MODELLING THE RUBBER TREE SYSTEM

By

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ABSTRACT

An effort is made to develop a model that aims to predict the growth and production of rubber under different environmental conditions as well as different agroforestry options. The work begins with the development of the simple static model, namely *Hevea Version 1.0*, which acts as a *precursor* for development of a dynamic model.

The dynamic model, which was developed using STELLA Research Software Environment and Microsoft EXCEL is then linked to the current agroforestry model WaNuLCAS (Water, Nutrients, and Light Capture in Agroforestry Systems). STELLA is the software for building system models while Microsoft EXCEL provides data analysis, list keeping, calculations as well as presentation tools. Two sub-models were added, namely a Tapping sub-model and a Tapping Panel sub-model, as a part of process to improve the efficiency of the overall model predictions. The model was run for 20 years, representing the economics life of rubber, and the outputs of the simulation were compared with observed data for validation purposes. Results from the statistical analysis showed that the model was able to simulate the girth, latex production, above-ground biomass, leaf and twigs and wood

production with efficiencies (EF) of 0.83, 0.97, 0.70, -0.15 and -4.90 respectively. EF measures the accuracy of the model in performing simulation as compared to experimental data. An optimum value of EF is 1. The negative value for leaf and twigs and wood production indicated that the observed mean value is better than predicted value.

An economic analysis, based on the output of the dynamic model for different rubber agroforestry system options, showed that the option of planting maize as an intercrop with rubber before tapping, followed by selling rubber wood at the end of a 20-year of rotation gave the highest Net Present Value, Internal Rate of Return, Benefit-Cost Ratio and Annual Equivalent Value compared with the option of planting rubber as monocrop.

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

In Malaysia, about 1.4 million hectares of a total 25 million hectares of arable land (5.6%) are planted with rubber, yielding about 650,000 tonnes of rubber annually. The rubber planting industry is divided into two sectors: the smallholder sector and the estate sector (MRRDB, 1992). The smallholder sector usually consists of land units of less than three hectares, and can be classified into two main groups: independent smallholdings (consisting of individuals and sub-divided holdings) and organised holdings. Individual holdings are units owned by individuals or families, while sub-divided holdings are plots of rubber land that have resulted from the fragmentation of estates. Organised smallholdings are those in land schemes developed by the Federal Land Development Authority (FELDA), the Federal Land Consolidation and Rehabilitation Authority (FELCRA) and various state governments and statutory authorities, notably the Rubber Industry Smallholders' Development Authority (RISDA).

Currently, the smallholder sector plays a major role in the growth and development of the Malaysian rubber industry, comprising 87% of the total rubber area and accounting for 78% of the total natural rubber (NR) production.

The estate sector is made up of larger production units ranging from 40 – 1,000 ha of land. These estates are more efficiently operated than smallholdings, being managed on commercial lines.

Estates manage their own replanting and are more readily disposed to accepting new technologies and new technical improvements. This sector covers 22% of Malaysian natural rubber production.

However, in spite of the significant contribution made by the smallholder sector to the growth of the industry, most smallholder operations are characterised by low productivity and low income. This is mainly due to uneconomic-sized holdings, capital deficiency and low adoption of available technologies (Ibrahim, 2000). Unlike the estate sector, which enjoys the advantage of size and technical expertise, and a predisposition to quickly take up new ideas, smallholders operating on their own are generally lacking in capital, knowledge and basic amenities and have little choice in to whom they sell their rubber and at what price. Recognising that the development of the smallholder sector is the key to the continued viability of the industry, the government has set up a number of agencies with clearly defined roles to help the smallholders. These include FELDA, FELCRA, RISDA and the Malaysian Rubber Development Corporation Berhad (MARDEC).

FELDA is the principle agent for large-scale land settlement schemes involving smallholders and has planted more than 180,000 ha of high yielding rubber trees for smallholders. FELDA buy raw material from smallholders and also provides the facilities for capital-intensive processing technology, producing premium grades of technically specified rubber, such as Standard Malaysian Rubber (SMR) and latex concentrate.

FELCRA is responsible for the rehabilitation of state land schemes and for redeveloping alienated but otherwise idle lands. Over 130,000 ha have been developed under the FELCRA development programme, of which more than 30% is under rubber plantations primarily for smallholders.

RISDA provides replanting grants to enable smallholders to replant their holdings with new and high-quality rubber clones.

Apart from replanting, RISDA's other main task is to provide extension support for smallholders in modern techniques of rubber cultivation (MRRDB, 1987). MARDEC is primarily involved in the processing and marketing of rubber from smallholders. Its main objective is to improve the quality of their rubber through central processing and marketing facilities.

Under the various smallholder development schemes, different types of development project have been implemented to suit the specific conditions in different areas and the smallholder operations concerned. Where conditions permit, land consolidation has taken place and rubber is planted on a commercial basis.

However, in areas where smallholders are reluctant to give up their land and choose to remain on their rubber holdings, the Malaysian Rubber Board offers support for alternative farming practices, such as integrated farming systems or intercropping, to achieve optimal returns from the farm.

The potential productivity of the rubber tree system depends on the outcome of competition between related components (i.e. biological, socioeconomics etc) within the system.

Due to the potentially very time-consuming and costly nature of collecting data on the entire range of practices and parameters involved, it is therefore proposed that modelling approaches can be used to organise the available information and to overcome some of these limitations.

1.2 Aims and objectives

The overall aim of this work is to develop a model to estimate growth and rubber production in rubber tree systems, considering different planting densities, planting patterns, tapping systems and management across a range of environmental conditions. While the principal objective is to develop a dynamic model, the development of a static model is first described in Chapters 3 to 5 as a *precursor* to the development of dynamic modelling work.

1.3 Hypotheses

Depending on the smallholder's choice, rubber is planted under different planting densities as well as alternative planting patterns and as a result, the growth (girth) rate and rubber production of rubber trees varies due to competition for resources (such as nutrients, water, light etc) and environmental factors (i.e. soil series, topography) as well as the use of different management practices (i.e. intercropping, establishment of cover crops etc).

To test the efficiency of the model, a set of hypotheses is developed which then can be checked against the predictions of the model for validation. The hypotheses are:

- the growth of rubber as indicated by girth increment rate will progressively decline with increasing density (number of trees per hectare)
- the higher the planting density, the greater the delay in reaching tappable size (>45cm), therefore prolonging the immaturity period of rubber for two years or more
- lower planting densities are expected to give better growth and higher yields per tree
- under conventional tapping systems, the yield of rubber correlates positively with the girth.

Given the above aims and hypotheses, the general objectives of this work are:

1. to estimate the growth and production of rubber under different planting densities using a simple model
2. to simulate the effect of different soil type and climatic conditions on the immaturity period of rubber
3. to simulate the effects of soil and climate on growth and rubber production of rubber
4. to simulate the effect of management on growth and rubber production
5. to estimate the production of rubber wood under different planting densities
6. to develop a tapping panel and rubber production sub-model using dynamic modelling approaches
7. to carry out economic analyses for different rubber agroforestry options.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Natural rubber (*Hevea brasiliensis*) was discovered by travellers to Central and South America from Spain (Columbus) in the 15th Century and from France (la Condamine, Fresneau) in the 18th Century. The commercial exploitation of rubber trees started in the 19th century, based on trees of various species found in the Amazonian Rain Forest (MRRDB, 1987). The genus *Hevea* is a member of the Euphorbiaceae comprising 10 species of which Para rubber or *Hevea brasiliensis* is the only genus planted commercially. *Hevea brasiliensis* (Plate 2.1) was brought to Malaysia more than a century ago. As a native of tropical rainforest, rubber trees can be grown in other tropical regions such as Asia (i.e. Thailand, Indonesia, India, China, Sri Lanka etc.) and Africa (i.e. Nigeria, Ivory Coast, Cameroon). It is one of the most closely studied and carefully tended plants (MRRDB, 1987).

Plate 2.1: Rubber trees (*Hevea brasiliensis*)

(Source: MRRDB, 1987)

The world's increasing appetite for natural rubber has led to the development of new clones capable of higher rubber production. This is achieved using hand pollination, leading to the production of seeds in three-chambered pods that explode to scatter the seeds (MRRDB, 1987). The collected seeds are germinated in nurseries and the seedlings are grown in polybags for about three months, after which the buds of the selected clones are grafted on to the stem of stock plants (Plate 2.2).

Plate 2.2: Budding with selected clones (green budding -insertion method)

(Source: MRRDB, 1987)

The buds then sprout to form a new tree, which has the characteristics of the plant donating the bud. The same process is used to produce millions of plants, which are grown in the nursery until they develop two whorls of leaves, after which they are transplanted in the field where they are carefully tended and kept free of weeds by regular tilling (MRRDB, 1987).

Rubber trees are quick growing, erect with a straight trunk, which is usually grey and smooth but varies in both colour and surface texture (MRRDB, 1987).

Hevea brasilensis is the tallest species of the genus: in the wild, the trees may grow up to over 40 meters and live for over 100 years (Webster and Paardekooper, 1989) but in plantations they rarely exceed 25 m because the growth is reduced by tapping. Tapping begins (Plate 2.3) when the tree reaches maturity (>45 cm in girth) at about four to five years and usually will be replanted after 20 years as yields fall to uneconomic levels.

Plate 2.3: Tapping in progress

(Source: MRRDB, 1987)

2.2 The Rubber Industry in Malaysia

As one of the world's major natural rubber (NR) producers, Malaysia contributes about 15% of the total world demand, despite a decreasing trend in the plantation area (Figure 2.1) due to the conversion of land from rubber to oil palm plantations, housing and industrial projects.

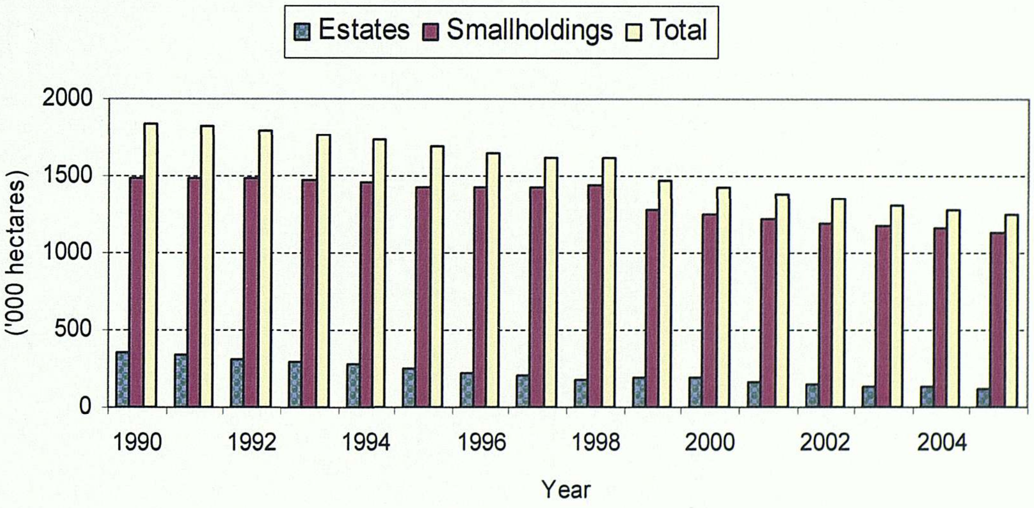


Figure 2.1: Rubber planting area in Malaysia from 1990 -2005 (Source: MRB, 2004; 2005)

Apart from being a major natural rubber producer, Malaysia is also a major exporter of rubber products. Malaysia earns (Ringgit Malaysia) RM6 billion (1US$=RM3.77) from the wide range of rubber products exported yearly (MRB 2004; 2005).

Malaysia leads the world in the production of dipped goods (e.g. latex gloves, catheters etc) industry both in volume and in quality. There are over 300 companies making a wide range of rubber products, which are exported to over 60 countries around the world. Malaysia also is the world largest supplier of medical gloves, catheters and latex threads (MRB, 2004; 2005).

With the inherent high quality of Malaysian rubber as well as strong research and development support in design, development and manufacturing, Malaysia rubber products have found wide acceptance internationally (MRB, 2004; 2005). The value of exported natural rubber (NR) and rubber products from 1994 – 2004 is shown in Figure 2.2.

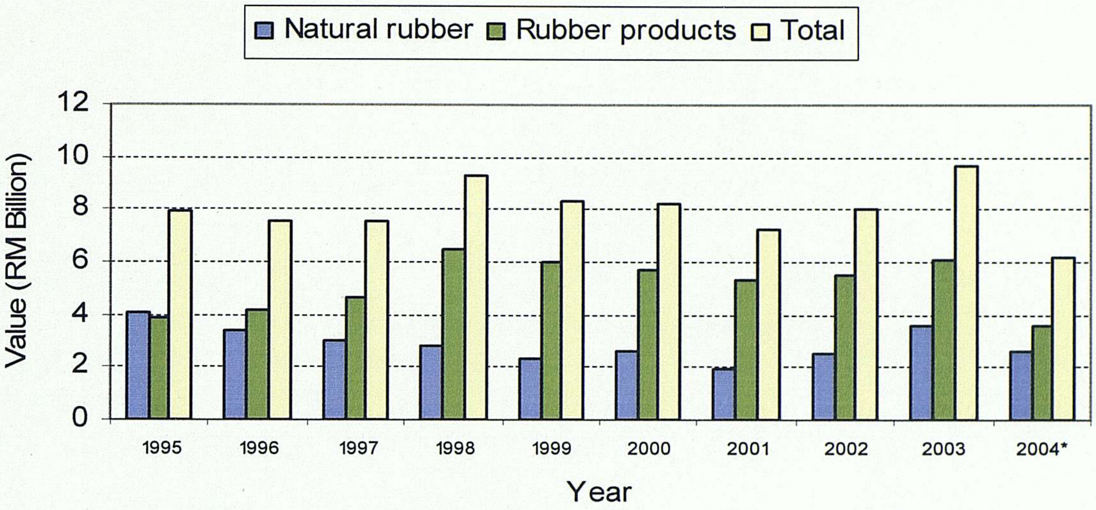


Figure 2.2 : Export of NR and Rubber Products,
1994 – 2004 (RM Million)
* data from Jan – Jun 2004 (Source: MRB, 2005)

2.3 Climatic Requirements

2.3.1 Rainfall

As an indigenous species of tropical rainforest, *Hevea* generally performs best in tropical lowland climates with an annual rainfall of 1500 - 2500 mm per year, evenly spread throughout the year and with not more than one dry month. Ideally, the number of rainy days should range from 100 – 150, because any increase on this can lead to interference with the tapping process because rainwater causes coagulation of latex on the tapping cut (Watson, 1989b).

In Malaysia, with around 2500 mm rainfall per annum and no severe dry period, conventional planting techniques give satisfactory establishment of rubber. However in northern Malaysia (Alor Setar, 6^0 N), which only receives about 1770 mm rainfall and with a four-month moisture deficit annually, budded stumps of RRIM600 and GT1 clones planted in July establish well but are very susceptible to drought during the subsequent dry period over December to March (Pushparajah, 1983).

Budded transplants grown to the two-whorl stage proved much better suited to drought periods than other types of planting stock. In areas further north, e.g. Cox Bazaar, Bangladesh (23^0 N) and Xuan Loc, Vietnam (12^0 N), the longer dry seasons demand increased resistance. In Thailand, experiments have shown that it is feasible to plant rubber beyond 18^0N in regions where the rainfall is 1200 – 1500 mm annually, falling over only 120 days of the year (Watson, 1989b).

In these areas, there is a marked dry season of six months, creating a severe moisture deficit and a temperature range between 14^0C to 38^0C. As a result, the growth of rubber in this area is slower and takes six months longer to reach tappable size compared with some southern areas (Watson, 1989b).

The return of regular rainfall at the end of the dry season has a beneficial effect on production. Both the total annual rainfall and rainfall distribution throughout the year are important limiting factors for production. Dry-season and rainy-season rainfall have different effects on production, determined according to the amount of soil water reserves (Watson, 1989b).

Jacob *et al.* (1989) also reported a positive correlation between the rainfall deficit measured at the beginning of dry season and accumulated rubber production loss during the same season (January to May in Cambodia) for four consecutive years (Figure 2.3).

