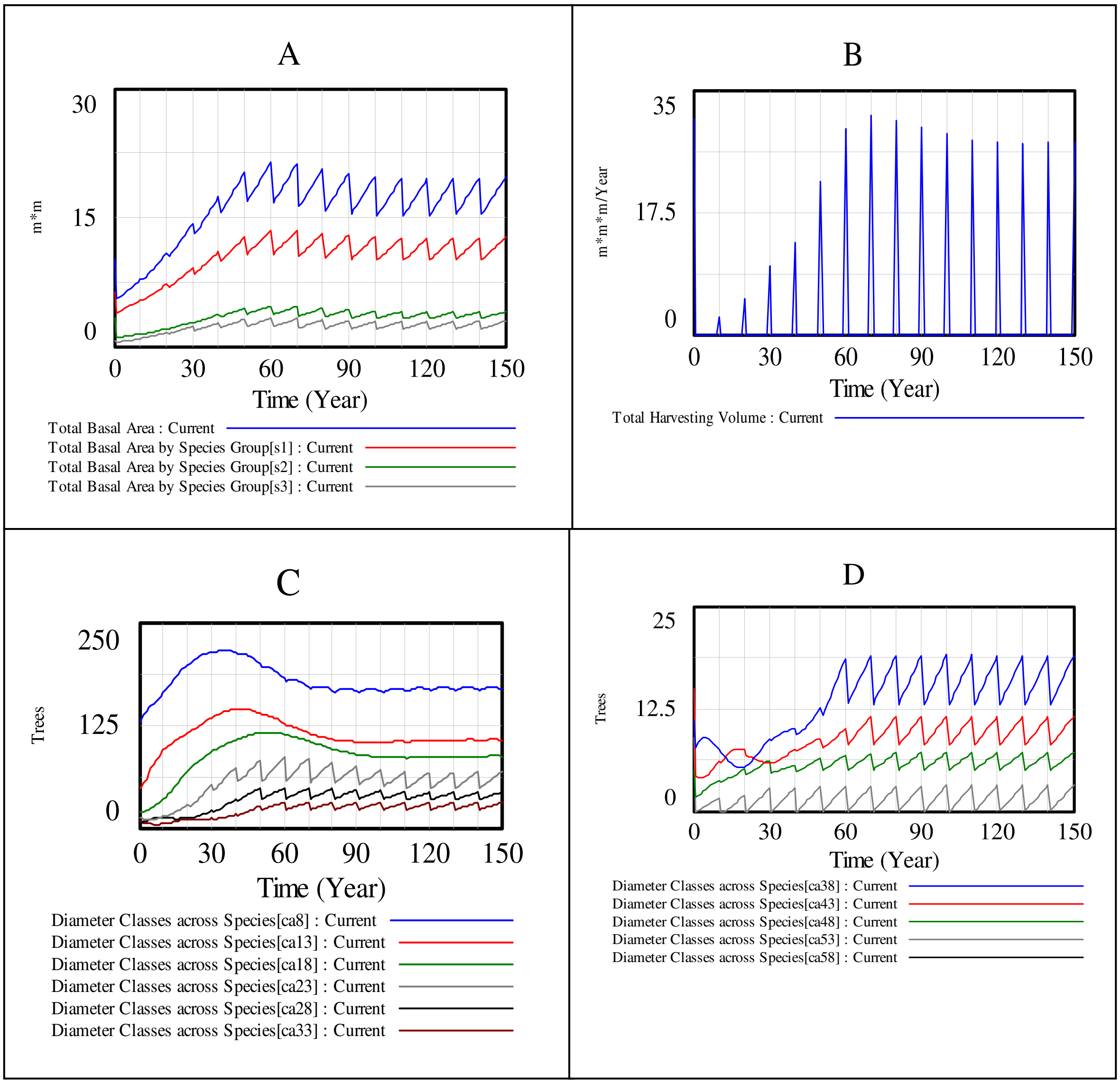

Fig. 7.5 Simulation results of the growth model for plot A8 over 150 years following the harvesting method of q-factor guide with slight modification that cutting no trees in small diameter classes. A – Basal area (m^2ha^{-1}) by species group, the stable state obtains after some 50 years. B- Total harvesting volume (m^3ha^{-1}). C, D- Dynamics of diameter classes.

From the comparison of the simulation results between two methods above, it is clear that the application of harvesting regime of q-factor guide associated with the rule of cutting no small trees in diameter classes of 8.5, 13.5 and 18.5 cm is suitable for production practice. Therefore we use this method to simulate all the plots of group A in order to find out their return time. The results are given in table 7.3.

The return times for the twelve plots are different. The values of return time range from 20 to 60 years. It shows that return time depends on the stand basal area.

Table 7.3 Return time of the group A plots.

Plot	Site quality	Basal area (m^2ha^{-1})	Return time (year)
A1	2	18.35	30
A2	2	20.74	60
A3	1	25.05	30
A4	1	20.77	50
A5	3	19.62	30
A6	1	18.63	30
A7	3	19.36	20
A8	3	10.15	60
A9	3	14.35	40
A10	2	17.60	60
A11	2	15.36	60
A12	3	18.26	20

The stands with high basal area usually have lower return time than that of the stand with low basal area. For example, for plot A3 with high basal area of 25.03 m^2, it takes only 30 years to reach to the target state while for plot A8 with very low basal area, it takes 60 years. However, the return time depends not only on the stand basal area, but also on the initial distribution. Typical examples are plot A12 and plot A2 which have different initial distribution states shown in Fig. 7.6. Plot A 12 has an initial distribution very close to the target distribution. Therefore, it takes only about 20 years to reach the target distribution, just after two cuttings. Plot A2 has a quite high basal area of 20.74 m^2ha^{-1}. However, its initial distribution was very far from the target distribution. Therefore, it takes about 60 years to regulate this stand towards the target state.

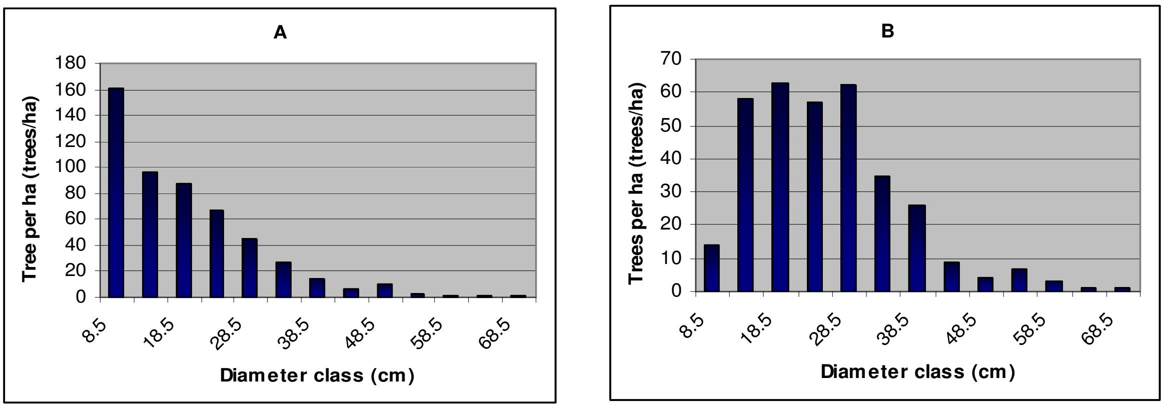

Fig. 7.6 Diameter distribution of example plots. A- Plot A12, B- Plot A2

7.3 Evaluation of Effects of Wildfires on Long-Term Sustainable Forest Growth and Yield

In this section the growth model was used to simulate the effects of wildfire on the long-term yield of the Dipterocarp forests over a period of 200 years. The wildfire was assumed to occur with different frequencies and intensities. When each wildfire occurs, it causes the number of recruits to decrease. Simulations were calculated for the following scenarios: there were four intensity levels of wildfire that cause the mortality of recruitment proportion as follows: 100%, 75%, 50% and 25%. For each intensity level of wildfire there were five following frequency levels of wildfire: control (no wildfire), every year, every two years, every three years and every four years. As a result, there are 20 simulation scenarios. The initial stand in these simulation scenarios was the average stand state over twelve plots of group A and it was assumed on site quality 1. The harvesting method of q-factor guide with harvesting cycle of ten years was applied.

The simulation results are presented in Fig. 7.7. The graphs in this figure show very clearly the effects of distinct regeneration deficiencies due to wildfire on long-term yield. The higher the intensity and frequency of the wildfires the lower the long-term yield. For the first 100 years, the difference between yields of the stand with different wildfire frequencies was rather small. The reason is that when the initial stands are the same, the number of trees in large diameter classes is still high enough to supply the stable harvesting volume in each cycle. However, after 100 years due to the wildfires, the number of trees in the stand significantly decreases. Thus, the harvesting volumes in these stands differed clearly. The decrease of harvesting volume was the largest in case of wildfire occurring every year with no recruitment surviving a fire.