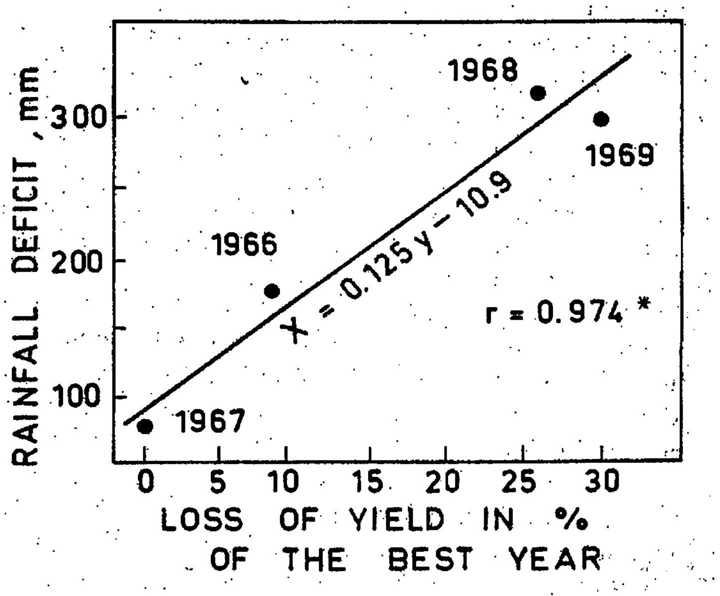


Figure 2.3: Relation between rainfall deficit and loss of yield in percentage (%)

(Source: Jacob *et al.,* 1989)

2.3.2 Moisture Conditions

The natural habitat of *Hevea brasiliensis* occurs mainly on sites subject to brief or slight inundation. Soil moisture is important particularly during the immature period (prior to tapping) of rubber cultivation.

A long dry period influences not only the survival of rubber seedlings but also prolongs the immaturity period. In Ivory Coast, where the dry period is 5 months, results showed that irrigated rubber were opened for tapping 5½ years after planting compared with 7 years in unirrigated stands (Watson , 1989b).

2.3.3 Temperature

In the Amazon basin, the natural habitat of *Hevea*, a uniform temperature of about 31° C is obtained at noon, falling to 23° C at night, with a mean annual temperature of 27 °C. In Kampuchea, Pratummintra (2000) reported that uniform temperatures, with an annual mean between 24 °C to 27 °C, are favourable for a good latex flow. In Peninsular Malaysia, rubber is cultivated in the lowlands, i.e. land below 152 m with a mean annual temperature of about 27 °C (Yew, 1982).

The rubber growing areas in China lie between 18^0 and 24^0 N and are affected by typhoons, colder temperatures and marginal rainfall from 1200 to 2500 mm per year.

Cold weather, originating from Siberia, results in damage, mainly occurring when the night temperature falls below 5 ^{0}C and rises sharply to 15 - 20 ^{0}C in a day.

In milder cases, the leaf margins shrivel, spots appear on the leaf lamina, shoots die back or split and there is latex exudation. In severe cases, whole leaves become discoloured and die off. However, different clones or individuals vary greatly in cold hardiness. For some clones, winter injury symptoms may be observed at 4 °C to 5 °C.

Watson (1989b) reported that the annual mean temperatures of some major rubber growing countries including Brazil, Malaysia and Thailand fall between 23 - 30 °C . Within this range, higher monthly temperatures result in increased yields. The relationship between monthly temperature (^{0}C) and rubber yield (gtt) is given in Figure 2.4. The variability in monthly temperature is also reported to have influence on production of rubber (Tupy, 1989).

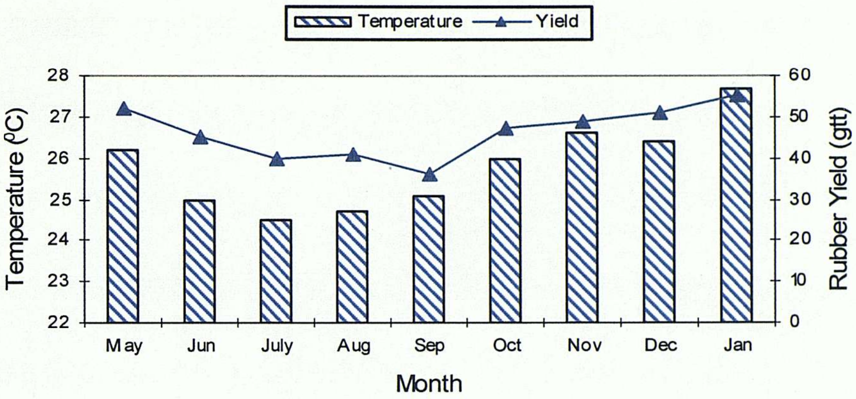


Figure 2.4: Relationship between mean monthly temperature (^{0}C) and rubber yield (gtt – gram tree^{-1} tapping^{-1}) of the GT1 rubber clone (Source: Tupy, 1989)

2.3.4 Sunshine

The influence of sunshine hours on rubber growth and productivity is mediated through its effect on photosynthesis and water availability. Under limited soil moisture availability, longer periods of sunshine duration will have a negative effect on photosynthesis and growth. Any conditions contributing to good supply of water to tissues or limiting loss of water by evapotranspiration (ET) is favourable for prolonged flow of latex.

Seasonal variations in the availability of water and sunlight affect the dry rubber content (DRC) levels (Vijayakumar *et al.*, 1989). The duration and intensity of sunshine has a significant influence on sucrose levels in the latex as well as rubber yield (Tupy, 1989). An increase in sunshine duration towards the end of the rainy season is often associated with an increase in rubber production. The relationship between monthly sunshine and rubber yield is shown in Figure 2.5.

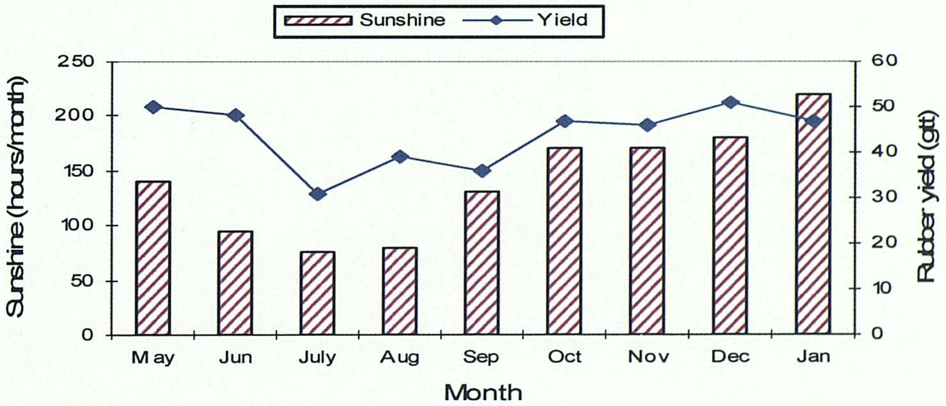


Figure 2.5: Relation between monthly sunshine (hours month^{-1}) and rubber yield (gtt) of the GT1 clone. Source: (Tupy, 1989)

2.4 Soils

Hevea is generally considered undemanding as regards soil type. However, its development and productivity depend on the quality of the root system development, followed by availability of water and nutrients. Relief (topography) plays an essential role in rubber cultivation because steep topography increases cost of installation (protection against erosion) and difficulties for harvesting. Wong (1977) reported that girth of rubber were higher on gentler slopes (i.e. 0-35% slope - 57.2 cm) compared with steep slopes (52%, slope - 54.0 cm).

This was because of the shallower soil profiles on steeper areas, together with excessive soil erosion, while shallower slopes are favourable for drainage. Soil depth is a decisive factor in the development of the taproot and the lateral root system. Compact layers, lateritic crusts or ground water levels at less than one meter below the surface limit rooting, resulting in poor growth, low latex production and even uprooting.

The physical structure and texture of the soil is important to ensure satisfactory root activity and good moisture retention capacity. Desirable soil physical properties for rubber are: soil depth up to 100 cm or more, well drained profiles, good soil structure (e.g. strong, moderately strong, medium, fine sub-angular blocky structure), good soil texture with proportionate amounts of sand, silt and clay (preferably a minimum amount of 35% clay to retain moisture and nutrients and about 30% of sand to allow for good aeration and drainage) (Zainol, 1978 : Jacob *et al.*, 1989).

Soil chemical properties also play as an essential key for growth and production of rubber. The desirable chemical properties are; absence of saline/acid sulphate conditions, moderate levels of nitrogen (>0.11 % total N), phosphorus (>250 ppm P), potassium (>0.5 me %) and magnesium (>0.76 me%) (Pushparajah, 1983), no trace element deficiencies and a pH of around 4.5- 5.5.

2.5 Rationale of the modelling approach

Research is commonly conducted in order to understand farming systems, to solve particular problems and hence to provide a particular solution under experimental conditions. The results gained from one experiment may not be applicable to a similar situation under different conditions. Research data is becoming more precise but is limited, being expensive and time-consuming to obtain. A modelling approach can overcome some or all of those limitations and can provide new insights into crop processes for future research (Matthews and Stephens, 1998). Models are particularly useful in extending the results of one or two years of field data to a wider range of years, in situations where a full scale, long-term experiments would be prohibitively expensive.

Simulation models are continually being improved to make more complete use of available data, with appropriate complexity to predict or produce an outcome or useable solutions of interactions.

Mathematical equations that quantitatively describe the system under study through the use of computer programs provide approximate solutions to the original problems (Matthews, 2002).

Simulation can be used to describe all entities, attributes and activities, as they exist at one point in time, and to establish meaningful relationships between given variables and the system under considerations (Matthews, 2002). Simulation approaches allow yield predictions to be made and hence to quantify plant production and likely year-to-year variation. They also provide a way of organising knowledge for a better understanding of, and deeper insight into complex interactions, and can identify those processes which are important in determination of productivity.

Parameters of important variables can be used to predict responses to agronomic manipulations (e.g. changes in plant density, planting distance, tapping systems, type of crops etc). In this respect, the advantage of modelling is to be able to simulate the behaviour of a complex system and generalise the response to a change in agronomic practices, hence allowing evaluation of different situations (Matthews, 2002).

Thus, the researcher must comprehensively understand the whole system in terms of its components and how these components relate to each other in a functional way.

2.6 Role of models

Models are usually designed to serve particular purposes. There is no perfect model, which can be used for all purposes in any crop, but the results of models from different disciplines and locations offer a way of improving the efficiency and/or reducing the cost of some research.

The trend in modelling has been a progression from simple models to very complex ones, followed by a return to simple approaches. This is because simpler models are more easily understood and have proved to be adequate for many purposes. The ultimate simulation model should be simple yet comprehensive enough to predict the growth of different varieties under any agro-climatic conditions. The use of models in research programs (Matthews, 2002) has the potential to increase efficiency by emphasizing process-based research, rather than the study of site-specific effects.

2.6.1 Models as research tools

Matthews (2002) stated that crop simulation models were originally developed as research tools. Boote *et al.* (1996) see models as providing a structure to a research programme while being particularly valuable for synthesizing research understanding. The modelling process must become a truly integrated part of the research activities if the efficiency of research is to be increased (Boote *et al.*,1996). Experimentation and model development need to proceed jointly as new knowledge to refine and improve models. The following are some of the uses of models in research:-

- identification of gaps in our knowledge
- generation and testing hypotheses, and as aids in experimental design
- determining the most influential parameters operating within a system
- providing a medium for better communication between various researcher disciplines
- solving common problems between researchers, experimenters and producers.

Shorter *et al.* (1991) stress the need for an integrated, multidisciplinary approach between plant breeders, crop physiologists and crop modellers.

The emergence of simulation models for a large number of crops provides tools that may be useful in helping to increase the efficiency of the crop improvement process. Crop-soil models offer a cheaper and quicker complementary approach (Shorter *et al.,* 1991) and can easily evaluate a number of alternatives strategies in term of their sustainability. Models are able to indicate future trends and prescribe appropriate action to minimize harmful effect such as the use of suitable crops, adapted varieties, changes in management and cultural practices (Shorter *et al.,* 1991).

2.6.2 Models as decision support tools

After a system model has passed field-testing and validation and both modellers and field scientist are satisfied with the results, it should be advanced to the second stage of application. The field-tested model can be used as a decision aid or decision support system (DSS) to develop best management practices, including site-specific management or 'precision agriculture'. It can also be used as a tool for in-depth analysis of problems in management, environmental quality and global climate change (Ahuja *et al.*, 2002). Some examples of DSSs are the IBSNAT(International Benchmark Site Network for Agrotechnology Transfer) and APSIM (Agricultural Production Systems Simulator).

The IBSNAT was created with the aim of both accelerating the transfer of agrotechnology to increase food security and minimizing environmental degradation. IBSNAT has been used at local level in Albania, South Africa, Thailand and Hawaii (Tsuji *et al.*, 2002). The output from the system has allowed scientists, educators, extension specialists and decision makers to analyse technology options and enable them to match the biological requirements of the crops to land characteristics.

APSIM was developed to simulate biophysical process in farming systems, in particular where there is interest in the economic and ecological outcomes of management practice in the face of climatic risk (Keating *et al.,* 2003). APSIM can be used to simulate soil water balance, soil organic matter, surface residues and nitrogen transformation dynamics for maize, sorghum and legume pastures.

There are no DSSs that cover all crop types, organic amendments and inorganic fertilisers (Stephens and Middleton, 2002). A fully comprehensive model needs to be capable of making recommendations for the application of organic and inorganic fertilisers to a wide range of crops and agricultural systems. Models can help in the formulation of long-term strategies or policies at both farm, regional or national level by simulating and taking into account complex factors over long periods. Stoorvogel (1995) considered that the integration of different models and tools is an effective way to analyse different land use scenarios.

He suggested that researchers (e.g. agronomists, economists) could compensate for the limitations in one model, making this an ideal methodology for multidisciplinary research and integration of socio- economic and agroecological data.

The use of computer and computer simulation in education are increasingly important and a common practice in developing countries. Young and Heath (1991) observed that simulation models are the most widely accepted approach to computer assisted learning (CAL) focusing on problem-based learning.

2.6.3 Some current agroforestry models

Some models are currently available for modelling different aspects of agroforesty systems. These are respectively Soil Changes Under Agroforestry (SCUAF), CENTURY and Water, Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS).

2.6.3.1 Soil Changes Under Agroforestry (**SCUAF**)

SCUAF is able to predict changes under specified agroforestry systems within a given environment. SCUAF is a simple model, easy to understand and user-friendly. It is a deterministic model, designed to predict the effects of interactions between agroforestry systems and soil (Young *et al.*, 1998). The model predicts changes in soil fertility, crop yield and tree biomass over time by simulating the breakdown rate of plant material and soil nutrient uptake by plants. SCUAF operates on an annual cycle and is able to simulate N and P cycles while soil organic C is simulated in two soil humus fractions (stable and labile fractions), but soil water is not modelled in this case.

SCUAF can be used to compare agroforestry systems comprising different components of agriculture or forestry and can therefore be construed to mean 'Soil Changes Under Agriculture, Agroforestry and Forestry". While it does not directly include an economic component, it can be used to provide input and output values for economic analysis (Young *et al*., 1998).

SCUAF was actually designed as a tool in planning agroforestry experiments but it has been used in research and education and simulates soil-plant processes using process-response relationships.

SCUAF has been used to assess the potential of *Gliricidia* fallow systems as an alternative to traditional shifting cultivation systems in South East Asia (Macandog, 2002). It has also been used to compare the feasibility of planting *Gmelina* with alternative open field farming systems in Claveria, Northern Mindanao, Philippines (Macandog, 2002).

Results of the cost-benefit analysis revealed that the higher economic benefits gained from the *Gmelina*-improved fallow system included revenues from maize yield, fuelwood from *Gmelina* prunings, *Gmelina* timber yield and animal-related benefits such as draught power and live weight gain. After two 7-year timber cycles, the cumulative net present value of the *Gmelina* hedgerow system was double that of the maize open field farming system.

2.6.3.2 CENTURY

CENTURY is a model used to simulate changes in soils, primarily organic matter (Parton *et al*., 1992). The model is based on the functional pools of soil organic matter and divides soil C into ‘active’, ‘passive’ and ‘slow’ pools. It also simulates the long-term dynamics of carbon (C), nitrogen (N), phosphorus (P), and sulphur (S) for different plant-soil systems, including grasslands, agricultural crops, forest and savanna. CENTURY runs with a monthly time step, using major input variables such as monthly average maximum and minimum air temperature, monthly precipitation, lignin content of plant material, plant N, P, and S content, soil texture, atmospheric and soil N inputs, and initial soil C, N, P, and S amounts.

CENTURY is a complex model that needs a large amount of input data for simulation purposes. There are different sub-models for CENTURY, namely the Grassland and Forest sub-models (Parton *et al*., 1992). The grassland/crop and forest systems have different plant production sub-models which are linked to a common soil organic matter sub-model.

The soil organic matter sub-model simulates the flow of C, N, P, and S through plant litter and the different inorganic and organic pools in the soil.

CENTURY has been used to simulate the steady state of soil organic matter levels in grassland location in Great Plains in the U.S.A. (Parton *et al.*, 1987).

2.6.3.3 Water, Nutrient and Light Capture in Agroforestry Systems **(WaNuLCAS)**

WaNuLCAS is a complex model that emphasizes the common principles underlying a wide range of tree-crop agroforestry systems. The model can be used for agroforestry systems ranging from hedgerow intercropping, taungya and other mixed cropping systems (van Noordwijk and Lusiana, 1999). A key feature of the model is the description of uptake of water and nutrients (i.e. N, P) on the basis of root length densities of the tree and crop, plant demand factors and effective nutrient supply at a given soil water content. Light capture is treated on the basis of the leaf area index of both crop and tree components and their relative height in each zone. The model represents a four- layer vertical profile, with four horizontal zones, a water and N balance and uptake requirements by crops and trees.

WaNuLCAS can be used both for simultaneous and sequential agroforestry systems and can assist the user to understand the variety of options ranging from improved fallow, rotational and simultaneous forms of hedgerow intercropping.

It also includes management options such as tree spacing, pruning regimes and choices of species planted. The model also allows for various tree characteristics such as dynamic root distribution over the four layers as well as zone, canopy shape above the horizontal zone, litter quality, maximum growth rate and speed of recovery after pruning. As none of the above models is developed purposely to simulate the rubber tree system, therefore the following work describes the development of a simple static model (Chapter 3) as a *precursor* to dynamic modelling work (Chapter 6) which will be explained later.

CHAPTER 3

STATIC MODELLING APPROACHES

3.1 Introduction

A test of the success of introducing certain technologies to rubber growers is whether these technologies can easily be implemented and adopted by smallholders. As rubber is one of the most important agricultural industries in Malaysia and provides the livelihood of a large segment of the Malaysian population, efforts need to be made to ensure that all available technologies are well disseminated to smallholders through all channels of extension work. Modelling is considered as one of the tools that can be used in education and training (Matthews, 2002) as well as in extension activities. This chapter therefore attempts to explain how the development of a simple static model, outlining the relevant equations and parameters, may be used in this capacity.

Modelling for the simple static model was carried out using SPSS Inc. SigmaPlot for Windows (2001) and Microsoft EXCEL computer software.

As mentioned before, this modelling work is a *precursor* to the development of the dynamic modelling work that will be described in Chapter 6. The work below describes assumptions, the static model outline, derivation of parameters, model description and its limitations. Derivations of equations and parameters were based on the results from the relevant literature on rubber production, as described further down. All results and equations were then compiled as a static model, developed using Microsoft EXCEL program as *Hevea Version 1.0*.

3.2 The outline of the static model

The static model is divided into two sub-models, namely the Growth (*GR*) and Rubber Production (*RP*) sub-models. A schematic diagram of the model is shown in Figure 3.1 and the interface is illustrated in Figure 3.2.

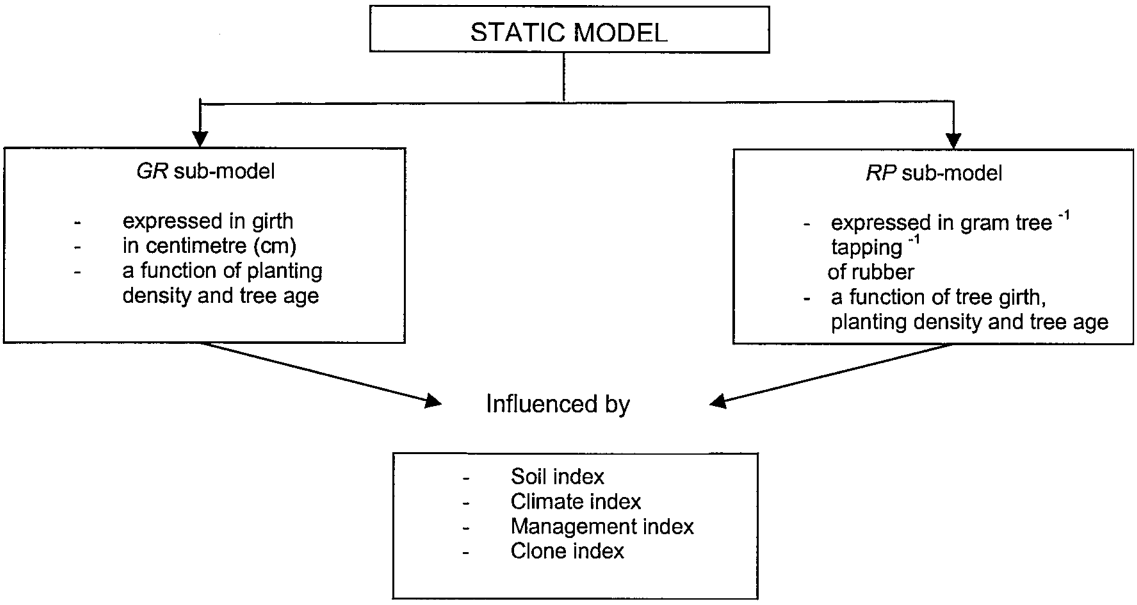


Figure 3.1: Schematic diagram of the static model

The following set of assumptions is made before running this static model:

- the planting stocks (2-whorl budded stocks) are uniform for all experimental sites;
- optimal management practices (i.e. fertiliser, weed control, pest control etc.) are applied at all experimental sites;
- optimal growth conditions (refer unit 2.3 in Chapter 2) occur at all experimental sites (i.e. rainfall, temperature, sunshine etc.);
- tapping starts at similar times (i.e. 0700hrs) and is carried out on good quality tapping panels.

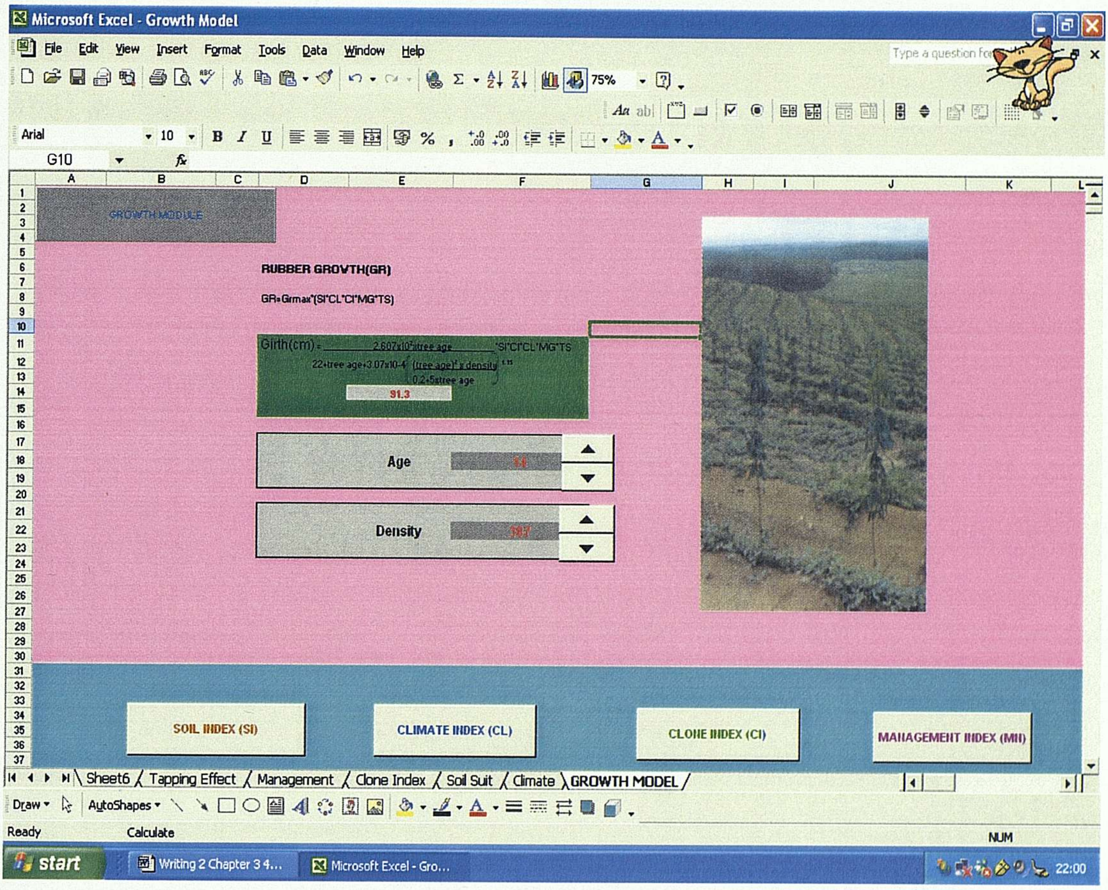


Figure 3.2: The interface of the Rubber Growth (*GR*) sub-model

3.3 Description of Rubber Growth (*GR*) sub-model

Hevea has sometimes been described as a plant able to grow on most soils in the tropics, but its maximum performance and economic viability is restricted due to other factors such as soil, climate, management practices, etc. As all these factors have a great influence on the rubber tree, this study attempts to create a static model that can be used to simulate the effect of different factors (i.e. soil, climate etc) on growth and rubber production.

In this model, the growth of rubber is influenced by different factors, expressed as a Soil Index (*SI*), Climate Index (*CL*), Management Index (*MGg*) and Clone Index for growth (*CIg*), such that the actual growth (GR_{actual}, or girth) is expressed as:

$$GR_{actual} = GR_{max} (SI \times CL \times MGg \times CIg) \qquad 1$$

Girth is the main parameter used to determine the growth of rubber and is measured at 160 cm above ground. The maximum girth (GR_{max}) of rubber is a function of tree age and density (trees ha^{-1}) and can be expressed as;

$$GRmax = \frac{2.37 \times TAge \times \phi}{22 + TAge + 3.7 \times 10^{-4} \times \left[\frac{TAge^{2} \times D}{0.2 + 5 \times D}\right]^{1.35}} \qquad 1a$$

(Adapted from Purnamasari *et al.,* 2002)

Where

TAge = Tree age from time of planting (years)

D = Tree density (number of trees ha^{-1})

Φ = 120 (a constant representing clonal yield performance)

SI, CL, MGg and *CIg* are performance indices varying between 0 to 1.0, based on the Rubber Research Institute of Malaysia's

(RRIM) Planting Recommendations (RRIM, 1980; 1995; 1998) as well as the results of past experiments (Appendix 1).

GR_{max} refers to optimal conditions, represented in this model by 1.0 for each index (*SI, CL, MG, Clg*).

Iyer *et al*. (1985) have studied the effect of planting densities on tree girth for the PR261 rubber clone. PR261 is one of the class 1 clones recommended for large scale planting (RRIM,1980).

Other class 1 clones are GT1, RRIM600, PB217, PR255 and PR261. The results for observed and simulated rubber girth are shown in Figure 3.3.

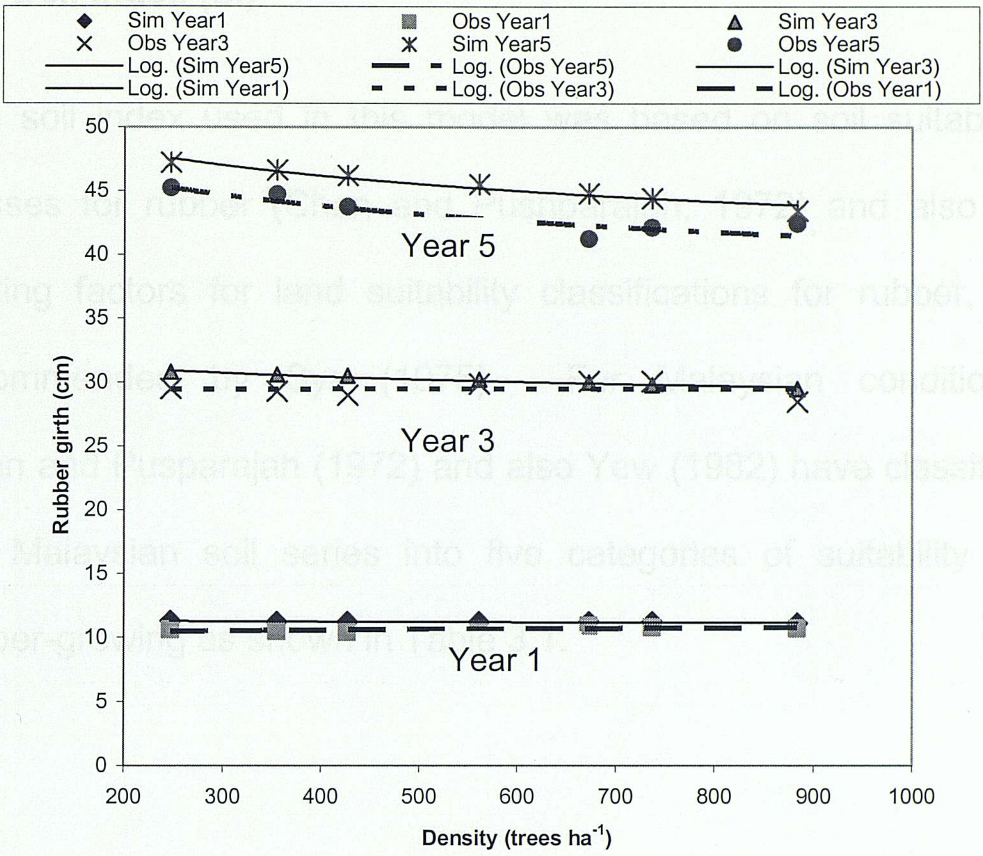


Figure 3.3: The observed and simulated effects of different planting densities on the girth of clone PR261 on class I soil (Iyer *et al.*, 1985)

The result shows that the higher the planting densities, the lower the girth of individual trees. Also, as the plantation ages, tree girth increment tends to decrease due to competition for resources such as light, water, space and nutrients.

3.4 Soil Index (*SI*)

The soil index used in this model was based on soil suitability classes for rubber (Chan and Pushparajah, 1972) and also on limiting factors for land suitability classifications for rubber, as recommended by Sys (1975). For Malaysian conditions, Chan and Pusparajah (1972) and also Yew (1982) have classified the Malaysian soil series into five categories of suitability for rubber-growing as shown in Table 3.1.

Table 3.1: Suitability classification of some common Malaysian soil series for rubber production

Soil Class/(index value)	**Properties/ Physical limitations**	**Comment**	**Some Malaysian Soil Series in this class**
Class I (1.0)	**No limitation** Depth - > 200 cm Texture - Sandy clay, Clay loam, Silty Clay loam Gravel and stones (%) - <15% ; pH - 5 - 6 Drainage - well drained ; Altitude - < 200 m Nutrient status – high to medium ; Slope - < 3%	Soils that have no limitation for rubber cultivation	Munchong, Jeram Prang, Segamat Kuantan, Rengam Jerangau, Yong Peng Bungor
Class II (0.9)	**Minor limitation** Depth - 150 - 200 cm Texture - Fine sandy clay loam, Loam, Clay Silty clay Gravel and stones (%) - 15 – 20 % ; pH - 4.5 - 5 Drainage - well drained ; Altitude - 200 - 500 m Nutrient status - medium to low ; Slope - 3 - 8%	Soils that have one or more minor limitations	Harimau, Senai Batang Merbau, Subang, Kulai
Class III (0.8)	Moderate limitation Depth - 100 - 150 cm Texture - Coarse sandy clay loam, Sandy loam Gravel and stones (%) - 20 - 90 % ; pH - 4 - 4.5 Drainage - moderately well drained ; Altitude - 500 - 600 m Nutrient status – low to very low ; Slope - 8 - 20%	Soils that have at least one moderate limitation	Holyrood, Ulu Tiram Pohoi, Tampoi, Lunas Serdang, Kuala Brang
Class IV (0.6)	**Serious limitation** Depth - > 50 -100 cm Texture - Loamy sand Gravel and stones (%) - 90% ; pH - 6.5 - 7.0 Drainage - Imperfectly drained ; Altitude - 600 - 800 m Nutrient status - low to very low ; Slope - 20 -35%	Soils that have more than one serious limitation	Batu Anam, Durian Malacca,Gajah mati Marang, Kedah, Seremban
Class V (0.4)	**Very serious limitation** Depth - <50 cm Texture - Sand, Peat Gravel and stones (%) - >90% ; pH - <4 or >7 Drainage - poor, very poor drained ; Altitude - > 800 m Nutrient status - low to very low ; Slope - > 35 %	Soils that have at least one very serious limitation	Selangor, Briah Sungai Buloh, Linau

Based on Chan and Pusparajah (1972); Sys (1975)

Yew (1982) compared the yields of the RRIM600 clone planted on different soil classes based on their suitability (Table 3.1), showing that as expected the better the soil, the better the yield of rubber (Figure 3.4).