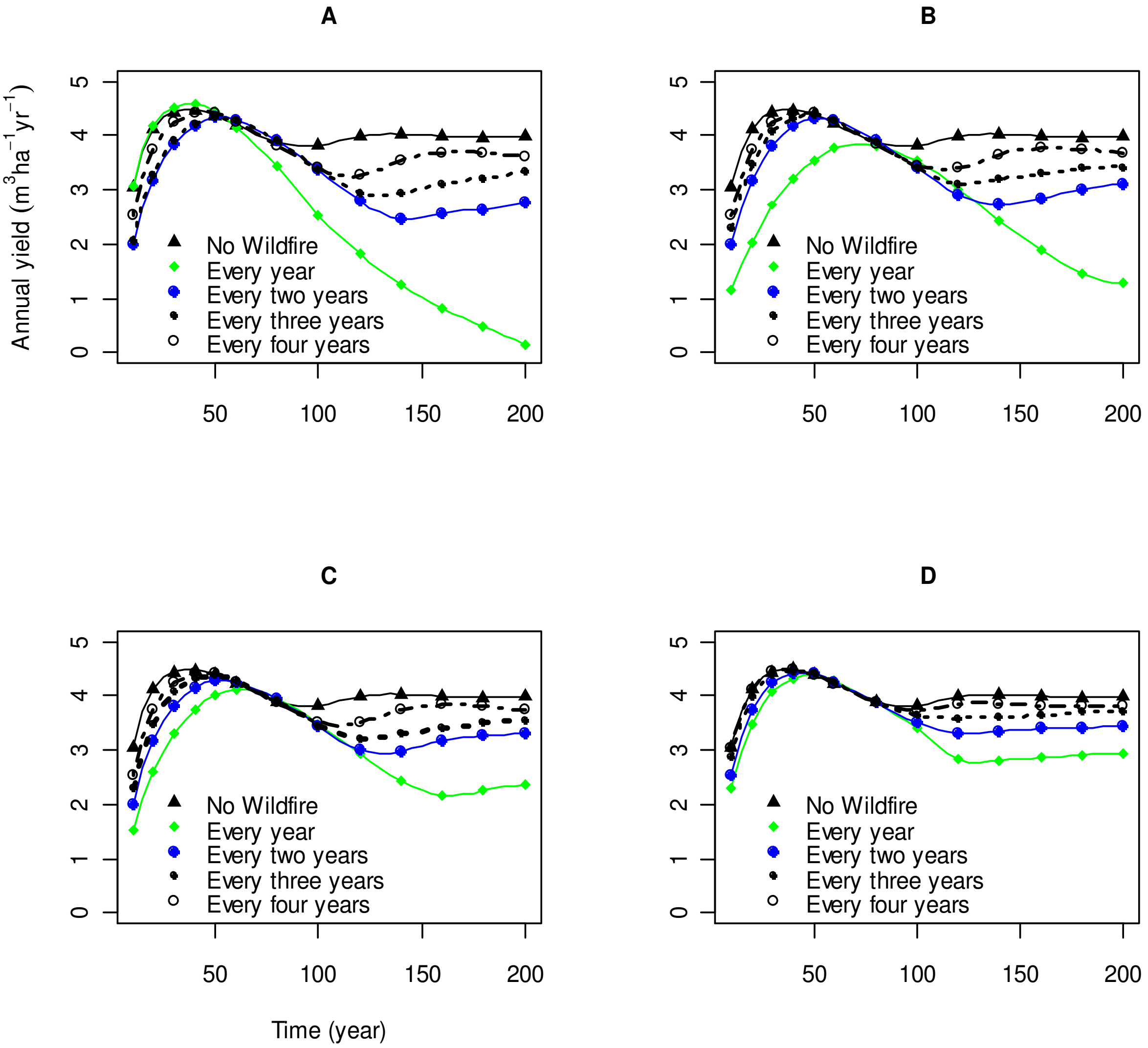

Fig. 7.7 Simulated effects of wildfires with different frequencies and intensities on long-term yield. A- 0% of the recruits survive a wildfire. B- 25% recruits survive. C- 50% recruits survive. D- 75% recruits survive.

The simulated mean annual volume increments over 200 years are given in Table 7.4. Compared to the scenario of no wildfire occurring, the average long-term annual yields decreased from 5% in the stand with wildfire occurring every four years and lowest intensity to 40% in the stand with wildfire occurring every year and with highest intensity.

Table 7.4 Average annual long-term yields with different intensities and frequencies of wildfire (unit of yield: $m^3ha^{-1}yr^{-1}$)

	Frequency of wildfire occurrence				
Intensity	Every year	Every two years	Every three years	Every four years	No wildfire
No recruitment	2.39	3.12	3.29	3.52	3.81
25% recruitment	2.57	3.22	3.44	3.57	
50% recruitment	2.88	3.31	3.49	3.60	
75% recruitment	3.44	3.60	3.72	3.75	

However, the more important issue is that when wildfire frequently occurs, the structure of forest is heavily disturbed over time. Fig. 7.8 below illustrates the diameter distribution of stands after 200 years corresponding to wildfire occurring with the highest intensity and frequencies of every two, three and four years versus no wildfire occurring.

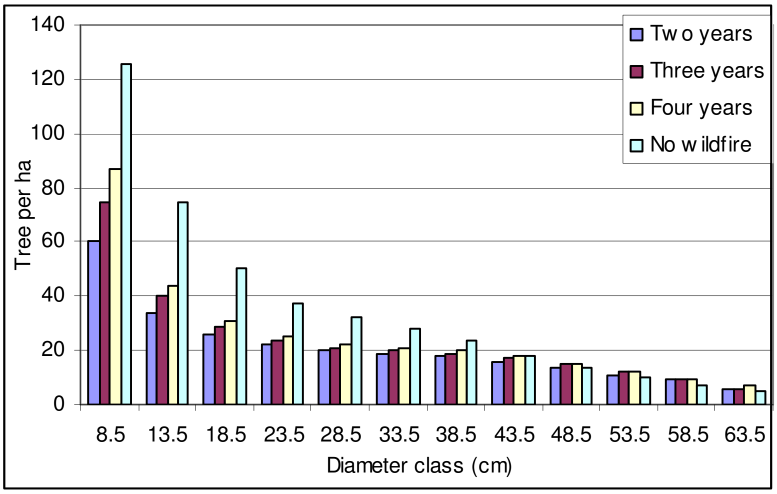

Fig. 7.8 Diameter distribution of the stands with different wildfire frequencies at the time of 200 years. The highest columns present the distribution of the stand with no wildfire, it is close to the target diameter distribution.

The wildfires reduce the number of recruitments so much, that the regulation of the stand towards the target distribution can not be reached. Compared to the target distribution, there is always a lack of trees in the small diameter classes. Particularly, in the case of wildfires occurring every year, under the harvesting rule applied, large trees with a given diameter would be cut while no new trees come from recruitment. The growing stock of the stand gradually declines. Therefore, after approximately 150 years this stand would be nearly gone. In all other scenarios, the forest seems to come into an equilibrium. The level of this equilibrium is dependent on fire frequency and intensity.

In concluding this section, a few remarks are in order. Firstly, the wildfire affects on trees and forest in several ways, it not only decreases the number of recruits, but also may reduces tree growth. However, information about that is not available at present, so that this information can only implement after observation on permanent plots. Secondly, the simulations above were just based on assumptions about wildfire frequency and intensity. And thirdly, we assumed that one year after a wildfire, the recruitment can go on as usual. Once more detailed information about wildfires is available, the model can be applied to simulate its consequences more specifically.

Besides the example applications of the growth model presented above, there are several other applications for scientific and practical purposes such as calculating the diversity indices of a stand over time, calculating the assortment products, using the model to calculate the yields of other silvicultural prescriptions, developing hypotheses about forest dynamics, and using the model as a effective tool for teaching students in modelling forest growth, etc. These applications will be explored in follow-up works to this thesis.

Chapter 8

Discussion

8.1 Growth Model Approach and Parameterization

The choice of the model approach, a size class model, was primarily based on the availability of data and it fits better into the information flow of Vietnamese forest management than more complicated models. It is also much more flexible and detailed than simpler models such as models based on mean stand variables (e.g. Hoyer, 1975; Bruce *et al.*, 1977; Binklay, 1980; Curtis *et al.*, 1982). In comparison to the higher resolution models such as process models (e.g. Landsberg, 1986; Battaglia and Sands, 1998; Ditzer *et al.*, 2000; Köhler and Huth, 2004) or individual-tree based models (e.g. Shugart *et al.*, 1980; Liu and Ashton, 1998; Kürpick *et al.*, 1997; Pretzsch, 1997, 2007) which require several input variables such as tree height, crown dimension, tree position, etc. usually difficult and time-consuming to collect, data sources for the chosen model approach were feasible to obtain from the available permanent plots. This is more suitable and practical to the actual situation in Vietnam where the system of permanent plots has just begun to establish a few years ago.

Statistical fitting is very important to ensure that a growth model will be sufficiently precise for management purposes. In this study, the selection of predictor variables for model components including diameter increment, mortality and recruitment was based on biological knowledge and available data. In the process of fitting the models, any variable that violates the biological rules should be rejected from the models. Compared to automatically selecting predictor variables using a pure statistic method, fitting a growth model based on ecologically important variables is a better approach. If a model is ecologically illogical, it will not perform well for any data set other than one used for model development (Hamilton, 1986). This study adopted this approach to develop the diameter increment and mortality functions for three species groups of the Dipterocarp forests. The following predictor variables were present in the functions: diameter, diameter squared, stand basal area, basal area of larger trees and site quality. The estimated parameters were consistent with ecological expectations. In the final diameter increment models, the positive sign of diameter and negative sign of diameter squared can capture the inverse U-shape indicating a biological suitability that trees grow slowly at the beginning, more quickly when trees become bigger, reaching a maximum point and then gradually decline (see Fig. 5.9A). This function has its biological limitation: as an extrapolation would yield implausible, trees with very large diameters can get negative diameter increments. However, such tree sizes are not realistic in the Dipterocarp forests and the function was most convenient to fit compared to a typical increment function. The sign of stand basal area and basal area of larger trees in the major model components including diameter increment, mortality and recruitment models are all plausible reflecting the effect of competition factor. Trees grow faster under low density than high density conditions. When stand basal area increases, amount of recruitment will decrease and mortality proportion will increase. As suggested by Wykoff *et al.* (1982), Monserud and Sterba (1999) crown related variables such as crown diameter or crown ratio have been commonly used to model tree growth and mortality. However, these considerations apply to individual-tree models and are not feasible to a lower-resolution model as developed in this study. In addition, no crown related variables were available in the data set and therefore, could not be used here.