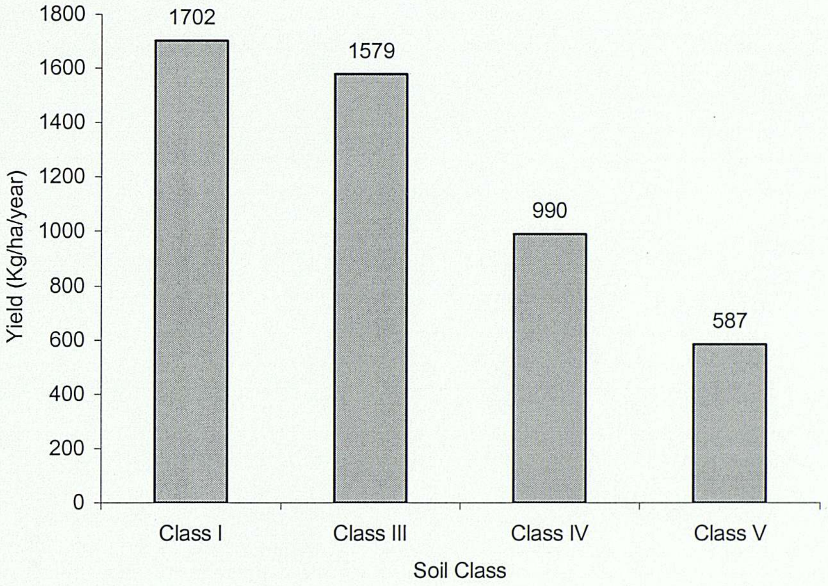


Figure 3.4: Rubber yield (kg ha^{-1} $year^{-1}$) of the RRIM600 clone planted on different soil classes in Malaysia (Source: Yew, 1982)

3.5 Climate Index (*CL*)

Hevea generally performs best in the tropical lowland climate. Thus, different climatic conditions would be expected to adversely affect growth and production of rubber. In this model, the climate index is a function of sub-indices comprising rainfall *(Ri)*, light (*Li*) and temperature (*Ti*) and expressed as;

$$CL=f(\text{Rainfall}(Ri) \times \text{Light Index}(Li) \times \text{Temperature Index}(Ti)) \qquad 2$$

Where *f* means is the function of *Ri, Li and Ti*

The calculation of the climate sub-index is explained below. The value ranges from 0 to 1.0, with 1.0 reflecting the climate that is best for rubber cultivation. Each sub-index equation is derived using statistical software SPSS Inc. SigmaPlot 2001 for Windows and Microsoft EXCEL XP, based in turn on the relationship between relative rubber growth or yield performance against the climate parameters with the highest correlation coefficient (R^2).

3.5.1 Rainfall (*Ri*)

Rainfall between 1500 to 2500 mm per year is generally considered optimal for rubber cultivation. Figure 3.5 shows the overall effect of rainfall on the girth of rubber, indicating that annual rainfall between 1000 to 1100 mm is sufficient for rubber to survive, but above 1200 mm performance is much improved.

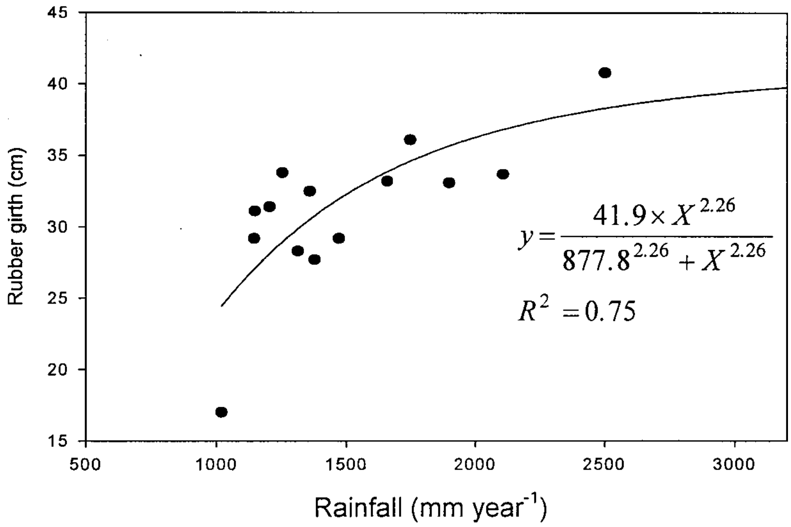


Figure 3.5: The effect of the rainfall on the actual girth (cm) of clone GT 1 after four years of planting. GT1 clone is a class I rubber clone planted in most rubber-producing countries, especially South East Asia (IRRDB, 1988).

In this model, a rainfall index is calculated based on relationship between *relative* girth and the amount of rainfall. The relative growth rate is calculated based on the girth at that particular rainfall level over the maximum girth of rubber (IRRDB, 1988). The results from the regression analyses from the SigmaPlot software shows that the equation below is best fit with the highest R^2 (0.75) and written as follows;

$$Ri = \frac{1.037 \times R^{2.26}}{898.2^{2.26} + R^{2.26}} \qquad 2a$$

R = *Rainfall in mm year*$^{-1}$

The *Rainfall* (Ri) index is in between the range of 0 to 1.

3.5.2 Light Index (*Li*)

In this model the *Li* is calculated based on results from Tupy (1989) where the average monthly sunshine (*SS*) (direct radiation) hours data was plotted against the *relative* yield of rubber (Figure 3.6). The relative yield of rubber here is based on the yield of rubber for a particular quantity of sunshine, divided by the maximum yield of rubber.

The *Li* is expressed as follows:

$$Li = \frac{1.018 \times SS^{2.13}}{52.78^{2.13} + SS^{2.13}} \qquad 2b$$

$R^2 = 0.62$

The relationship between the average monthly sunshine hours and the yield of rubber for GT1 shows that longer sunshine hours are positively correlated with the yield of rubber (Figure 3.6).

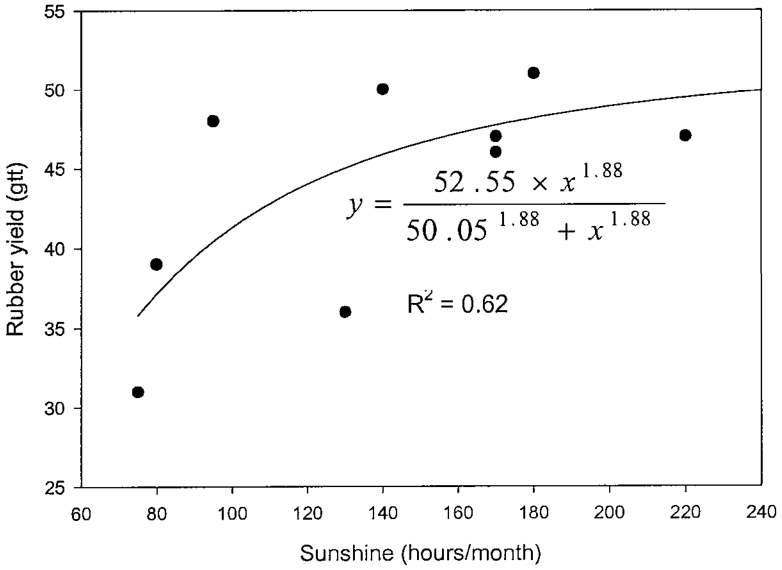


Figure 3.6: The relationship between sunshine received on GT1 rubber yield (gtt - gram tree $^{-1}$ tapping $^{-1}$) of the clone (Source: Tupy, 1989)

The *Li* will give a value of 0 or 1 to reflect the optimum amount sunshine that is adequate for growth of rubber. These results were then compared with the observed effects of sunshine on clone GT1 (Figure 3.7).

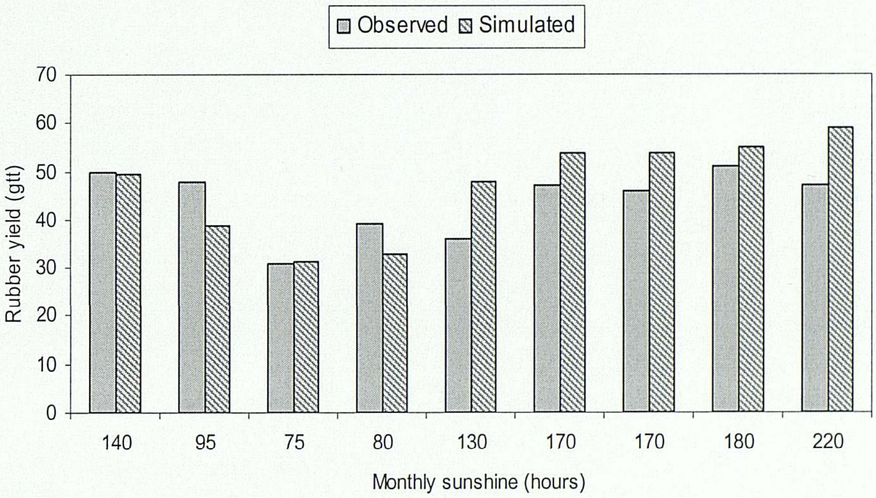


Figure 3.7: Observed and simulated results from *Hevea Version 1.0* of the effect of sunshine on rubber yield of clone GT1 from Tupy (1989)

3.5.3 Temperature Index (*Ti*)

Based on data for the GT1 clone from Tupy (1989), the relationship between the yield of rubber and the monthly mean temperature (^{0}C) shows an increase in between 24-28°C, followed by a decline at or after 30 °C (Figure 3.8).

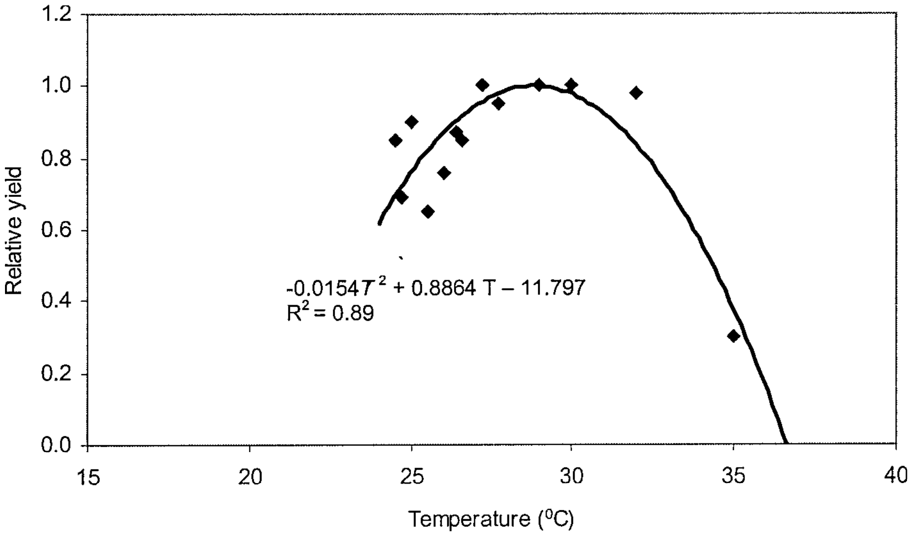


Figure 3.8: The relationship between the monthly mean temperature and relative yield of rubber from the GT1 clone
(Source: Tupy , 1989)

The temperature index (*Ti*) is calculated based on the *relative* yield of rubber against the temperature.

The relative yield is calculated based on the yield of the particular month divided by the highest yield of rubber and the equations that best fit ($R^2 = 0.89$) is as follows;

$$T_i = -0.0154T^2 + 0.8864\,T - 11.797 \qquad 2e$$

$$(24^0C < T < 28^0C)$$

$$R^2 = 0.89$$

Where *T* values between $24\text{-}28^0C$ are assumed good for rubber plantations.

Since there is no data to relate the effect of temperature directly to growth (girth), it was assumed that the temperature index (*Ti*) for growth is similar to that for rubber production (equation 2e). This assumption seems valid as the yield of rubber is positively related to the girth of rubber trees (Sethuraj, 1985; Gomej *et al.*, 1989).

The simulation result for the effect of temperature (^{0}C) on yield of rubber is shown in Figure 3.9.

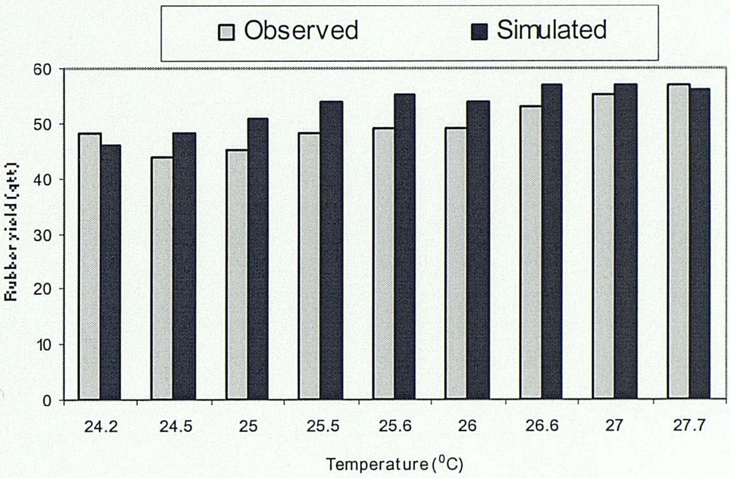


Figure 3.9: Observed and simulated results of the effect of temperature on rubber yields of the GT1 clone (Source: Tupy, 1989)

3.6 Clone Index (*CIg*)

Grist and Menz (1995) have shown how the girth is affected by tapping at different girth sizes between tapped and untapped. Based on Templeton (1969), the girth increment of a tapped tree is 58.7% (0.587) less than the girth increment of untapped rubber tree. If tapping is started when the tree is too young and slender, subsequent growth and girth will be poor and the relationship is written as:

$CIg = GR_{actual}$ x $site\ index$ x $(1.0 - 0.587)$ if tree is tapped before it reaches 45 cm girth (<45cm).

where CIg = the clone index for the growth model

For the trees that remain untapped either before or after the girth has reached 45 cm, the girth is calculated as;

$$CIg = GR_{actual} \times site\ index \times (1.0/0.587)$$

If the trees are tapped after the girth has reached >45 cm, then *Clg = 1.0 x site index*

The *site index* (Table 3.2) is based on incidence in Malaysia of *Phytophthora, Corynespora, Colletotrichum, Oidium* and Pink diseases (*Cortisium salmonicolor*) as shown in Figures 3.13, 3.14, 3.15 and 3.16 below.

Table 3.2: Examples of *Clg site i*ndices for different clones based on RRIM Planting Recommendations (RRIM, 1980; RRIM, 1998)

	Site Index (*site*)				
Clone	**GT1**	**PR261**	**PB260**	**RRIM600**	**PB255**
Resistance to pink disease	0.8	1.0	0.6	0.6	0.6
Resistance to *Oidium*	0.8	0.6	0.8	0.8	0.6
Resistance to *Colletotrichum*	0.8	0.8	0.6	0.6	1.0
Resistance to *Corynespora*	0.8	0.8	0.8	0.8	0.8
Resistance to *Phytopthora*	0.6	0.6	0.8	0.6	0.6

3.7 Management Index (MG_g)

Rubber is grown under a wide range of management conditions either as monocrop or in mixture with other crops. During the immature period, it is important to establish conditions that favour the growth of rubber. Leguminous cover crops are often established due to their capability to provide N from nitrogen fixation and to provide a clean, weed-free surface in the strip-planted areas. If no understorey crops are established, weed growth will compete for available growth resources such as nutrients, water and space. It is important to include the effect of ground cover as this may affect growth and production of rubber in a positive or negative way. Watson (1989a) reported that rubber trees planted with leguminous cover crops treatment could be tapped 11 months earlier than when crops were left weedy with natural grasses.

Maximum (or optimal) management inputs are given both to immature and mature crops, including the establishment of leguminous cover crops and complete weeding in the planting row up to the width of the canopy.

The trees are also fertilised according to RRIM Fertiliser recommendations (Pushparajah and Yew, 1977; Chan *et al.*, 1972 and Nor, 1995). Trees are pruned to a height of about 2.4 m to produce a suitable length of clean trunk for tapping while pest and disease control is applied when necessary. On the other hand, minimum management inputs refer to conditions where the trees are given only fertiliser as a basic requirement for growth. Chan and Pushparajah (1972) made a comparison of the effects of management practices such as different ground cover species, weeding practices and fertiliser inputs on rubber yield on different soil series and with different rubber clones. They showed that that the optimum management practices gave considerably higher yields than with minimum management inputs (Figure 3.10). Eusof *et al.* (1997) also reported that the trees planted with optimum management inputs reached tappability (trees that can be opened for tapping) sooner, achieving 53% more girth than with minimum management inputs. This occurrence could be due to increased fractional light interception by rubber canopy as well as crops planted underneath of rubber (Rodrigo *et al.,* 2002).