The growth model in this study consists of four sub-models: diameter increment, mortality, recruitment and harvest, permitting to estimate the growth of forests for a long time with quite reliable results. For the diameter increment model, all parameters are significant at 95% confidence level with the exception of the parameter of SQ1 for species group 3. This indicated that the difference of diameter increment of species group 3 between site quality 1 site quality 2 is not obvious. This can be attributed that either the data base of species group 3 are not sufficient to clear the difference between site quality levels or the classification of site quality is not suitable for species group 3. In fact, the method of site quality classification was based on the relationship between height and diameter, and the data for constructing this relationship was obtained mainly in species group 1, therefore the best results were found in group 1. However, the proportion of species group 3 in the stands is very low, so it does not affect significantly to the results of growth and yield projections of the model. Compared to the studies of growth of Dipterocarp forests that established only a single diameter increment function for all species (Sac, 1994; Con, 1991), the species classification into three species groups in Dipterocarp forests in this study has achieved good results. This is displayed on the graphics of partial effect of variables on diameter increment (Fig. 5.9, Chapter 5). The trend of diameter increment curves between three species groups is clearly different, especially for species group 3. In addition, contrasting to previous studies, the competition factor was included into the functions reflecting a significant effect of stand basal area on diameter increment. This factor will improve the accuracy and biological plausibility of the model's behavior.

For calibrating mortality models, several authors used logistic regression and obtained good results (e.g. Monserud, 1976; Hamilton, 1986; Vanclay, 1989; Monserud and Sterba, 1999; Yang *et al.*, 2003; Palahí *et al.*, 2003; Jutras *et al.*, 2003; Zhao *et al.*, 2004). Following these authors, we used a logistic model to fit the data for three species groups. Significant variables of the models include tree size, basal area and basal area of larger trees. Several studies (Buchman *et al.*, 1983; LeBlanc and Foster, 1992; Kobe, 1996; Pedersen, 1998; Filion *et al.*, 1998; Wyckoff and Clark, 2000; Ogle *et al.*, 2000; Yang *et al.*, 2003; Bigler and Bugmann, 2003) suggested that diameter increment is a good indicator for estimating mortality rates. However, data of diameter increment for mortal trees was not available in this study, and thus, this variable was not included in the model.

The results for species group 1 and 2 are better compared to group 3, as the amount of data was quite large (see Fig. 5.11, Chapter 5). This is especially true for group 1 whose number of dead trees recorded was quite high and distributed from small trees to large ones. The negative parameter of diameter and the positive parameter of diameter squared capture the U-shaped mortality trend. It indicated that mortality rates are high when trees are small, and decrease with increasing tree size. For large old trees mortality rates start to increase due to the senescent situation and therefore the U-shaped mortality trend is expected. The unexpected results were seen in group 3: here, mortality rates appeared not to depend on diameter (Fig. 5.11). In this group only 24 trees were recorded as dead during the observation interval of five years and the diameters of these trees concentrated within a small range from 6 to 23 cm. Such a small number of data is clearly not enough to establish a reliable mortality function. According to Favrichon (1998), poor estimates of mortality in largest diameter classes could have a strong effect on the model behavior. However, the proportion of tree number of species group 3 is very low (about 5%) and it consists mainly of small trees. So they do not significantly affect estimations of total stand yield with the model. As shown, the model runs stable and the oscillation of stand basal area is in a plausible range. For all three species groups, we can not see any significant effect of site quality on mortality rates; this is in agreement with the results of Yang *et al.* (2003) and Yao *et al.* (2001).

The recruitment model showing annual number of recruits for the three species groups was estimated by linear regression. The number of recruits was positively proportional to the number of trees of the species group and negatively proportional to stand basal area (Fig. 5.12, Chapter 5). Due to insufficient data, only a single function was established for three species groups. The data for establishing recruitment function included only 12 observations of twelve permanent plots with a growth interval of five years. The quantity of recruitment data was very low, so this submodel must be considered to be preliminary despite its general plausibility. The behaviour of the recruitment model will significantly affect the long-term projections of stand growth and yield. Clearly, its behaviour has a strong influence on the presented assessment of effects of different wildfire levels on long-term yield. While the number of recruitment trees was dependent on species and stand density, the likelihood of annual recruitment is also correlated with logging intensity. A logging occasion may destroy the small trees but it reduces stand density and creates canopy gaps, and therefore stimulates regeneration thereafter. In this study, the effect of logging on recruitment and mortality was not included because there is no approved information available. However, this would be a very important factor in estimating the long-term growth and yield of the stand and should be considered in further studies.

8.2 Simulation Results of the Growth Model

The model was calibrated with data of twelve one-hectare permanent plots with growth interval of five years. Ideally, data sets should be divided into two parts, one for building the model and the other for validating the model. However, due to the comparably small data base they have been completely used to calibrate the model. The presented short-term validation is only for checking the accuracy of data fitting, therefore the small difference between predicted and observed values does not come as a surprise (see Tables 6.1, 6.2 and Fig. 6.1, Chapter 6). It is very important to validate the model with independent data in the future. The results of such validations will quantify the model's accuracy more thoroughly. In about four years, the group B plots in the study area will supply an adequate data source for this purpose.

In addition to statistical validation, the model needs to be checked for plausibility of the simulated forest dynamics. This was done by simulating an average stand for a long time in the absence of natural forces or human disturbance. The results of this kind of evaluation showed that the model behavior is consistent with biological knowledge and practical experience of long-term stand growth (Fig. 6.2, Chapter 6). The basal area oscillates over time, as it is typical for systems like forests with long-delayed negative feedbacks. Low stand basal area triggers a high number of recruits, this increases stand basal area again. However, it takes a long time until recruits are large enough to contribute substantially to basal area. So, more and more recruits are growing into the stand. After few decades, when they are big, they almost stop recruitment due to overlarge basal area. Thus, when the big trees start to die, there are enough younger trees to immediately close the gaps. So the basal area reduces greatly, starting the whole cycle again. Such delayed negative feedbacks typically cause systems to oscillate over time, even after one thousand years a steady state had not been reached. However, the range of the stand basal area is within plausible limits. For the long-term dynamics of stand distribution, not only the basal area but also the number of trees and their distribution by size, change according to a plausible succession patterns (Fig. 6.3, Chapter 6). This evolution of the stand is in agreement with the findings of Buongiorno and Michie (1980), Lin *et al.* (1998).

In this study, the inclusion of the competition factors into the model components allowed the growth model to be used to determine the desired stand density that supplies maximum yield. The simulation results showed that at low density or low growing stock, the stand produced low yield. However, when stand density increases, the yield would increase to a maximum point and then decreases again even if stand density continues to increase. The reason is the increasing effect of competition among trees on their growth (see Fig. 7.2, Chapter 7). Based on this principle, the model was used to simulate alternative initial stand densities with the logging cycle of ten years for 100 years to find out the target diameter distribution that produces maximum sustainable yield. The target diameter distributions determined by means of scenario simulation for three site quality levels are suitable for the actual situation of the Dipterocarp forests and they should be proposed to be applied in production practice. Because the harvesting damage was not included into the model, there is a limitation that it can not be used to assess the effect of harvesting cycle on stand yield. However, by choosing a harvesting cycle of ten years which is suitable to the production practice, the model can provide good results.

Huy (1993) defined the yields of such stands corresponding to different stand densities and site quality levels based on stem analysis. His study results were based only on a single growth period of ten years, and they showed that the stands with standing volumes of about 210, 180, 160 and 150 m^3ha^{-1} for site qualities 1, 2, 3 and 4, respectively would produce maximum growth. However, the diameter distribution of these stands was not defined. Compared to the previous growth studies (Sac, 1984; Con, 1991; Huy, 1993; Dong, 2002), in this study factors such as mortality, recruitment and especially competition factor were included into the model. In addition, the growth model was applied into a simulation computer software Vensim, a dynamics system program, allowing it to simulate the stand dynamics for a long time with reliable results. Therefore, the model can be used to implement several applications in practice.

After Favrichon (1998), and Sist *et al.* (2003), the concern of the forest manager focuses particularly on changes of the stand characteristics after silviculture treatment and the ability of the forest to recover the initial natural state. For this application, the model was used to investigate the ability of disturbed stands to return to defined target states in terms of stand basal area and stem-number diameter distribution. The results compare favorably with the 30 to 60 years of return time predicted by Hone and Gwalter (1982). As stated above, there was no sufficient information for taking into consideration logging damages. Thus, this effect is not considered in the estimated return times. According to Kariuki *et al.* (2006), the individual-tree selection method creates small and scattered canopy gaps, so they may not influence recruitment significantly.

8.3 Effects of Wildfire

In this study, to evaluate the effects of wildfire on long-term yield of the Dipterocarp forests, the simulations were based on assumptions of different intensities and frequencies of wildfire occurrence. The assumed wildfire intensities and frequencies are in the range likely to exist in practice. It is assumed that when wildfire occurs, the number of recruits would decrease so that we can clearly see a decrease in the long-term yield. The level of decrease of stand yield depends strongly on intensities and frequencies of the wildfire (Fig. 7.7, Chapter 7).

When simulating the effects of wildfire on long-term yield, we assumed that recruitment can go on one year even after a fire, as usual. For future applications, this is easy to solve by including a stock where the recruits wait some time before they grow in to the lowest diameter class. The fire would then take away desired percentages from this stock. This would be more realistic.

Wildfires also probably affect on growth of trees with diameter of 6 cm and above. Thus, the presented results show correct tendencies, but the compounding effects of wildfires in Dipterocarp forests needs to be further studied in order to obtain more precise estimations.