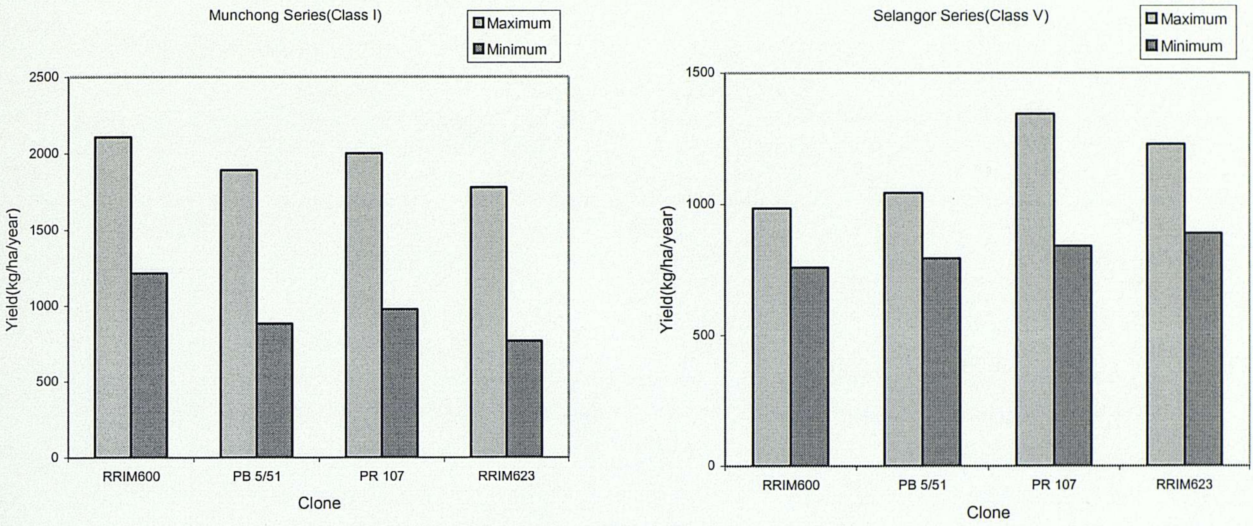


Figure 3.10: The effect of the maximum (optimal) and the minimum (only fertiliser) management inputs on yield of rubber on different soil series namely Munchong (Class I) and Selangor (Class V)

In this model the Management Index (MG_g) is calculated as a function of Ground Cover Index (*Gci*) and fertiliser effect (Fef_g) and is written as:

$$MG_g = f(Gci) \times Fef_g \qquad 3$$

3.7.1 Ground Cover *(Gci)*

Ground cover index is calculated using the following formula (Grist *et al.,* 1998):

$$Gci=0.50*\exp(\%L/1.445) \times (1-0.4\ (\%Weed\ control(WC)) \qquad 3a$$

Gci here is a function of the % light fraction (*L*) of ambient at ground level and the % of weed control (*WC*). *L* is the percentage of light penetrating rubber tree canopy covered area as well as planting strip that is occupied by other crops (i.e. natural weeds etc). *WC* defines the percentage of weeds (i.e. *Imperata* grass species, etc.) controlled (i.e. 40%) leaving the remainder weedy (60%). Percentages are expressed as 0.6 for 60% or 0.4 for 40%.

3.7.2 Fertiliser Effect (Fef_g)

Fertiliser experiments carried out by IPGM (1995) show that the girth rate of unfertilised rubber trees was 12% lower on average compared with fertilised plots (Figure 3.11).

Therefore in this model, *Fef* is defined as:

$$Fef_g = 1 - f_g \qquad \text{3b}$$

where $f_g = 0$ if the trees receive optimal fertiliser

$f_g = 0.12$ if the trees are unfertilised

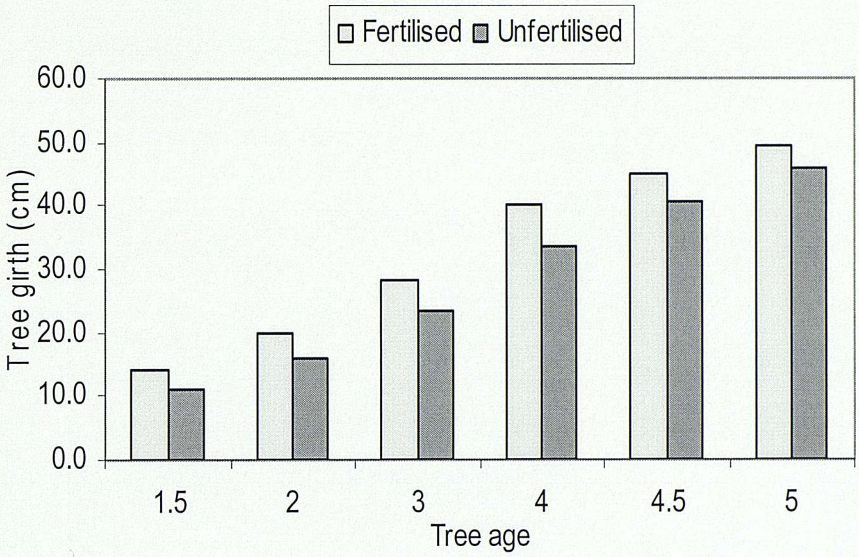
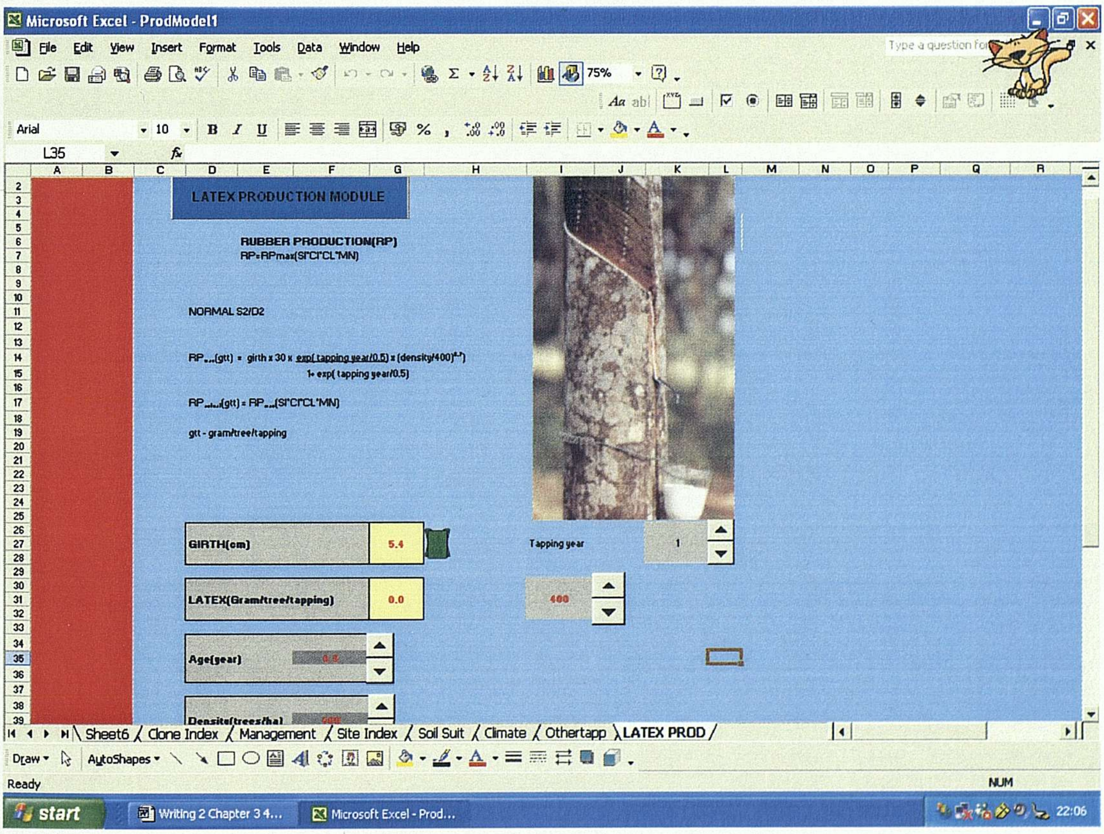


Figure 3.11: The comparison of fertilised and unfertilised rubber tree girth (cm) on class I soil for rubber clone RRIM901 (Source: IPGM, 1995)

3.8 Description of the Rubber Production (*RP*) sub-model

The interface of the *Hevea Version 1.0* Rubber Production model (*RP*) is shown in Figure 3.12. As described above, the production of rubber is influenced by the Soil Index (*SI*), Climate Index (*CL*), Clone Index (CI_p) and Management Index (MG_p) as follows:

$$RP_{actual} = RP_{max}(SI \times CL \times CI_p \times MG_p) \qquad 5$$



RUBBER PRODUCTION(RP)
RP=RPmax(SI*CI*CL*MN)

NORMAL S2/D2

RP[illegible](gtt) = girth x 30 x exp(tapping year/0.5) x (density/400)[illegible]) / 1+ exp(tapping year/0.5)

RP[illegible](gtt) = RP[illegible](SI*CI*CL*MN)

gtt - gram/tree/tapping

GIRTH(cm) 5.4

LATEX(Gram/tree/tapping) 0.0

Age(year)

Density(trees/ha)

Tapping year 1

400

Figure 3.12: The interface of *Hevea Version 1.0* Production sub model (*RP*)

The *SI and CL* indices are assumed to be similar to the *GR* (girth) model but *MG(MGp) and CI* for the rubber production (*CIp*) model are different from the growth model, the former because management (i.e. response to fertiliser) affects growth (girth) differently to rubber production. *Clp* is based on RRIM Planting Recommendations (RRIM, 1980; RRIM 1998) which will be introduced below (Table 3.3).

Watson (1989b) reported that the effect of fertiliser (NPKMg) on rubber yield was 27% more than unfertilised rubber, therefore $\boldsymbol{MG_p = Gci \times Fef_p}$. The last term ($Fef_p$) is written as;

$$Fef_p = 1 - f_p \qquad \text{5a}$$

Where $f_p = 0$ if the rubber trees receive optimal fertiliser inputs

$f_p = 0.27$ if the rubber trees are unfertilised.

Clonal performance *Clp* for rubber production was further divided into sub-indices based on performance in years 1-2 and 3-10 *(Y2nd x Y3rd)* according to RRIM Planting Recommendations (1998 – 2000), and disease incidence factors (*Site*). Each index is given a value of 0 to 1.0 to reflect the suitability of individual clones in a particular area, otherwise it is set to a default value of 1 during the simulation processes.

The clonal performance *CI* for rubber production is defined as:

$$Clp = (Y2nd \times Y3rd) \times Site \qquad 6$$

Where

$Y2nd$ = first two years yield index

$Y3rd$ = third year to tenth year yield index

$Site$ = site index

The site index is based on incidence in Malaysia of *Phytophthora, Corynespora, Colletotrichum, Oidium* and Pink diseases (*Cortisium salmonicolor*) as shown in Figures 3.13, 3.14, 3.15 and 3.16. The values for particular clones are given in Table 3. For example, the *Clp* value for the RRIM600 rubber clone in the *Oidium* disease area in second year of tapping, based on indices in Table 3.3 is:

$Y2nd = 0.8$

$Y3rd = 1.0$

$Site = 0.8$

$Clp = 0.8 \times 1 \times 0.8 = 0.64$

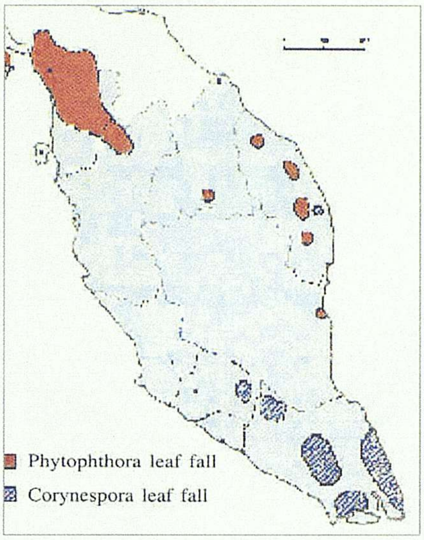


Figure 3.13: The area of incidence of *Phytopthora* and *Corynespora* diseases

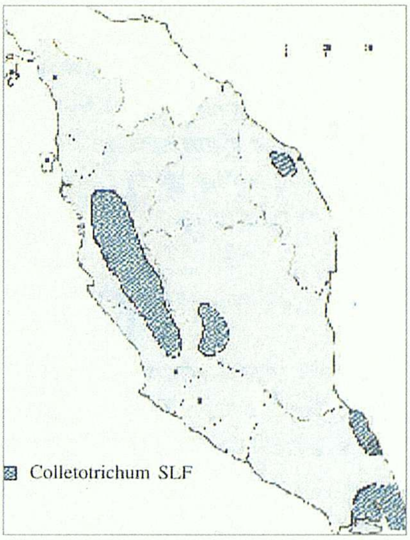


Figure 3.14: The area of incidence of *Colletotrichum* disease

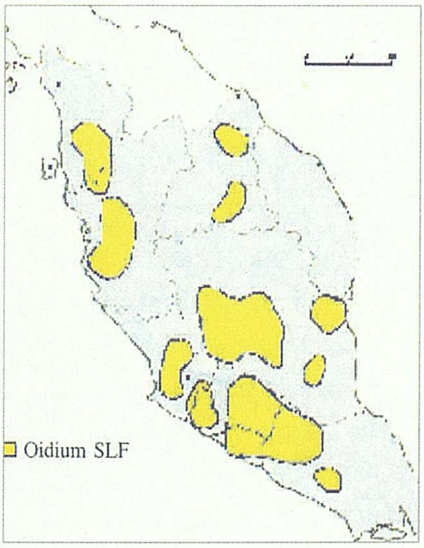


Figure 3.15: The area of incidence of *Oidium* disease

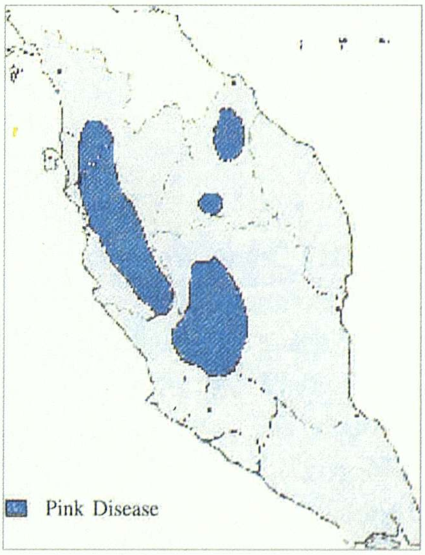


Figure 3.16: The area of incidence of *Pink* diisease

(Source: RRIM, 1980; RRIM, 1998 and MRB, 2003a)

Table 3.3: Examples of *Clp* Indices for different clones based on RRIM Planting Recommendations (RRIM, 1980; RRIM, 1998)

Clone	**GT1**	**PR261**	**PB260**	**RRIM600**	**PB255**
First 2^{nd} year yield (*Y2nd*)	0.8	1.0	1.0	0.8	1.0
Yield 3^{rd} year to tenth year (*Y3rd)*	1.0	1.0	1.0	1.0	1.0
Site Index (*site*)					
Resistance to pink disease	0.8	1.0	0.6	0.6	0.6
Resistance to *Oidium*	0.8	0.6	0.8	0.8	0.6
Resistance to *Colletotrichum*	0.8	0.8	0.6	0.6	1.0
Resistance to *Corynespora*	0.8	0.8	0.8	0.8	0.8
Resistance to *Phytopthora*	0.6	0.6	0.8	0.6	0.6

$RP_{(kg\ ha^{-1} year^{-1})}$ is a function of girth, tapping year and tree density (trees ha^{-1}) and is calculated as follows:

$$RP(_{kgha^{-1}year^{-1}})=girth\times 30\times\frac{exp\left(\dfrac{TYear}{0.5}\right)}{1+exp\left(\dfrac{TYear}{0.5}\right)}\times\frac{(D)^{0.7}}{400} \qquad 7$$

(adapted from Grist *et al.,* 1998)

where *Tyear* = Tapping year,

D = planted trees density (trees ha^{-1}) and *girth* in (cm)

In this model the maximum rubber production ($RP_{(max)}$) is expressed as grams tree^{-1} tapping^{-1} (gtt) and refers to conditions where rubber is tapped under optimal conditions. In this model, 1.0 for each index represents the optimal conditions of *SI, CL, Clp* and *MGp*. It is calculated as:

$$RP_{(max)(gtt)} = \frac{RP(kgha^{-1}year^{-1})}{no.trees\ tapped\ ha^{-1} \times tapping\ days\ year^{-1}} \times 1000$$

.

The relationships between yield and tapping year (RRIM, 1980) of rubber and also between yield (kg ha^{-1}), gtt, and planting density, based on experimental data (Ng *et al.*, 1979), are shown in Figure 3.17. The observed and simulated results for rubber yield, based on tapping year, are shown in Figure 3.18.