Besides the harmful effects on the number of recruits, wildfire may have some positive effects on recruitment. The fruits of Dipterocarp species have often wings, therefore they are often suspended on the vegetation and grass covers, the seeds can not germinate and will die. Wildfires may create a favorable condition for seeds to contact to the ground after that and they will germinate. This positive effect also needs to be studied in the future.

Chapter 9

Conclusion and Perspective

9.1 General Conclusion

9.1.1 The Growth Model Approach and Development

This study aims to develop a growth model for supporting sustainable management of the Dipterocarp forest in Central Highland of Vietnam. The final model is a size class model which was developed using data from 12 one-hectare permanent plots established in Dipterocarp forests in YokDon National Park with a growth interval of five years. Four primary model components including: diameter increment, mortality, recruitment and harvesting were fitted quite well with the empirical data. Classification of trees in Dipterocarp forests into three species groups has proved suitable and obtained good results in developing the model components. The final model was implemented in the framework of the modelling software Vensim DSS 5.7a.

The model covers the tree number dynamics of three species groups in 76 one-cm dbh classes from 6 to 81 cm. The objectives of the thesis, the development of a size class model based on differential equations for the Dipterocarp forests and presentation of its applications, have been achieved. A thorough evaluation on different aspects such as evaluation of model approach, model validation and evaluation of simulator has been carried out. The selection of the model approach as a size class model is appropriate to the available data and satisfactory to the objectives of application in sustainable forest management. While the study focused on the Dipterocarp forests in Central Highlands of Vietnam, the model approach used in this study has a general applicability in many forest types and its simulation results can also serve as a reference for research on different forest types in Vietnam.

The study results showed that the simulation runs in general were quantitatively and qualitatively plausible.

9.1.2 Model Applications

The model can be applied effectively in several aspects. Firstly, it can be used for sustainable forest management as illustrated in this study. Secondly, it may have an impact on forest science: the model can be used to develop hypotheses about forest dynamics, that can be tested in a very focused way with empirical data. Thirdly, for education: such a model can be used for teaching students in forest growth and in modelling (as Vensim is based on an internationally known notation principle), it can be also used for training forest managers, community representatives, politicians and other people who make decisions about forests. As stated by Rayner and Turner (1990), growth and yield models in forestry are necessary not only to project changes occurring in forests and hence to facilitate forest management planning and decision making, but also to augment stand management research and evaluation. Short-term planning usually determines the operational levels of yields using the available information on inventory of the forest. Long-term planning may involve yield predictions and regulation that require simulation of forest tree and stand responses to changes in composition, structure and other anticipated treatments beyond the range of available data. Both short and long-term forest planning involve evaluation and selection of alternative management options through ecological, economic and social criteria. In this context, the model can be used as a tool to facilitate the visualization of cause-and-effect relationship of various alternatives. By using the method of scenario analysis, the model can be applied to simulate the effect of various initial states on the yield of stands. Based on these simulation results, the target diameter distributions for different site quality levels which will produce maximum yield were determined. The target diameter distribution for each site quality determined has the form of a negative exponential distribution with the three following determination variables: stand basal area, q-quotient and maximum diameter. This is a very good guideline for sustainable mixed uneven-aged Dipterocarp forest management in Vietnam. Especially, for the policy of forest land allocation to local people of Vietnamese government in recent years, researchers in Vietnam try to find out guidelines to support this policy. However, up to now there were no really effective tools for predicting the growth and yield of uneven-aged, mixed forests. The developed model will serve as a good tool for supporting necessary information to managers in decision making on sustainable management. In case of forests that were allocated to households according to policy of Vietnamese government recently, shorter logging cycle of five or ten years can be tested to supply not only large timber but also firewood to the current needs of local people. For the forests under management of the state enterprise, the main purpose is to produce large timber, so the harvesting cycles to be tested may be longer, from 20 to 40 years or more. The growth model can be used not only to estimate summaric stand values, but also the assortment products for alternative silvicultural prescriptions.

The presented example applications of the model showed that the model can be also used to answer actual management questions. One was to estimate the recovery time that given overharvested stands need to reach a defined target state. Another was to estimate the effects of wildfires on long-term yield. The model output, consisting of charts and tables can provide forest researchers and managers with a broad set of information and visualizations, to help them drawing their decisions objectively.

9.1.3 Data Assessment

There are some aspects beyond the scope of this study that need to be mentioned. Among them are the effects of logging on mortality and recruitment, assessment of quantity and quality of recruitment after a wildfire occurred, the effects of wildfire on tree growth. These aspects directly affect on growth and yield of forests. However, due to insufficient data they are not included in this study. It is necessary to further research on these aspects in the future. Model building helps to identify such lacks of knowledge.

Another aspect is the amount of data available for this study. The duration of only a single growth interval of five years and the number of plots were obviously not enough to develop a growth model that covers the entire range of site conditions in Dipterocarp forests. In addition, the small dataset for developing mortality and recruitment models should affect to the prediction of long-term growth and yield. There were no data set aside for cross-validation of the model. This suggests that establishment and maintenance of a system of more permanent plots in the future are necessary. On such plots, e.g. different site qualities, stand densities, and harvesting concepts on stand dynamic and growth could be explored systematically. When data from such permanent plots are available, they will be valuable data sources to recalibrate and validate the growth model. The data from plot group B as established in this study will be the basis for a first important step. However, under the current conditions, there was no other choice as to use the limited data sets to construct a growth model. This is strongly supported by Buongiorno (1996), who stated: "*Although long-term observations of forest growth are hard to get, much can be done with just two measurements, taken a decade or so apart, from a cross-section of sample plots. A tally of trees by species and size class at the beginning and end of the interval, plus a record of the trees that have been cut and those that have died, is enough to build such a growth model. This kind of data is often available from ordinary management records. If mortality data do not exist, they can often be guessed from experience. Such "soft" data* *may lack formal rigor, but they will produce a practical model in short order. It is then relatively easy to check if the model mimics growth reasonably well. I believe that it is much better to have an eclectic model to help management than no model at all, or to wait decades for the perfect data and the perfect model (which do not exist anyway)*".

9.2 Perspective of the Study

As stated in the previous sections, the growth model in this study was constructed based on limited data sources. Therefore, the use of model applications in production practice is limited to Dipterocarp forest areas whose site conditions are similar to those of permanent plots in the study. In the future, it is necessary to establish permanent plots covering a broader range of site conditions to obtain more reliable data sets. Data sets collected in research plots should include not only diameter, height, mortality, recruitment but also additional parameters such as: crown dimension, tree position, etc. accounted for different disturbance factors such as: wildfire, harvest, etc. Once obtained the additional data sets, a number of following studies needs to be implemented:

9.2.1 Recalibration of the Growth Model and Extension of its Applications

When additional data from research plots are available, they will be used to recalibrate the main model components of the growth model. Within the framework of Vensim it is easy to replace old model components with new ones. On this basis, the model will be applicable to the entire range of site conditions and the accuracy of estimations with the model will be improved. With this improved model and more information relevant to social and economical issues, other applications of the growth model in particular contexts of forest management will be further explored. Once the data about effects of harvesting on recruitment and mortality is available, it will be incorporate into the model in order to assess the effect of the harvesting cycle on stand yield. That enables to analyse the harvesting cycle that provides a maximum yield. With the information about the timber price and harvesting cost available, the model can be used to calculate of the net present value (NPV) of the stand. With the establishment of the allometric equations for different parts of the tree, the growth model can be used to calculate the biomass of the stand. In addition, when information about the proportion of carbon amount in different parts of the tree is available, we can used the model to define the accumulation of carbon amount as well as the ability of carbon sequestration of the Dipterocarp forests.

In Chapter 7 the model was used to simulate the effect of wildfires on long-term yield. However, these simulations were just based on the assumption that recruitment decreases when a fire occurs. In fact, it may affect the forests in several aspects. Studies on effects of wildfire on all aspects need to be seriously considered in the future. When data of the effect of wildfire on aspects such as mortality, tree growth and recruitment, etc. is obtained from the long-term observations on research plots, the growth model will be recalibrated to provide the reliable projections that reflect the actual status more specifically. Besides the effect of wildfire, other natural factors such as disease, water-logged in the rainy season and drought in the dry season often occur in the Dipterocarp forests. These factors are also attributed to the reason of dead trees, reduced increment. They should be taken into account and included into the model.

9.2.2 Development of Growth Models for other Forest Types in Vietnam

The growth model in this study was developed for Dipterocarp forests in the Central Highlands of Vietnam that are uneven-aged, multi-species deciduous forests. However, the model approach can be applied to other forest types such as evergreen, semi-evergreen forests or plantation forests. With data sets to be collected from permanent research plots, the model components can be calibrated to fit for such forests. At present, as mentioned in Chapter 3, the Forest Inventory and Planning Institute of Vietnam are conducting a network of permanent plots through out the country including different forest types. Data collected from these permanent plots can be used to construct growth models for the different forest types. This is an important and necessary work for sustainable forest management because at present there is still no effective model available.

9.2.3 Technical Development

Up to now, the growth model has been calibrated successfully. However, as mentioned before it cannot be operated by the forest managers themselves. For them, a user interface would be needed that makes input and output easy and hides the complexity of the model itself. Such a user interface can also be designed with Vensim. So, for the further steps the following works need to be carried out: creating a comfortable user interface for non-scientific users, fitting input and output to the data structure of state forest enterprises (This could be the first step to simulating whole forest enterprises), technically implementing all kinds of model improvements and enlargements.

In order to manage all that, I plan to train students at my home university in Vietnam to become modeling specialists during their BSc, MSc or PhD theses. So, I could form a group of people who are not only able to work scientifically on interesting topics, but who also can implement their results into an operational model. This would significantly accelerate future development. In addition, I could introduce fellow scientists from other disciplines (social science, economics) into this modelling technique that may lead to a very interesting kind of model, where e.g. forest development could be linked to community development. For these purposes, Vensim will be an ideal software platform.