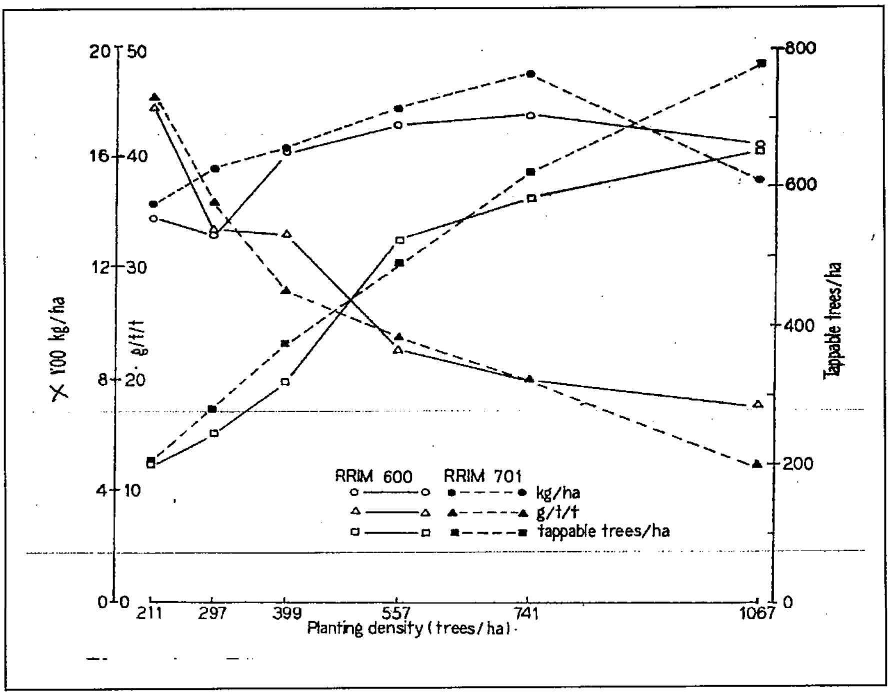


Figure 3.17: The relationship between yield (kg ha^{-1}), gtt, tappable stand and planting density of rubber clones RRIM600 and RRIM701

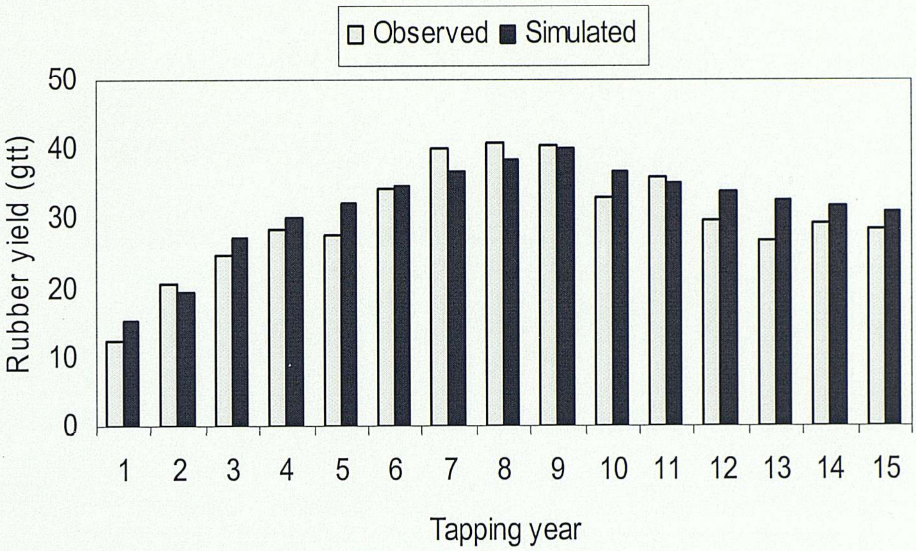


Figure 3.18: The relationships between yield and tapping year of the GT1 rubber clone, using observed experimental data (RRIM, 1980) and model simulations

CHAPTER 4

MODEL VALIDATION

4.1 Introduction

The accuracy of a certain model can be done through validation processes. Validation is better understood as a process that results in an explicit statement about the behaviour of a model (Rykiel, 1996).

To determine the accuracy of the developed static model (Chapter 3) for predicting the growth and rubber production, simulated values from the model were compared to the experimental data. As the developed model is primarily going to be used for Malaysian and Indonesian conditions, where GT1 clone (data mostly used to derive equations in Chapter 3) is widely planted (RRIM, 1980;1998; BPM, 2002), data from the RRIM Planting Recommendations (RRIM, 1980;1995;1998 and MRB, 2003a), data from the RRIM's experiments (Appendix 1) and the Report on Yield and Growth for Recommended Rubber Clones in Indonesia (BPM, 2002) are used for validation purposes.

Validation also will be extended to other widely planted rubber clones (e.g. RRIM901, PR255, PR261, PB260, and RRIM600) in Malaysia and Indonesia.

These validation processes is important as it gives an indicators whether the developed model demonstrates an ability to simulate growth as well as rubber production in a wide range of clones. If the output of the model is well corresponds with the experimental data, then the model is an adequate representation of a rubber tree system. If not, then it will provide some basis for improvement of the developed model.

The validation processes is carried out by using a set of statistical analyses based on Loague and Green (1991) to evaluate the performance or accuracy of the developed model.

The mathematical expressions that describe the analyses are presented as in Table 4.1 below.

Table 4.1: Mathematical expressions of the statistical analyses used for model validation (Loague and Green, 1991)

Criterion	Symbol	Calculation formula	Range
Maximum error	ME	$Max\vert Pi - Oi \vert\vert_{i=1}^{n}$	≥ 0
Root mean square error	RMSE	$\left[\sum_{i=1}^{n}\left(\frac{Pi - Oi^2}{n}\right)\right]^{0.5} \cdot \frac{100}{\sigma}$	≥ 0
Coefficient of determination	CD	$\frac{\sum_{i=1}^{n}(Oi - \sigma)^2}{\sum_{i=1}^{n}(Pi - \sigma)^2}$	≥ 0
Modelling efficiency	EF	$\frac{\left(\sum_{n=1}^{n}(Oi - \sigma)^2 - \sum_{n=1}^{n}(Pi - \sigma)^2\right)}{\sum_{n=1}^{n}(Oi - \sigma)}$	≤ 1
Coefficient of residual mass	CRM	$\frac{\left(\sum_{n=1}^{n}Oi - \sum_{n=1}^{n}Pi\right)}{\sum_{n=1}^{n}Oi}$	≤ 1

Where

Pi = the predicted values

Oi = the observed values

n = the number of samples

σ i= the mean of the observed data

The lower limit for the maximum error, root mean square error and coefficient of determination (ME, RMSE and CD) is zero, while the maximum value for the modelling efficiency (EF) is one. Both EF and coefficient residual mass (CRM) can become negative. If EF is less than zero, the model-predicted values are worse than simply using the observed mean. The CD is a measure of the proportion of the total variance of observed data explained by the predicted data.

4.2 Validation of the rubber growth (*GR*) sub-model

As the main criterion used to determine the growth of rubber is the development of tree girth, the comparison of observed versus simulated girth is shown in Figure 4.1 below. The graph shows that the model is able to simulate the girth of rubber with a good correlation ($R^2 = 0.92$) for a range of different clones.

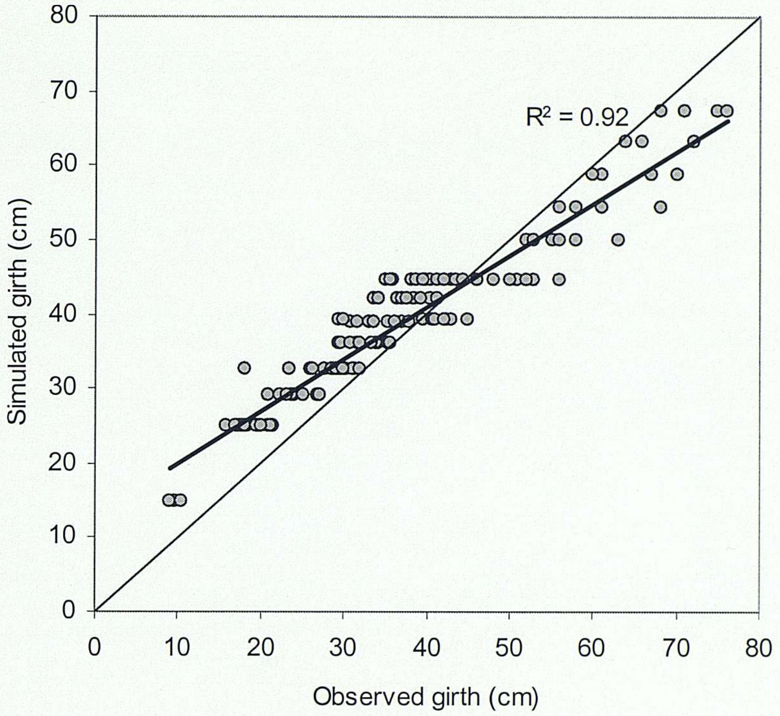


Figure 4.1: Observed vs simulated rubber growth (girth) for a range clones, land use sectors and soil types from Malaysia and Indonesia. Clones include - RRIM901, PR255, PR261, PB260, and RRIM600 (Source: IPGM, 1995; 1996; 1997; CMU, 1998; 1999; 2000; 2001; BPM, 2002)

Taking individual clones, it is possible to examine how different management practices affect the accuracy of model prediction. Figure 4.2 shows observed and simulated values compare for the growth of clone RRIM 901, planted under different land use sectors (estate and smallholder).

This demonstrates that the model is able to simulate the girth of rubber under different land use sectors with a reliable correlation coefficient (R^2 = 0.99). The ability of model to predict the growth of this clone on different soil classes (class I and class II) also showed a good relationship (R^2 = 0.99) between observed and simulated values (Figure 4.3; IPGM, 1995; 1996).

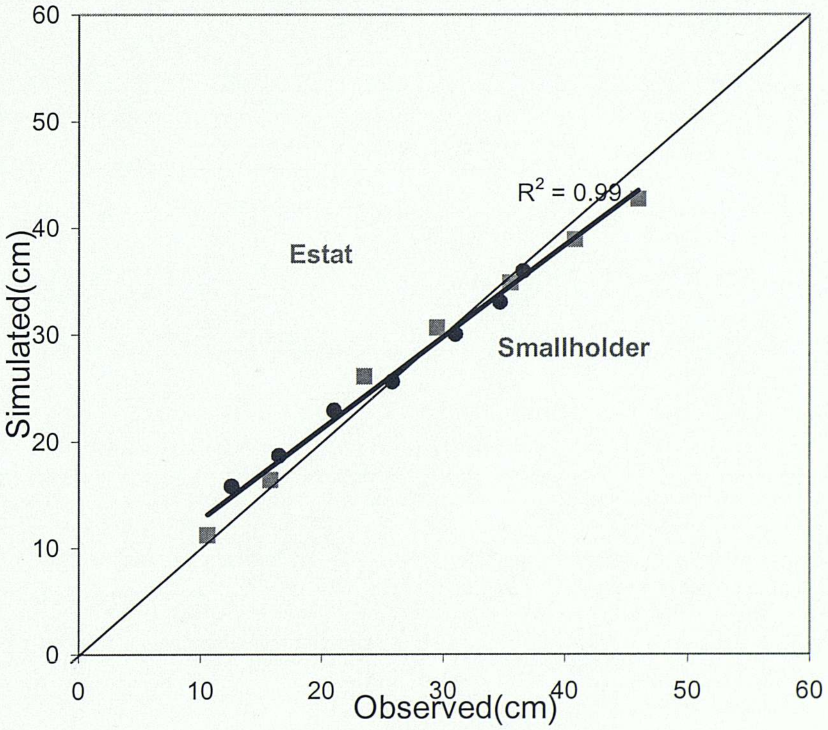


Figure 4.2: The observed vs simulated girth for RRIM901 in different land use sectors (■ - estate and ● - smallholder) (Source: IPGM, 1995; 1996)(Jhan, 2002)

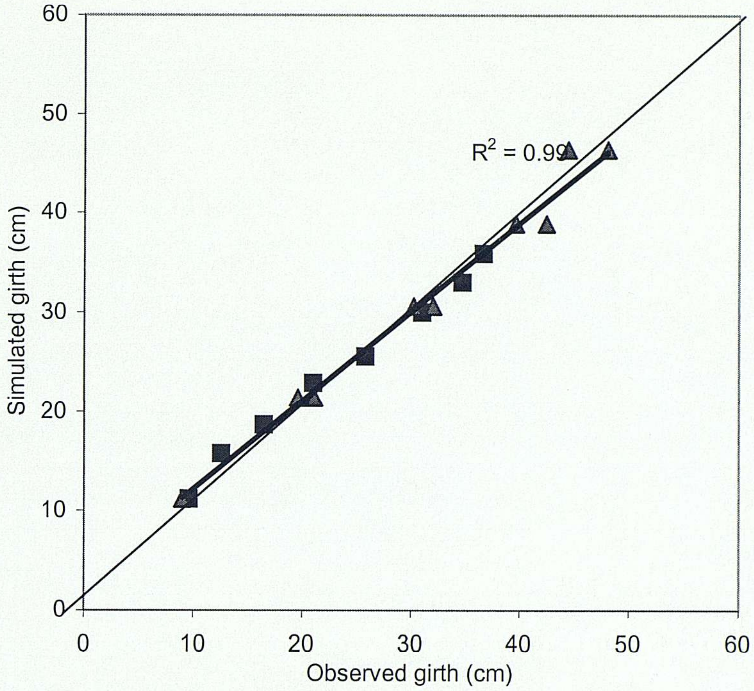


Figure 4.3: Observed vs simulated growth for rubber clone RRIM901 on class I (▲) and class II soils (■) (Source: IPGM, 1995; 1996)(Jhan, 2002)

As above, the statistical criteria defined by Loague and Green (1991) were used to evaluate the modelling efficiency for growth (girth) for a range of clones, land use sectors and soil classes. The results are given in Table 4.2.

Table 4.2: Statistical analysis for observed versus simulated growth (girth)

Parameters	Value
n	157
Maximum Error (ME)	8.0
Root Mean Square Error (RMSE)	15.5
Coefficient of Determination (CD)	1.94
Modelling Efficiency (EF)	0.87
Coefficient of Residual Mass (CRM)	-0.05
R^2	0.92

The coefficient of determination (CD) from this analysis is used to expresses the ratio of the scatter of simulated and observed values. Statistically, the lower limit for CD is 0 while the value that closer to 1 is a good value.

Negative values for EF means that modelling variability is greater than experimental variability (Rinaldi *et al.*, 2003). Negative (< 0) values of modelling efficiency (EF) indicate that the mean of the observed values is a better estimate than that derived from simulations.

Positive (> 0) coefficient of residual mass (CRM) values indicates a tendency to underestimate the observed values, while negative ones indicate a tendency to overestimate (Loague and Green, 1991). In this case the CRM is -0.05, indicating that this model overestimates the growth of the rubber. The possible reasons are explored below (Chapter 5).

4.3 Validation of the rubber production (*RP*) sub-model

The clones simulated ranged from GT1, RRIM600, PB260, PR261, PR255, PB217 and PM10 planted in Malaysia and Indonesia. The relationship between observed rubber production and predicted values from the simulation indicates a tendency towards overestimation of rubber yields (Figure 4.4), while the model validation statistics show a good correlation (R^2 = 0.98) between observed and simulated yields, with 0.97 (97%) model efficiency. These results are discussed further in Chapter 5.

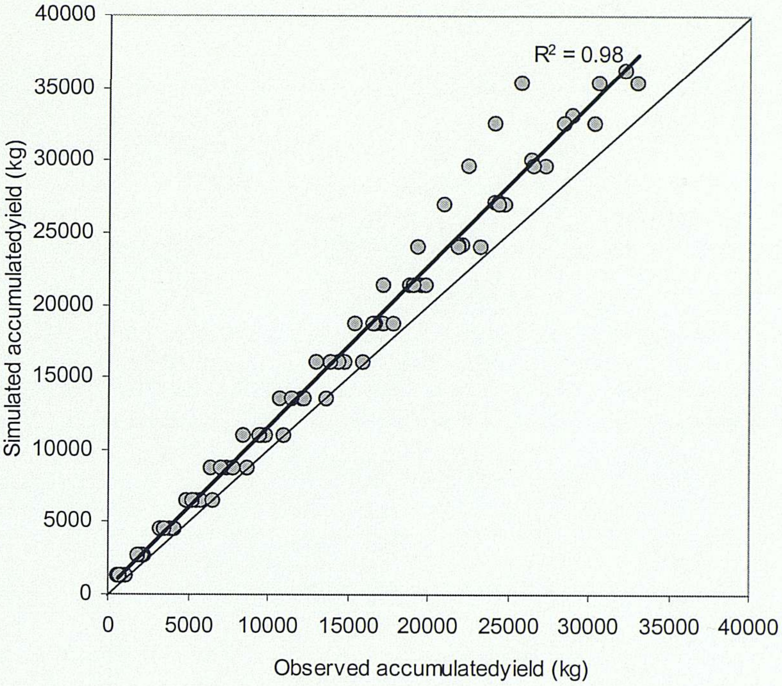


Figure 4.4: Observed and simulated results for yield of rubber for different clones (GT1, RRIM600, PB260, PR261, PR255, PB217 and PM10) from growth trials in Malaysia and Indonesia (Source: RRIM, 1980;1995;1998; BPM, 2002)

Statistical analysis of the *RP* sub-model to predict rubber production from different range of clones is shown below (Table 4.3).

Table 4.3: Statistical analysis of the *RP* sub-model to predict rubber production from different range of clones from Malaysia and Indonesia

Parameters	**Value**
n	82
Maximum Error ME)	9.5 tonnes
Root Mean Square Error (RMSE)	19.30
Coefficient of Determination (CD)	0.77
Modelling Efficiency (EF)	0.97
Coefficient of Residual Mass (CRM)	-0.14
R^2	0.98

CHAPTER 5

DISCUSSIONS AND CONCLUSIONS FOR STATIC MODELLING APPROACHES

From the above statistical analyses and validation results, the simulated results appear to fit well with experimental data, with modelling efficiencies of 0.87 for girth and 0.97 for rubber production for a range of clones and environments (Table 4.2 and 4.3). However, there is a tendency for the model to overestimate the growth and production of rubber. As the growth of rubber is influenced by many factors such as the selection of planting material, weather conditions, agro-management factors and tapping regimes, refinement of the model with respect to these causes needs to be taken into account.

5.1 Selection of planting material

The successful establishment of nursery stock in the field depends on the type and quality of planting materials. The type of material, e.g. stock derived from 2-whorl polybag budding, 2-whorl budded stumps, green budding, brown budding etc., will determine the performance of each type according to environmental conditions such as climate, soils and management.

This in turn influences the immaturity period of rubber (i.e. the period before trees are ready to be tapped) and consequently the production of rubber (Webster, 1989; Table 5.1).

Table 5.1: Relative performance of different types of rubber planting material in relation to the immaturity period (prior to tapping)

Type of planting materials	Immaturity period (months)
2-whorl budded stump	57
2-whorl polibag budding	59
Green budding In the field	61
Brown budding in the field	67

As the simple model assumed that the planting stock was uniform (i.e. 2-whorl budded stumps) for every experimental site, the use of different types of planting stocks, with longer immaturity periods, could be the reason for overestimation. This is because 2-whorl budded stumps grow faster than the other stock types.

5.2 Weather conditions

Successful establishment of nursery stock is also related to weather conditions. Even though conventional recommendations dictate that rubber planting is carried out during wet season, dry periods occurring after planting may cause casualties depending on the type of planting stock or planting materials used. Any replacement then depends on the availability of planting materials.

Hence, the growth of rubber in the field tends not to be uniform due to different planting dates, consequently resulting in lower than expected girthing rates. The longer the time taken for replacement, the more the girth of the trees varies, giving low average girth measurements. Since this model assumes uniform growth conditions, the simulation results will tend to overestimate growth, especially in the early stages.

5.3 Tapping factors

Over 98% of the water taken up by the rubber root system is released into the atmosphere by transpiration through stomata or by evapotranspiration from various parts of rubber tree. This phenomenon plays an important role in rubber synthesis, since less available water in laticiferous (latex) tissue affects production, particularly in the afternoon.

This was demonstrated by Pakianathan *et al.* (1989), who reported that different tapping times in the day influenced the production of rubber. An experiment on 10 plots consisting 58 trees plot^{-1} showed a 16% reduction in yield when tapping was carried out in the afternoon (0100 hours) compared with morning tapping (0700 hours). They also reported that the trees tapped at 0700, 0900 and 1100 hours had decreased yields of 4% and 15% respectively, in relation to yields tapped at 0700 hours. Paardekooper and Sookmark (1969) examined the relationship between rubber yield and hours of tapping (Figure 5.1), showing a decline in yield during the morning, offset by a marginal increase in dry rubber content.

However, since the static model assumes tapping is normally carried out at 0700 hours, results for tapping later than 0700 hours in the observed values will be overestimated.

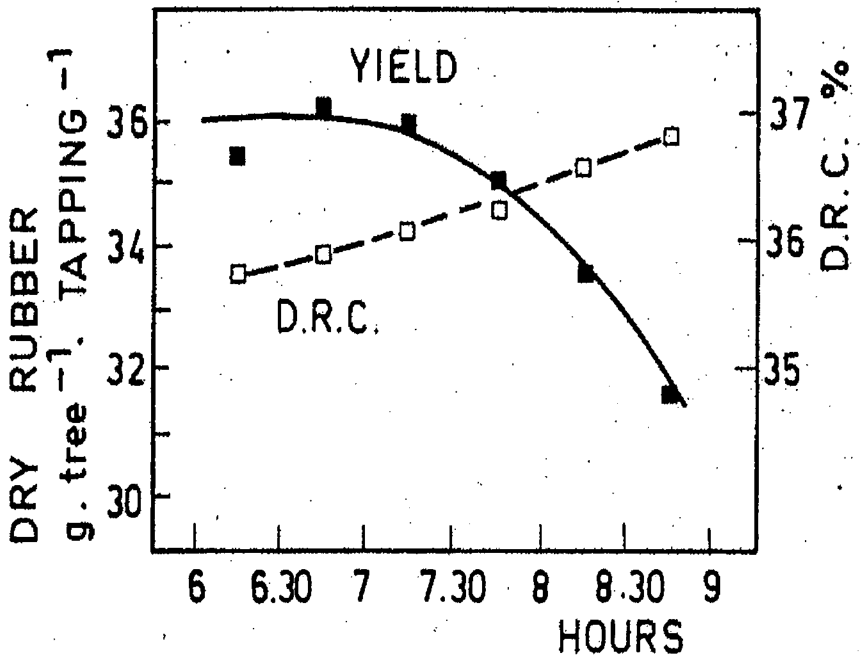


Figure 5.1: The relationship between rubber yield (gtt = gram tree^{-1} tapping), dry rubber content (DRC) and time of tapping.

(Source: Paardekooper and Sookmark , 1969)

5.4 Availability and quality of tapping panel

The thickness of the bark shaving removed at each of tapping plays an important role in rubber production. This is because a poor tapping panel reduces rubber yield (Gomez, 1983), as tapping cannot be carried out properly. Excessive bark consumption and poor tapping quality will shorten the economic life of the tree. Since this model assumes tapping is carried out on good tapping panel, results for tapping on poor tapping panel in the observed values will be overestimated.

5.5 Conclusions

The *Hevea Version 1.0* model, which is developed by the author, demonstrates a reasonable ability to predict the growth in girth and rubber production in Malaysian and Indonesian rubber tree systems. Using a limited number of parameters relating to climate, soil, clone, management and tapping have been used, the model simulates with good efficiency (EF) of 0.87 for growth (girth) and 0.97 for rubber production.

Even though this is a simple static model and primarily developed as *a precursor,* it still has advantages such as:

- an ability to simulate growth and production for a range of different rubber clones;
- ease of construction, as few input parameters are involved;
- the facility to make improvements or adjustments simply, as the relationships between parameters are relatively few;
- use as a starting point for beginners and as a step to using and understanding more complex models;
- use as an extension tool for end users (smallholders), as it is easy to understand.

Several influencing factors have not been included in this simple model, such as the effect of rubber trees on other crops, and vice versa, under rubber agroforestry planting options. Therefore at a further stage (CHAPTER 6), the work will extend the approach from simple static to dynamic models, in particular linking in and improving the agroforestry model WaNuLCAS (Water, Nutrient, Light Capture in Agroforestry Systems), which is built in the STELLA modelling environment.

CHAPTER 6

DYNAMIC MODELLING APPROACHES

6.1 Introduction

The work in this chapter aims to describe a dynamic modelling approach in order to predict growth and yield in rubber agroforestry systems, and to link this with a current Agroforestry model, namely WaNuLCAS (Water, Nutrients, Light Capture in Agroforestry Systems)(van Noordwijk *et al.,* 2004). A dynamic model is described by time, using differential equations; therefore, the future response of the system is determined by the present state of the system and the inputs. A dynamic model may continue to have time-varying responses and it is suitable for advance users or researchers. The objectives of this work are;

1. to develop a tapping panel sub-model and link this with a rubber production sub-model;
2. to refine the rubber production sub-model to include the tapping sub-model;
3. to link the developed sub-model to the current Agroforestry Model (WaNuLCAS).

6.2 Materials and methods

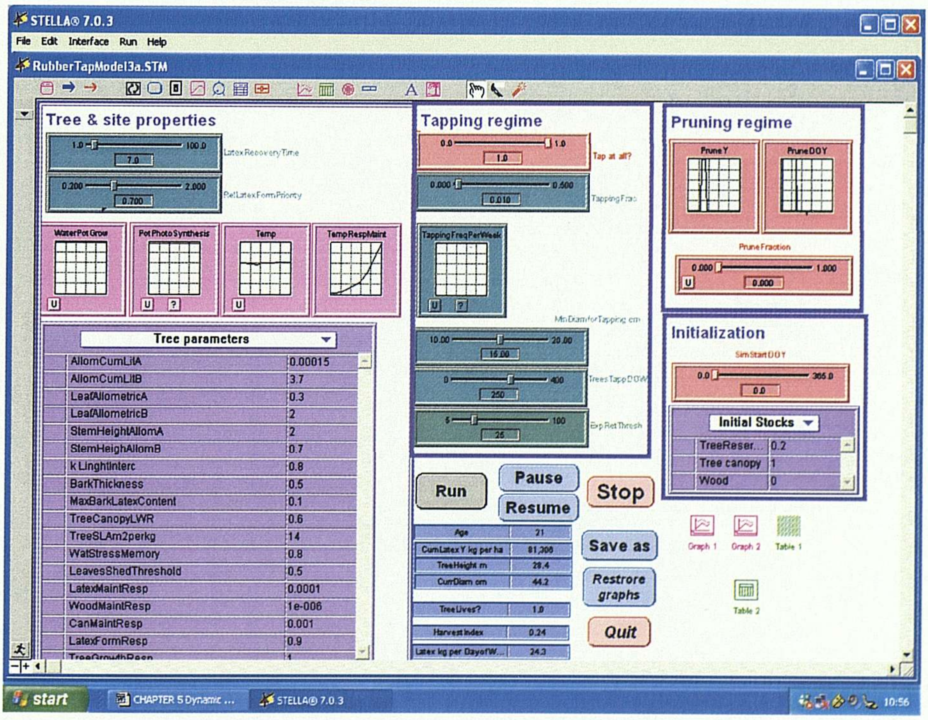
The basic modelling work was performed using a 'TreePotGro' sub-module. TreePotGro is a sub-module of WaNuLCAS, with environmental variables excluded. Two items of computer software were used in this modelling work: STELLA Research Software Environment (refer to 6.2.1) and Microsoft EXCEL. Microsoft EXCEL provides the automated tools for data analysis, list keeping and calculations as well as the presentation tools that need for reporting.

6.2.1 STELLA Research Software Environment

STELLA is a software tool for building systems models (STELLA Research, 1996). There are three levels or layers that the user can work within STELLA, depending on the complexity of the problems and the level of detail and organisation that is desired in the model. The purpose of the layering is to manage complexity both for model developers and for users. The three levels consist of three layers: the high-level mapping layer, the construction layer and the equation layer.

1. The high-level mapping Layer (Figure 6.1)

In this layer, users can create high-level maps and explore the dynamics of the model through a Tracing Button. The high-level mapping layer also facilitates user interaction through an input and output device. The mapping layer also allows users to overview the structure of the models and allows the model to be run using the 'Run Controller'.



LatexRecoveryTime	1.0	100.0	7.0
RelLatexFormPriority	0.200	2.000	0.700
Tap at all?	0.0	1.0	1.0
TappingFrac	0.000	0.500	0.010
MinDiamforTapping cm	10.00	20.00	15.00
TreesTappDOW	0	400	250
ExpRetThresh	5	100	25
PruneFraction	0.000	1.000	0.000
SimStartDOY	0.0	365.0	0.0

Tree parameters

AllomCumLitA	0.00015
AllomCumLitB	3.7
LeafAllometricA	0.3
LeafAllometricB	2
StemHeightAllomA	2
StemHeighAllomB	0.7
k LinghtInterc	0.8
BarkThickness	0.5
MaxBarkLatexContent	0.1
TreeCanopyLWR	0.6
TreeSLAm2perkg	14
WatStressMemory	0.8
LeavesShedThreshold	0.5
LatexMaintResp	0.0001
WoodMaintResp	1e-006
CanMaintResp	0.001
LatexFormResp	0.9

Initial Stocks

TreeReser...	0.2
Tree canopy	1
Wood	0

Age	21
CumLatexY kg per ha	81,300
TreeHeight m	28.4
CurrDiam cm	44.2
TreeLives?	1.0
HarvestIndex	0.24
Latex kg per DayofW...	24.3

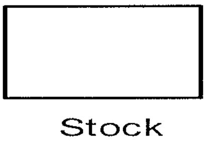
Figure 6.1: The high-level mapping layer of STELLA

2. The construction layer

The model construction layer is the level in which the user can construct and simulate the models. A system diagram in this layer displays the flows, reservoirs (stocks), converters and their inter-relationships (connectors). The model construction layer is used to specify the mathematical relationships that are used to run the model.

The four main building blocks described in this layer are as follows:

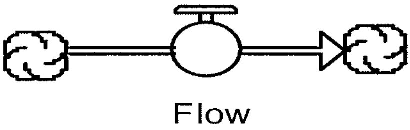
i. Stock



Stocks are accumulations, with functions to collect flows into and out of them. Stocks are also reservoirs as they accumulate the inflows passively, minus their outflows.

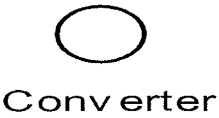
Reservoirs (Stocks) = Inflows – outflows

ii. Flows



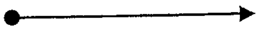
The flows fill (*inflows*) or drain (*outflows*) accumulations. The unfilled arrowhead on the flow pipe indicates the direction of the flow.

iii. Converters



Converters serve as '*controllers*' in the STELLA software. These hold values for constants, define external inputs to the model, calculate algebraic relationships and serve as the storeroom for graphical functions. In essence, the converter converts input into output.

iv. Connectors



Connectors operate to connect different elements in the models.

A simple example of linkages between these four building blocks is shown in Figure 6.2. The construction layer for rubber production is illustrated in Figure 6.3.

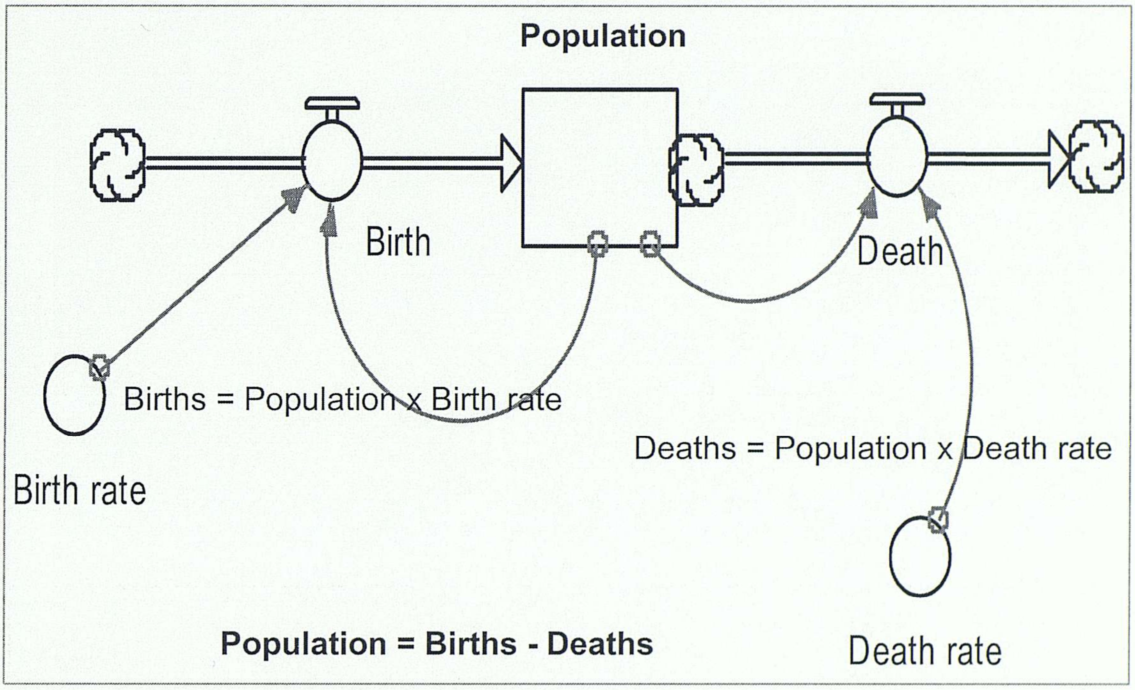


Figure 6.2: An example of the relationship between stocks, flows, converters and connectors