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Appendix

Table 01 List of tree species in the research plots in YokDon National Park.
For each species the group affiliation used in this work is shown

No	Local name	Scientific name	Family	Species group
1	An tức hương	*Styrax benzoin*	Styracaceae	3
2	Bằng lăng	*Lagerstroemia calyculata*	Lythraceae	1
3	Bình linh	*Vitex sumatrana*	Verbenaceae	2
4	Bời lời	*Litsea lancilimba*	Lauraceae	2
5	Bông gòn	*Ceiba pentandra*	Bombaceae	2
6	Bứa	*Grcinia oblongifolia*	Glusiaceae	3
7	Búi	*Masstixia arborea*	Cornaceae	3
8	Cà chít	*Shorea obtuse*	Dipterocarpaceae	1
9	Cám	*Parinari annamensis*	Chrysobalanaceae	2
10	Cẩm lai	*Dalbergia mamosa*	Fabaceae	2
11	Cẩm liên	*Shorea siamensis*	Dipterocarpaceae	1
12	Căm xe	*Xylia dolabriformis*	Mimosaceae	2
13	Cheo lông	*Engelhardtia spicata*	Juglandaceae	3
14	Chiêu liêu	*Terminalia alata*	Combretaceae	1
15	Choai	*Terminalia bellirica*	Combretaceae	2
16	Chồi mồi	*Antidesma ghaesembilla*	Euphorbiaceae	2
17	Chung bau	*Combretum trifoliatum*	Combretaceae	2
18	Cò ke	*Microcos paniculata*	Tiliceae	2
19	Cóc rừng	*Lumnitzera coccinea*	Anacardiaceae	3
20	Giáng hương	*Pterocarpus pedatus*	Fabaceae	2
21	Dầu đồng	*Dipterocarpus tuberculatus*	Dipterocarpaceae	1
22	Dầu trà beng	*Dipterocarpus obtusifolius*	Dipterocarpaceae	1
23	De	*Syndiclis lotungensis*	Lauraceae	2
24	Đẻn 5 lá	*Vitex quinata*	Verbenaceae	2
25	Găng gai	*Randia spinosa*	Rubiaceae	2
26	Gạo hoa trắng	*Bombax anceps*	Bombaceae	2
27	Gáo vàng	*Adina cordifolia*	Rubiaceae	2
28	Dẻ đỏ	*Lithocarpus ducampii*	Fagaceae	2
29	Gòn	*Ceiba pentandra*	Bombaceae	2
30	Gụ mật	*Sindora siamensis*	Caesalpiniaceae	2
31	Hồng rừng	*Paulownia fortunei*	Scrophulariaceae	2
32	Hóc quang	*Rhodoleia champion*	Hamamelidaceae	3
33	Kẹ núi	*Aesculus chinensis*	Hippocastanaceae	2
34	Kháo	*Phoebe cuneata*	Lauraceae	3

Table 01 (continued)

No	Local name	Scientific name	Family	Species group
35	Kiền kiền	*Hopea pierrei*	Dipterocarpaceae	1
36	Cò kẹ	*Grewia afpaniculata*	Tiliaceae	2
37	Kơ nia	*Irvigia malayana*	Irvigiaceae	2
38	Lim xẹt	*Peltophorum tonkinensis*	Caesalpiniaceae	2
39	Lộc vừng	*Barringtonia acutagula*	Lecythidaceae	2
40	Lòng máng	*Pterospermum diversifolium*	Sterculiaceae	2
41	Mã tiền	*Strychnos nuxblanda*	Loganiaceae	3
42	Me rừng	*Phyllanthus emblica*	Euphorbiaceae	3
43	Móng bò	*Bauhinia purpurea*	Caesalpiniaceae	3
44	Muồng đen	*Cassia siamea*	Fabaceae	2
45	Nhàu núi	*Morinda citrifolia*	Rubiaceae	3
46	Nhọ nồi	*Diospyros pilosella*	Ebenaceae	3
47	Núc nác	*Oroxylum indicum*	Bignoniaceae	3
48	Quao núi	*Stereospermum cylindricum*	Bignoniaceae	3
49	Giềng giềng	*Butea frondosa*	Legumimoseae	3
50	Sao đen	*Hopea odorata*	Dipterocarpaceae	1
51	Sến mủ	*Shorea roxburghii*	Dipterocarpaceae	1
52	Sọ chai	*Hopea recopei*	Dipterocapaceae	1
53	Sơn rừng	*Rhus succedanea*	Anacardiaceae	2
54	Táo rừng	*Ziziphus oenoplia*	Rhamnaceae	3
55	Táu mật	*Vatica odorata*	Dipterocarpaceae	1
56	Lành ngạnh	*Cratoxylon sp*	Clusiaceae	3
57	Thẩu tấu	*Aporosa sp*	Euphorbiaceae	3
58	Thị rừng	*Diospyros sp*	Ebenaceae	3
59	Thừng mực	*Wrightia tomentosa*	Apocynaceae	3
60	Trám trắng	*Canarium album*	Burseraceae	2
61	Trâm vối	*Syzygium cuminii*	Myrtaceae	2
62	Vên vên	*Anisoptera costata*	Dipterocarpaceae	1
63	Vừng	*Careya sphaerica*	Lecythidaceae	2
64	Xoài rừng	*Mangifera longipetiolata*	Meliaceae	2

Table 02 Parameters of height curves of the twelve group A plots according to the Petterson function $h = 1.3 + \left(\dfrac{d}{a_0 + a_1 \times d} \right)^3$

Plot	Species group	a_0	a_1	R^2	Number of observations
A1	1	1.7116	0.3415	0.88	258
	2	2.0385	0.3541	0.89	64
	3	1.2789	0.4175	0.70	27
A2	1	1.5629	0.3461	0.80	228
	2	2.4792	0.3432	0.88	30
	3	1.6947	0.4015	0.86	34
A3	1	1.8833	0.3240	0.93	171
	2	1.6515	0.3622	0.86	97
	3	1.4027	0.3960	0.78	52
A4	1	2.0848	0.3244	0.88	116
	2	1.9934	0.3518	0.88	32
	3	1.0096	0.4346	0.74	50
A5	1	1.7735	0.3533	0.88	350
	2	1.4275	0.3810	0.86	60
	3	1.4275	0.4145	0.75	17
A6	1	1.9728	0.3259	0.87	242
	2	1.5522	0.3537	0.80	62
	3	1.0973	0.4044	0.78	22
A7	1	2.1661	0.3520	0.85	339
	2	1.4823	0.3934	0,83	52
	3	1.8510	0.4021	0.79	28
A8	1	2.0211	0.3645	0.89	185
	2	1.8183	0.3917	0.85	44
	3	2.2810	0.3876	0.80	23
A9	1	1.7082	0.3739	0.84	160
	2	1.5917	0.3835	0.91	68
	3	2.1290	0.3908	0.79	22
A10	1	1.6630	0.3452	0.90	127
	2	1.5082	0.3794	0.86	59
	3	1.4320	0.4028	0.91	10
A11	1	2.0626	0.3426	0.90	108
	2	1.8000	0.3678	0.91	71
	3	1.1573	0.4145	0.74	17
A12	1	1.8003	0.3557	0.85	441
	2	2.1707	0.3506	0.91	38
	3	1.9377	0.3888	0.89	20

Table 03 Parameters of height curves of the 21 group B plots according to the Petterson function

Plot	a_0	a_1	R^2	Number of observations
B1	2.0643	0.3290	0.85	38
B2	2.2450	0.3283	0.85	32
B3	2.8985	0.3267	0.83	32
B4	1.7126	0.3512	0.85	34
B5	2.4915	0.3254	0.83	33
B6	1.6876	0.3502	0.84	29
B7	2.2237	0.3509	0.8	41
B8	2.6766	0.3243	0.82	43
B9	2.7226	0.3234	0.79	39
B10	2.3567	0.3303	0.83	39
B11	2.7761	0.3034	0.81	32
B12	1.7219	0.3614	0.82	43
B13	1.7179	0.3634	0.85	40
B14	1.5417	0.3569	0.75	38
B15	1.5457	0.3641	0.82	33
B16	2.1417	0.3383	0.86	37
B17	2.0862	0.3307	0.76	36
B18	1.4679	0.3621	0.65	36
B19	1.8089	0.3440	0.82	31
B20	1.1329	0.3533	0.83	33
B21	1.1329	0.3533	0.82	33

Table 04 Growth and Yield Characteristics of the group A plots

			Remaining stand					**Dead trees between measurements**					**Increment/Year**	
Plot	**Year**	**Species group**	**N (tree/ha)**	**BA (m^2/ha)**	**V (m^3/ha)**	**Dg (cm)**	**Hg (m)**	**N (tree/ha)**	**BA (m^2/ha)**	**V (m^3/ha)**	**Dg (cm)**	**Hg (m)**	**BA (m^2/ha)**	**V (m^3/ha)**
A1	2002	1	329	13.073	89.118	22.7	15	16	0.151	0.625	11.9	9.4		
		2	82	4.403	27.707	26.1	13.7	3	0.117	0.683	22.3	12.6		
		3	45	0.871	3.713	15.7	9.3	2	0.012	0.033	8.7	6.9		
		Sum	**456**	**18.347**	**120.538**			**21**	**0.279**	**1.341**				
	2007	1	313	14.965	103.845	24.7	15.7						0.378	2.945
		2	79	4.752	30.088	27.7	14.1						0.07	0.476
		3	43	1.018	4.371	17.4	9.7						0.03	0.132
		Sum	**435**	**20.736**	**138.395**								**0.478**	**3.533**
A2	2002	1	281	16.093	111.367	27	16.5	11	0.273	1.576	17.8	13.5		
		2	66	4.077	24.728	28	13.7	3	0.13	0.752	23.5	12.4		
		3	33	0.57	2.215	14.8	8.6	2	0.063	0.25	20	10		
		Sum	**380**	**20.74**	**138.31**			**16**	**0.466**	**2.578**				
	2007	1	270	18.142	128.121	29.2	17						0.41	3.351
		2	63	4.377	26.962	29.7	14.2						0.06	0.447
		3	31	0.638	2.527	16.2	9						0.014	0.062
		Sum	**364**	**23.158**	**157.61**								**0.483**	**3.86**
A3	2002	1	237	17.375	147.808	30.6	18.7	15	0.395	2.598	18.3	14.2		
		2	148	6.566	39.803	23.8	13.7	14	0.271	1.318	15.7	11.1		
		3	55	1.108	4.826	16	10.1	5	0.114	0.484	17.1	10.4		
		Sum	**440**	**25.049**	**192.438**			**34**	**0.781**	**4.399**				

			Remaining stand					**Dead trees between measurements**					**Increment/Year**	
Plot	**Year**	**Species group**	**N**	**BA**	**V**	**Dg**	**Hg**	**N**	**BA**	**V**	**Dg**	**Hg**	**BA**	**V**
A3	2007	1	222	18.707	160.359	32.8	19.3						0.266	2.51
		2	134	7.006	43.103	25.8	14.2						0.088	0.66
		3	50	1.192	5.297	17.4	10.5						0.017	0.094
		Sum	**406**	**26.905**	**208.76**								**0.371**	**3.264**
A4	2002	1	164	16.313	136.076	35.6	19.1	5	0.1	0.525	15.9	11.9		
		2	43	3.979	28.133	34.3	15.8	7	0.13	0.591	15.4	10.3		
		3	61	0.482	1.654	10	7.8	3	0.026	0.082	10.4	8		
		Sum	**268**	**20.774**	**165.863**			**15**	**0.256**	**1.198**				
	2007	1	159	17.892	150.849	37.9	19.6						0.316	2.955
		2	36	4.131	29.617	38.2	16.5						0.031	0.297
		3	58	0.638	2.266	11.8	8.4						0.031	0.122
		Sum	**253**	**22.661**	**182.732**								**0.377**	**3.374**
A5	2002	1	439	15.724	98.294	21.4	13.3	23	0.334	1.766	13.6	10.1		
		2	71	3.339	19.329	24.5	11.8	3	0.045	0.181	13.8	11.8		
		3	29	0.561	2.354	15.7	9.4	1	0.015	0.052	13.7	8.9		
		Sum	**539**	**19.624**	**119.977**			**27**	**0.393**	**1.999**				
	2007	1	416	17.553	111.045	23.2	13.9						0.366	2.55
		2	68	3.615	21.051	26	11.8						0.055	0.344
		3	28	0.628	2.671	16.9	9.7						0.013	0.064
		Sum	**512**	**21.796**	**134.768**								**0.434**	**2.958**
A6	2002	1	314	14.196	103.145	24	16	24	0.43	2.14	15.1	11.8		
		2	76	3.693	24.159	24.9	15.2							
		3	19	0.739	3.641	22.3	12							

			Remaining stand					Dead trees between measurements					Increment/Year	
Plot	**Year**	**Species group**	**N**	**BA**	**V**	**Dg**	**Hg**	**N**	**BA**	**V**	**Dg**	**Hg**	**BA**	**V**
A6		**Sum**	**409**	**18.629**	**130.945**			**24**	**0.43**	**2.14**				
	2007	1	290	15.853	118.263	26.4	16.8						0.331	3.024
		2	76	4.146	27.387	26.4	15.5						0.091	0.646
		3	19	0.849	4.237	23.8	12.2						0.022	0.119
		Sum	**385**	**20.847**	**149.887**								**0.444**	**3.788**
A7	2002	1	552	15.058	79.074	18.6	11	23	0.301	1.149	12.9	8.4		
		2	73	3.982	21.709	26.4	12.3							
		3	31	0.316	0.974	11.4	6.9	2	0.019	0.05	10.9	6.7		
		Sum	**656**	**19.356**	**99.316**			**25**	**0.32**	**1.199**				
	2007	1	529	17.495	91.859	20.5	11.7						0.487	3.045
		2	73	4.282	23.309	27.3	12.4						0.06	0.32
		3	29	0.36	1.158	12.6	7.3						0.009	0.037
		Sum	**631**	**22.136**	**116.326**								**0.556**	**3.402**
A8	2002	1	207	6.327	35.182	19.7	11.1	6	0.033	0.077	8.4	5.8		
		2	59	3.222	16.607	26.4	11.5	5	0.041	0.117	10.3	6.7		
		3	37	0.604	2.039	14.4	7.5	2	0.02	0.049	11.3	6.2		
		Sum	**303**	**10.154**	**53.828**			**13**	**0.092**	**0.243**				
	2007	1	201	7.3	40.834	21.5	11.7						0.195	1.13
		2	54	3.46	17.937	28.6	11.9						0.048	0.266
		3	35	0.725	2.571	16.2	8.1						0.024	0.106
		Sum	**290**	**11.486**	**61.3415**								**0.266**	**1.503**
A9	2002	1	255	8.973	49.067	21.2	12.9	9	0.13	0.57	13.6	9.3		
		2	89	4.77	26.591	26.1	12.7	3	0.034	0.121	11.9	8.5		

			Remaining stand					Dead trees between measurements					Increment/Year	
Plot	**Year**	**Species group**	**N**	**BA**	**V**	**Dg**	**Hg**	**N**	**BA**	**V**	**Dg**	**Hg**	**BA**	**V**
A9	2002	3	37	0.605	2.017	14.4	7.7	4	0.065	0.204	14.4	7.7		
		Sum	**381**	**14.348**	**77.675**			**16**	**0.229**	**0.894**				
	2007	1	246	10.234	56.546	23	12.4						0.252	1.496
		2	86	5.154	28.877	27.6	12.9						0.077	0.457
		3	33	0.65	2.257	15.8	8.2						0.009	0.048
		Sum	**365**	**16.037**	**87.681**								**0.338**	**2.001**
A10	2002	1	170	12.389	89.707	30.5	16.9	4	0.057	0.286	13.5	11		
		2	93	4.548	25.838	25	13.1	7	0.187	0.921	18.5	11.5		
		3	12	0.663	3.421	26.5	11.8							
		Sum	**275**	**17.6**	**118.966**			**11**	**0.244**	**1.206**				
	2007	1	166	13.91	101.943	32.7	17.4						0.304	2.447
		2	86	4.915	28.265	27	13.4						0.073	0.485
		3	12	0.738	3.822	28	12						0.015	0.08
		Sum	**264**	**19.563**	**134.03**								**0.393**	**3.013**
A11	2002	1	164	9.065	59.952	26.5	14.8	2	0.007	0.014	6.6	4.9		
		2	104	5.49	32.787	25.9	13.3	7	0.071	0.279	11.4	8.2		
		3	30	0.805	3.726	18.5	10.5	3	0.058	0.239	15.6	9.9		
		Sum	**298**	**15.36**	**96.465**			**12**	**0.136**	**0.532**				
	2007	1	162	10.35	69.423	28.5	15.3						0.257	1.894
		2	97	5.948	35.72	27.9	13.7						0.092	0.586
		3	27	0.855	3.985	20.1	10.8						0.01	0.052
		Sum	**286**	**17.154**	**109.128**								**0.359**	**2.533**
A12	2002	1	485	15.553	89.485	20.2	12.7	18	0.293	1.414	14.4	10.3		

			Remaining stand					Dead trees between measurements					Increment/Year	
Plot	**Year**	**Species group**	**N**	**BA**	**V**	**Dg**	**Hg**	**N**	**BA**	**V**	**Dg**	**Hg**	**BA**	**V**
A12	2002	2	62	2.172	12.197	21.1	12	1	0.003	0.006	6.4	4.3		
		3	23	0.534	2.151	17.2	9.2							
		Sum	**570**	**18.259**	**103.832**			**19**	**0.296**	**1.419**				
	2007	1	467	17.859	104.851	22.1	13.3						0.461	3.073
		2	61	2.435	13.849	22.5	12.5						0.053	0.33
		3	23	0.631	2.615	18.7	9.7						0.019	0.093
		Sum	**551**	**20.925**	**121.315**								**0.533**	**3.497**

Table 05 Growth and Yield Characteristics of the group B plots

Plot	**Species group**	**N/plot** (trees)	**N/ha** (trees)	**G/plot** (m^2)	**G/ha** (m^2)	**V/plot** (m^3)	**V/ha** (m^3)	**Dg** (cm)	**Hg** (m)
B1	1	109	436	4.35	17.42	28.97	115.90	22.6	14.7
	2	6	24	0.31	1.22	2.18	8.71	25.5	15.8
	3	10	40	0.21	0.86	1.18	4.71	16.5	12.0
	Sum	**125**	**500**	**4.88**	**19.50**	**32.33**	**129.31**		
B2	1	173	692	3.91	15.63	20.48	81.93	17.0	11.5
	2	4	16	0.24	0.94	1.53	6.11	27.4	15.8
	3	16	64	0.19	0.78	0.81	3.22	12.4	8.9
	Sum	**193**	**772**	**4.34**	**17.35**	**22.82**	**91.26**		
B3	1	72	288	3.40	13.59	22.81	91.25	24.5	12.7
	2	2	8	0.10	0.42	0.58	2.31	25.7	13.1
	3	24	96	0.77	3.08	3.97	15.88	20.2	10.9
	Sum	**98**	**392**	**4.27**	**17.09**	**27.36**	**109.44**		
B4	1	138	552	4.38	17.54	26.66	106.62	20.1	13.3
	2	11	44	0.46	1.82	2.83	11.34	22.9	14.3
	3	19	76	0.75	3.00	5.03	20.14	22.4	14.1
	Sum	**168**	**672**	**5.59**	**22.36**	**34.52**	**138.09**		
B5	1	115	460	3.03	12.13	16.05	64.19	18.3	11.5
	2	5	20	0.12	0.47	0.58	2.32	17.2	11.0
	3	25	100	0.29	1.17	1.07	4.27	12.2	8.0
	Sum	**145**	**580**	**3.44**	**13.76**	**17.70**	**70.78**		
B6	1	226	904	3.32	13.28	16.79	67.15	13.7	8.7
	2	27	108	0.50	1.99	2.53	10.13	15.3	9.5
	3	28	112	0.25	1.00	0.95	3.81	10.7	7.0
	Sum	**281**	**1124**	**4.07**	**16.28**	**20.27**	**81.08**		
B7	1	157	628	2.76	11.03	11.57	46.27	15.0	9.3
	2	1	4	0.02	0.06	0.06	0.23	14.3	9.0
	3	20	80	0.15	0.60	0.43	1.71	9.8	6.5
	Sum	**178**	**712**	**2.92**	**11.69**	**12.05**	**48.21**		
B8	1	62	248	3.19	12.77	20.51	82.03	25.6	14.0
	2	2	8	0.17	0.69	1.25	4.99	33.1	16.3
	3	18	72	0.15	0.60	0.41	1.65	10.3	6.3
	Sum	**82**	**328**	**3.51**	**14.06**	**22.17**	**88.67**		
B9	1	81	324	2.71	10.84	14.89	59.57	20.6	11.9
	2	4	16	0.07	0.29	0.29	1.15	15.1	9.1
	3	20	80	0.15	0.62	0.44	1.74	9.9	6.0
	Sum	**105**	**420**	**2.94**	**11.74**	**15.62**	**62.47**		
B10	1	137	548	2.41	9.63	11.24	44.96	15.0	9.9
	2	5	20	0.04	0.18	0.14	0.56	10.6	7.2
	3	12	48	0.10	0.42	0.38	1.52	10.5	7.2
	Sum	**154**	**616**	**2.56**	**10.23**	**11.76**	**47.05**		
B11	1	156	624	2.93	11.71	14.39	57.55	15.5	10.2
	2	4	16	0.02	0.06	0.03	0.12	7.2	4.3
	3	20	80	0.15	0.59	0.41	1.65	9.7	6.2
	Sum	**180**	**720**	**3.09**	**12.36**	**14.83**	**59.32**		
B12	1	127	508	3.46	13.82	18.85	75.39	18.6	12.0
	2	5	20	0.06	0.22	0.22	0.87	11.9	9.0
	3	28	112	0.33	1.33	1.40	5.60	12.3	9.2

Table 05 (continuation)

Plot	**Species group**	**N/plot** (trees)	**N/ha** (trees)	**G/plot** (m^2)	**G/ha** (m^2)	**V/plot** (m^3)	**V/ha** (m^3)	**Dg** (cm)	**Hg** (m)
B12	**Sum**	**160**	**640**	**3.84**	**15.37**	**20.46**	**81.86**		
B13	1	144	576	3.19	12.77	15.99	63.97	16.8	11.2
	2	12	48	0.17	0.70	0.76	3.05	13.6	9.8
	3	18	72	0.18	0.71	0.73	2.93	11.2	8.5
	Sum	**174**	**696**	**3.55**	**14.18**	**17.49**	**69.95**		
B14	1	101	404	3.16	12.65	18.75	74.99	20.0	13.5
	2	5	20	0.11	0.46	0.63	2.54	17.0	12.5
	3	12	48	0.24	0.98	1.32	5.28	16.1	12.1
	Sum	**118**	**472**	**3.52**	**14.08**	**20.70**	**82.81**		
B15	1	193	772	3.33	13.31	16.84	67.35	14.8	11.0
	2	1	4	0.05	0.19	0.26	1.03	24.3	14.1
	3	12	48	0.27	1.09	1.42	5.69	17.0	11.9
	Sum	**206**	**824**	**3.64**	**14.58**	**18.52**	**74.07**		
B16	1	212	848	3.22	12.89	14.52	58.10	13.9	9.7
	2	8	32	0.28	1.13	1.51	6.04	21.2	13.1
	3	5	20	0.07	0.27	0.29	1.14	13.1	9.2
	Sum	**225**	**900**	**3.57**	**14.29**	**16.32**	**65.29**		
B17	1	113	452	2.69	10.76	15.42	61.68	17.4	12.2
	2	10	40	0.28	1.10	1.68	6.71	18.7	12.9
	3	6	24	0.47	1.89	3.56	14.25	31.7	17.3
	Sum	**129**	**516**	**3.44**	**13.75**	**20.66**	**82.63**		
B18	1	79	316	3.67	14.69	22.65	90.59	24.3	14.6
	2	2	8	0.27	1.08	1.94	7.77	41.5	17.2
	3	7	28	0.18	0.73	1.12	4.47	18.2	12.8
	Sum	**88**	**352**	**4.12**	**16.50**	**25.71**	**102.83**		
B19	1	91	364	3.14	12.58	18.92	75.68	21.0	13.8
	2	31	124	0.67	2.66	3.69	14.76	16.5	12.0
	3	4	16	0.10	0.41	0.54	2.15	18.1	12.7
	Sum	**126**	**504**	**3.91**	**15.65**	**23.15**	**92.59**		
B20	1	263	1052	3.45	13.80	18.53	74.13	12.9	11.8
	2	5	20	1.24	4.97	10.40	41.62	56.2	20.0
	3	21	84	0.27	1.09	1.52	6.10	12.9	11.8
	Sum	**289**	**1156**	**4.96**	**19.86**	**30.46**	**121.85**		
B21	1	210	840	3.62	14.48	20.38	81.50	14.8	12.8
	2	2	8	0.02	0.09	0.10	0.39	11.7	11.1
	3	32	128	0.71	2.85	4.36	17.45	16.8	13.7
	Sum	**244**	**976**	**4.35**	**17.41**	**24.84**	**99.34**		

Detailed Text Descriptions of the Equations Used for the Growth Model Implemented in Vensim DSS 5.7a

 # Asign diameter classes:

```
Class:
        c6,c7, … ,c81
        ~
        ~           |
Class but Lowest:
         c7,c8, … ,c81
        ~
        ~           |
Class but Highest:
        c6,c7, … ,c80
        ~
        ~           |
Class Previous:
        c6,c7, … ,c80-> Class but Lowest
        ~
        ~           |
```

 # Asign values for diameter classes:

```
Diameters[Class]=
         6.5, 7.5, … , 81.5
        ~ cm
        ~           |
```

 # Aggregate 5-cm diameter classes:

```
Class Aggr:
        ca8, ca13, … , ca78
        ~
        ~           |
Class 6 10:
        c6,c7,c8,c9,c10
        ~
        ~           |
        ………………………..
Class 76 81:
        c76,c77,c78,c79,c80,c81
        ~
        ~           |
```

 # Asign species groups:

```
SpeciesGroup:
        s1,s2,s3
        ~
        ~           |
```

 # Calculate tree number of the 5-cm diameter classes for each species group:

```
Aggregated Diameter Class[ca8,SpeciesGroup]=
        SUM(Diameter Class[Class 6 10!,SpeciesGroup])
~
~                   |
        ………………………………………………..
Aggregated Diameter Class[ca78,SpeciesGroup]=
        SUM(Diameter Class[Class 76 81!,SpeciesGroup])
        ~ Trees
        ~           |
# Total tree number of three species groups for 5-cm diameter classes:

Diameter Classes across Species[Class Aggr]=
        SUM(Aggregated Diameter Class[Class Aggr,SpeciesGroup!])
        ~ Trees
        ~           ~           :SUPPLEMENTARY
                    |
# Total tree number for each species group:

Stem Number by Species Group[SpeciesGroup]=
        SUM(Diameter Class[Class!,SpeciesGroup])
        ~ Trees
        ~           |
# Basal area for each the diameter class of each species group:

Basal Areas[Class,SpeciesGroup]=
        3.14159/4 * Diameters[Class]^2 * Diameter Class[Class,SpeciesGroup]*Conversion Factor
        ~ m*m
        ~           |
# Basal area for 5-cm diameter classes of each species group:

Aggregated Basal Area Classes[ca8,SpeciesGroup]=
        SUM(Basal Areas[Class 6 10!,SpeciesGroup])
~
~                   |
……………………………………………………..
Aggregated Basal Area Classes[ca78,SpeciesGroup]=
        SUM(Basal Areas[Class 76 81!,SpeciesGroup])
        ~ m*m
        ~           |
# Total basal area for each species group:

Total Basal Area by Species Group[SpeciesGroup]=
        SUM(Basal Areas[Class!,SpeciesGroup])
        ~ m*m
        ~           ~           :SUPPLEMENTARY
                    |
# Basal area for 5-cm diameter classes of three species groups:

Basal Area Classes across Species[Class Aggr]=
        SUM(Aggregated Basal Area Classes[Class Aggr,SpeciesGroup!])
        ~ m*m
        ~           ~           :SUPPLEMENTARY
                    |
# Total stand basal area:
```

```
Total Basal Area=
        SUM(Basal Areas[Class!,SpeciesGroup!])
        ~ m*m
        ~           |
```

 # Total basal area of larger trees than the subject tree:

```
Cumulative Basal Areas[Class]=
        SUM(Help Factor[Class, Class Copy!] * Basal Areas[Class Copy!,SpeciesGroup!])
        ~ m*m
        ~           |
Help Factor[Class, Class Copy]=
        GET XLS CONSTANTS('Help_Factor_Matrix.xls', 'Tabelle1', 'A1')
        ~ Dmnl
        ~           |
Class Copy <-> Class
        ~
        ~           |
```

 # Volume of each diameter classes:

```
Volumes[Class,SpeciesGroup]=
        ((vpar1+vpar2*Diameters[Class]^2*Heights[Class,SpeciesGroup])*Diameter
        Class[Class,SpeciesGroup])/10000
        ~ m*m*m
        ~           |
```

 # Total volume of the stand:

```
Total Volume=
        SUM(Volumes[Class!,SpeciesGroup!])
        ~ m*m*m
        ~           ~           :SUPPLEMENTARY
                    |
```

 # Total volume of each species group:

```
Total Volume by Species Group[SpeciesGroup]=
        SUM(Volumes[Class!,SpeciesGroup])
        ~ m*m*m
        ~           ~           :SUPPLEMENTARY
        |
```

 # Calculate the dynamics of tree number in each diameter class:

```
Diameter Class[Class,SpeciesGroup]=
        INTEG(Ingrowth[Class,SpeciesGroup]-Harvesting[Class,SpeciesGroup]-
        Mortality[Class,SpeciesGroup]-Outgrowth[Class,SpeciesGroup],
        Initial Diameter Class[SpeciesGroup,Class])
        ~ Trees
        ~           |
```

 # The values of the initial diameter class:

```
Initial Diameter Class[SpeciesGroup,Class]=
        GET XLS CONSTANTS('Initial DClasses.xls', 'Tabelle2', 'B41')
        ~ Trees
        ~           |
```

 # The number of recruits for each species group:

Ingrowth[c6,SpeciesGroup]=
MAX((4.2+Total Basal Area*Param A+Stem Number by Species Group[SpeciesGroup]*Param B -0.807*SQ1-1.731*SQ2)*Unit Converter 3,0)
~ Trees/Year
~ |

 # Diameter increment for three species groups:

Potential Diameter Increment[Class,s1]=
(0.173*(Diameters[Class]/Unit Converter 1)^0.559-0.0215*Diameters[Class]/Unit Converter 1-0.00195*Total Basal Area/Unit Converter 2-0.053*SQ1-0.085*SQ2)*Unit Converter 4
~
~ |
Potential Diameter Increment[Class,s2]=
(0.176*(Diameters[Class]/Unit Converter 1)^0.473-0.0144*Diameters[Class]/Unit Converter 1 -0.00153*Total Basal Area /Unit Converter 2-0.04*SQ1-0.085*SQ2)*Unit Converter 4
~
~ |
Potential Diameter Increment[Class,s3]=
(0.218*(Diameters[Class]/Unit Converter 1)^0.525-0.0296*Diameters[Class]/Unit Converter 1-0.0025*Total Basal Area/Unit Converter 2+0.009*SQ1-0.04*SQ2)*Unit Converter 4
~ cm/Year
~ |

 # The growth rate for each diameter class and each species group:

Growth Rate[Class,SpeciesGroup]=
Diameter Increment[Class,SpeciesGroup]/Diameter Class Width
~ 1/Year
~ |
Diameter Class Width=
1
~ cm
~ |
Diameter Increment[Class,SpeciesGroup]=
IF THEN ELSE (Potential Diameter Increment[Class,SpeciesGroup] >0.01, Potential Diameter Increment[Class,SpeciesGroup], 0.01)
~ cm/Year
~ |

 # Number of trees in each diameter class upgrowth to the next higher class:

Outgrowth[Class but Highest,SpeciesGroup]=
Growth Rate[Class but Highest,SpeciesGroup]*Diameter Class[Class but Highest,SpeciesGroup]
~
~ |
Outgrowth[c81,SpeciesGroup]=
0
~ Trees/Year
~ |
Ingrowth[Class but Lowest,SpeciesGroup]=
Outgrowth[Class Previous,SpeciesGroup]
~
~ |

 # The probability of a dead tree for each species group:

```
Potential Mortality Rate[Class,s1]=
        (1+exp(-(-4.053-0.158*Diameters[Class]/UnitConverter1+0.0011*
        Diameters[Class]/UnitConverter 1)^2 +0.105*Total Basal Area/Unit Converter 2)))^-1
~
~               |
Potential Mortality Rate[Class,s2]=
        (1+exp(-(-7.781+15.584*1/(Diameters[Class]/Unit Converter 1)+0.139*Cumulative Basal
        Areas[Class]/Unit Converter 2)))^-1
~
~               |
Potential Mortality Rate[Class,s3]=
        (1+exp(-(-7.177+0.19*1/(Diameters[Class]/Unit Converter 1)+0.149*Cumulative Basal
        Areas[Class]/Unit Converter 2)))^-1
        ~ Dmnl
        ~       |
```

 # Number of dead trees for each diameter class and each species group:

```
Mortality[Class,SpeciesGroup]=
        Diameter Class[Class,SpeciesGroup]*Mortality Rate[Class,SpeciesGroup]
        ~ Trees/Year
        ~       |
Mortality Rate[Class but Highest,SpeciesGroup]=
        Potential Mortality Rate[Class but Highest,SpeciesGroup]*Mortality Help Factor
        ~
        ~       |
Mortality Help Factor=
        IF THEN ELSE (Total Basal Area >25, 1.2, 1)
        ~ 1/Year
        ~       |
```

 # Number of trees harvested in each diameter class and species group:

```
Harvesting[Class,SpeciesGroup]=
        MAX((DiameterClass[Class,SpeciesGroup]-Equilibrium[SpeciesGroup,Class])*
        Harvesting Control, 0)
        ~ Trees/Year
        ~       |
Harvesting Control=
        IF THEN ELSE(MODULO(Time, Harvesting Cycle)=0, 1, 0)
        ~ Dmnl
        ~       |
```

 # The values of desired diameter distribution:

```
Equilibrium[SpeciesGroup,Class]=
        GET XLS CONSTANTS('Initial DClasses.xls', 'Tabelle2', 'B41')
        ~ Trees
        ~       |
```

 # Harvesting volume in each diameter class and species group:

```
Harvesting Volumes[Class,SpeciesGroup]=
        ((vpar1+vpar2*Diameters[Class]^2*Heights[Class,SpeciesGroup])*Harvesting[Class,
        SpeciesGroup])/10000
        ~ m*m*m/Year
        ~       |
```

```
# Total harvesting volume for each species group:

Total Harvesting Volume by Species Group[SpeciesGroup]=
        SUM(Harvesting Volumes[Class!,SpeciesGroup])
        ~ m*m*m/Year
        ~        ~        :SUPPLEMENTARY
                 |
# Total harvesting volume for each harvest:

Total Harvesting Volume =
        SUM(Harvesting Volumes[Class!,SpeciesGroup!])
        ~ m*m*m/Year
        ~        |
# Total harvesting volume for all harvests:

Cumulative Harvesting Volume =
        INTEG (Total Harvesting Volume,0)
        ~ m*m*m
        ~        ~        :SUPPLEMENTARY
                 |
# Calculate tree height according to species group and site quality:

Heights[Class,SpeciesGroup]=
        (1.3+(1/(a[SpeciesGroup]+b[SpeciesGroup]/Diameters[Class]))^3)*Unit Converter 6
        ~ m
        ~        |
SiteQuality:
        good, medium,bad
        ~
        ~        |
# Define parameters of height fuctions:

a[SpeciesGroup]=
        IF THEN ELSE(SQ = 1, a1[SpeciesGroup,good], IF THEN ELSE(SQ = 2,
        a1[SpeciesGroup,medium], a1[SpeciesGroup,bad]))
        ~ Dmnl
        ~        |
b[SpeciesGroup]=
        IF THEN ELSE(SQ = 1, b1[SpeciesGroup,good], IF THEN ELSE(SQ = 2,
        b1[SpeciesGroup,medium], b1[SpeciesGroup,bad]))
        ~ cm
        ~        |
a1[SpeciesGroup,SiteQuality]=
        0.326589,0.344089,0.36168;    0.35438,0.365336,0.3831;    0.4099,0.4025,0.3959;
        ~ Dmnl
        ~        |
b1[SpeciesGroup,SiteQuality]=
        1.9281,1.7069,1.8762;    1.7413,1.8291,1.6328;     1.1985,1.4807,1.8935;
        ~ cm
        ~        |
# Asign site quality of the stand:

SQ=
        1, 2 or 3
```

```
        ~ Dmnl
        ~           |
# Dummy variables of site quality:

SQ1=
        IF THEN ELSE( SQ = 1 :OR: SQ = 3 , 0 , 1)
        ~ Dmnl
        ~           |
SQ2=
        IF THEN ELSE( SQ = 1 :OR: SQ = 2 , 0 , 1)
        ~ Dmnl
        ~           |
# The values of parameters of the functions and formulas of unit conversion:

Param A= -0.126
        ~ 1/(m*m)
        ~           |
Param B=
        0.017
        ~ 1/Trees
        ~           |
vpar1=
        -0.08069
        ~ m*m*m/Trees
        ~           |
vpar2=
        0.31144
        ~ m*m/(cm*cm*Trees)
        ~           |
Unit Converter 1=
        1
        ~ cm
        ~           |
Unit Converter 2=
        1
        ~ m*m
        ~           |
Unit Converter 3=
        1
        ~ Trees/Year
        ~           |
Unit Converter 4=
        1
        ~ cm/Year
        ~           |
Unit Converter 6=
        1
        ~ m
        ~           |
Conversion Factor=
        0.0001
        ~ m*m/(cm*cm)/Trees
        ~           |
# Simulation Control Parameters
```

```
INITIAL TIME  = 0
        ~ Year
        ~ The initial time for the simulation.
                |
FINAL TIME  = ….
        ~ Year
        ~ The final time for the simulation.
                |
TIME STEP  = 1
        ~ Year
        ~ The time step for the simulation.
                |
```