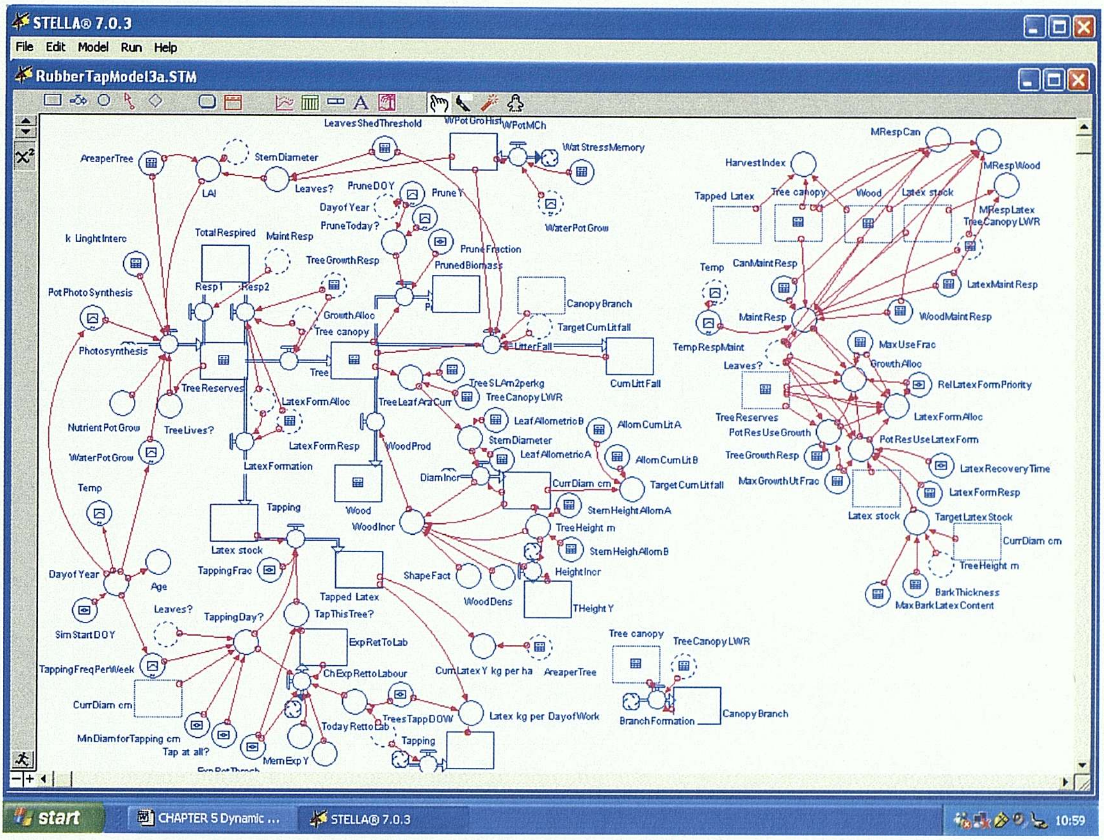
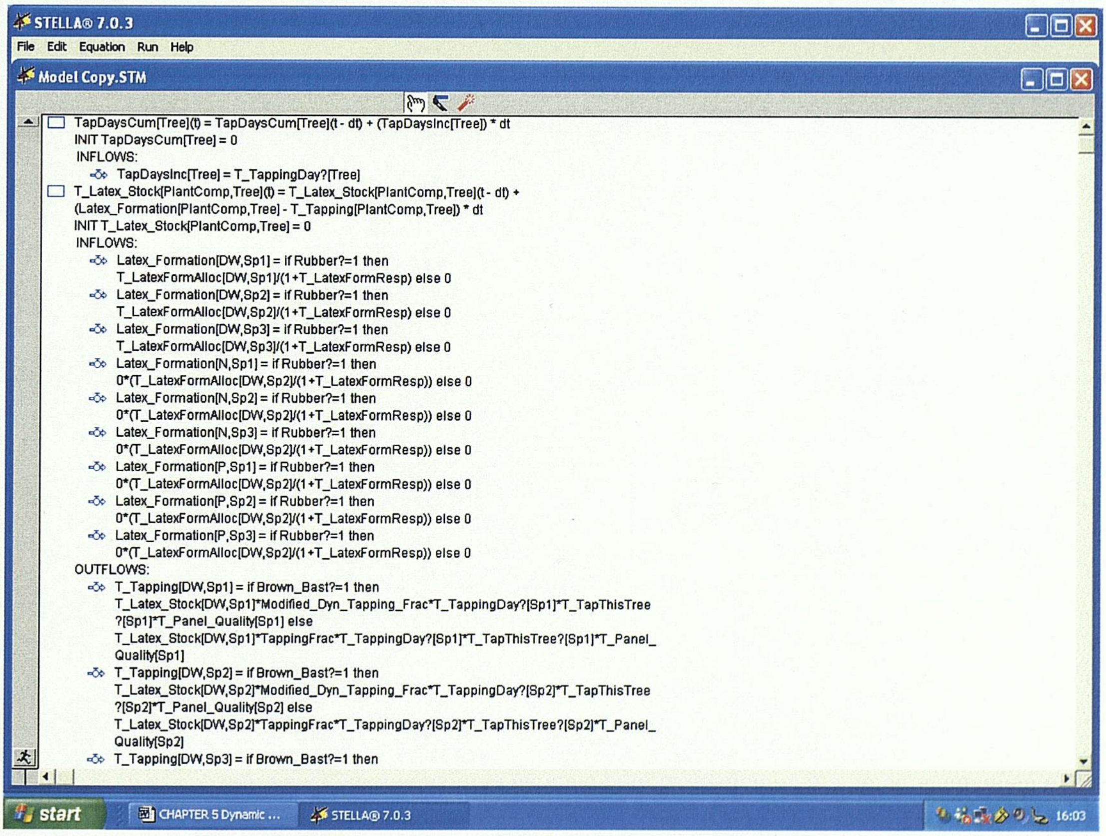


Figure 6.3: The Construction Layer of STELLA

3. The equation layer

The equation layer (Figure 6.4) allows the user to view the underlying equations behind the model and to modify them when necessary. This layer is normally used by the more advanced STELLA user, as it requires mathematical knowledge of the equations and how they are inter-related.

Whenever STELLA is launched, the equation layer automatically begins computing from the construction layer; however, we can readily move up to the high level mapping layer or down to the equation layer simply by clicking the up or down arrows in the upper left corner of the model building window.



```
☐ TapDaysCum[Tree](t) = TapDaysCum[Tree](t - dt) + (TapDaysInc[Tree]) * dt
  INIT TapDaysCum[Tree] = 0
  INFLOWS:
     TapDaysInc[Tree] = T_TappingDay?[Tree]
☐ T_Latex_Stock[PlantComp,Tree](t) = T_Latex_Stock[PlantComp,Tree](t - dt) +
  (Latex_Formation[PlantComp,Tree] - T_Tapping[PlantComp,Tree]) * dt
  INIT T_Latex_Stock[PlantComp,Tree] = 0
  INFLOWS:
     Latex_Formation[DW,Sp1] = if Rubber?=1 then
     T_LatexFormAlloc[DW,Sp1]/(1+T_LatexFormResp) else 0
     Latex_Formation[DW,Sp2] = if Rubber?=1 then
     T_LatexFormAlloc[DW,Sp2]/(1+T_LatexFormResp) else 0
     Latex_Formation[DW,Sp3] = if Rubber?=1 then
     T_LatexFormAlloc[DW,Sp3]/(1+T_LatexFormResp) else 0
     Latex_Formation[N,Sp1] = if Rubber?=1 then
     0*(T_LatexFormAlloc[DW,Sp2]/(1+T_LatexFormResp)) else 0
     Latex_Formation[N,Sp2] = if Rubber?=1 then
     0*(T_LatexFormAlloc[DW,Sp2]/(1+T_LatexFormResp)) else 0
     Latex_Formation[N,Sp3] = if Rubber?=1 then
     0*(T_LatexFormAlloc[DW,Sp2]/(1+T_LatexFormResp)) else 0
     Latex_Formation[P,Sp1] = if Rubber?=1 then
     0*(T_LatexFormAlloc[DW,Sp2]/(1+T_LatexFormResp)) else 0
     Latex_Formation[P,Sp2] = if Rubber?=1 then
     0*(T_LatexFormAlloc[DW,Sp2]/(1+T_LatexFormResp)) else 0
     Latex_Formation[P,Sp3] = if Rubber?=1 then
     0*(T_LatexFormAlloc[DW,Sp2]/(1+T_LatexFormResp)) else 0
  OUTFLOWS:
     T_Tapping[DW,Sp1] = if Brown_Bast?=1 then
     T_Latex_Stock[DW,Sp1]*Modified_Dyn_Tapping_Frac*T_TappingDay?[Sp1]*T_TapThisTree
     ?[Sp1]*T_Panel_Quality[Sp1] else
     T_Latex_Stock[DW,Sp1]*TappingFrac*T_TappingDay?[Sp1]*T_TapThisTree?[Sp1]*T_Panel_
     Quality[Sp1]
     T_Tapping[DW,Sp2] = if Brown_Bast?=1 then
     T_Latex_Stock[DW,Sp2]*Modified_Dyn_Tapping_Frac*T_TappingDay?[Sp2]*T_TapThisTree
     ?[Sp2]*T_Panel_Quality[Sp2] else
     T_Latex_Stock[DW,Sp2]*TappingFrac*T_TappingDay?[Sp2]*T_TapThisTree?[Sp2]*T_Panel_
     Quality[Sp2]
     T_Tapping[DW,Sp3] = if Brown_Bast?=1 then
```

Figure 6.4: Example of the equation layer in STELLA

6.3 Model structure

The conceptual rubber production model, which is built within the STELLA software environment, is shown in Figure 6.5 below.

The scheme begins with incoming biomass (through photosynthesis) by the trees, its use for respiration (for growth, latex formation and/or maintenance of living tissue) and production of latex and tree biomass. An option of pruning or not enables users to simulate the effect of pruning on growth and rubber production (van Noordwijk, 2004. Pers. Comm; Lusiana and Khasanah, 2005. Pers. Comm).

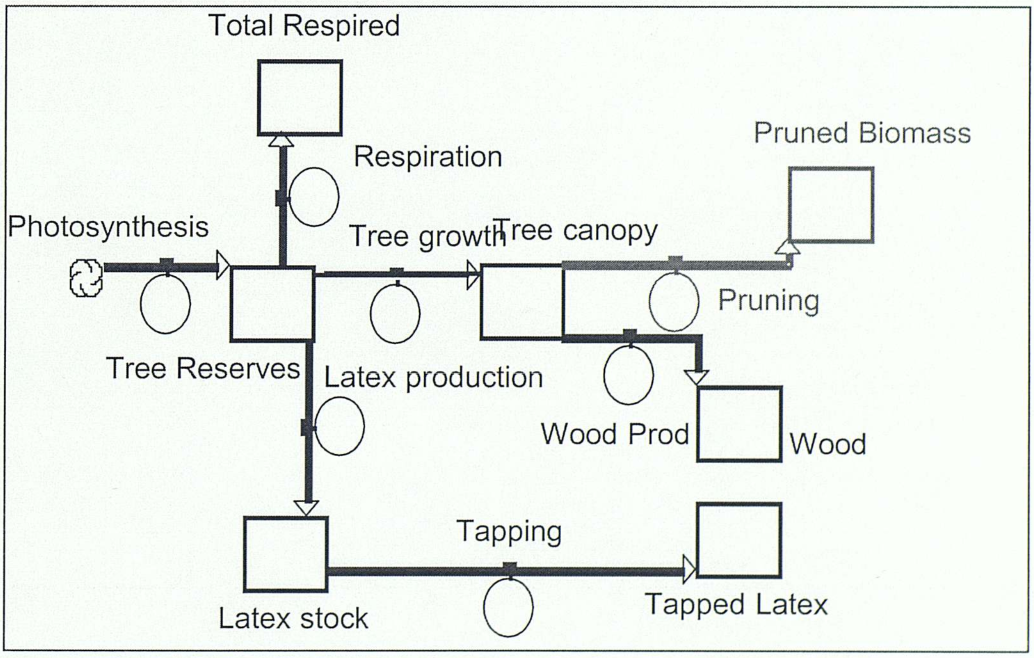


Figure 6.5: The overall conceptual rubber production model (Source: van Noordwijk, 2004, Pers. Comm)

Two more sub-models are added into this model to refine it: the tapping and tapping panel sub-models.

6.3.1 The Tapping Sub-model

The overall features of the Tapping Sub-model are shown in Figure 6.6.

There are four stocks in this sub-model, based respectively on maximum tree diameter, the amount of tapped latex stock, the number of tapping days and the expected financial returns from labour inputs: These are described separately below.

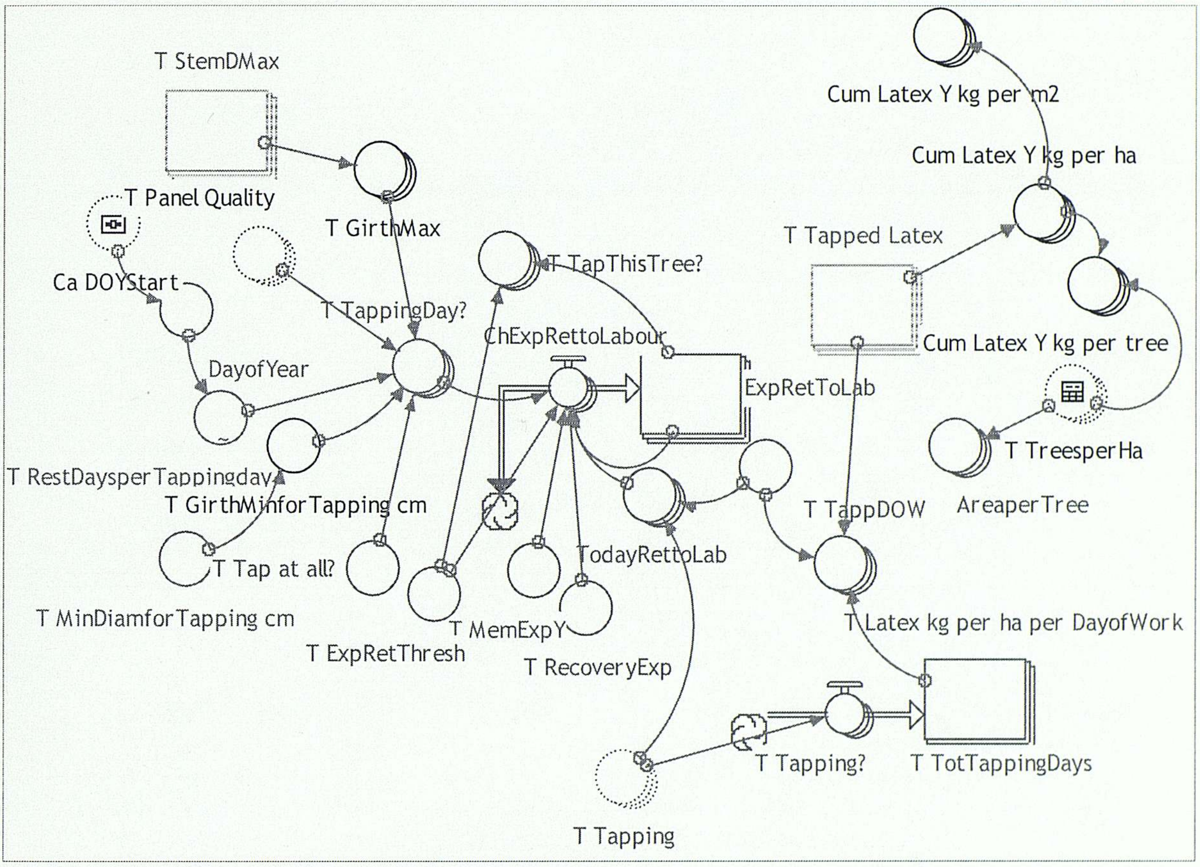


Figure 6.6: Features of the Tapping Sub model
(see text for explanation)

6.3.1.1 Maximum tree stem diameter stock (*T StemDMax*)

This is a '*ghost*' stock (term used in STELLA), represented by dotted lines (in Figure 6.6). This means that the stock is a 'copied stock' that is used elsewhere or linked with another sub-model.

T StemDMax stock represents the diameter of rubber trees. Rubber trees are opened for tapping once they reach a diameter of 7.2 cm (45 cm in girth), measured at 160 cm above ground.

T StemDMax (>45cm) acts as indicator as to whether the trees are ready to be tapped or not. In WaNuLCAS, the general biomass to stem diameter relationship (allometric equation, $Y=aD^b$) is used as the inverse to derive stem diameter from the tree biomass. The relation is;

$$T\_BiomAG = T\_BiomDiam1*T\_StemDiam^{T\_BiomDiamSlope}$$

where

T = Prefix T stands for tree

T_BiomAG = total above ground biomass of rubber tree

T_BiomDiam1 = biomass of a tree, diameter 1cm

T_StemDiam = *tree stem diameter*

T_BiomDiamSlope = *tree biomass diameter slope (power coefficient)*.

From the above equation, the stem diameter is calculated as follows:

$$T\_StemDiam = \left[\frac{T\_BiomAG}{T\_BiomDiam1}\right]^{1/T\_BiomDiamSlope}$$

and rubber tree girth (*T GirthMax*) is calculated as:

$T\ GirthMax = \pi * T\_StemDiam$

Where π is 3.14

In this model, *T_GirthMax* influences the number of tapping days within a particular period (e.g. in a year), or *T Tapping Day*. The total number of days of tapping is influenced by whether the tree is tapped or ready to be tapped, the quality of tapping panel (*T_Panel_Quality*) and the number of tapping rest days (*T_RestDaysperTappingDay*).

The equations are written as:

if T_Tap_at_all? < 1 then 0 else (1 = tapping starts; 0 = no tapping)
if T_Panel_Quality[Tree] = 0 then 0 else
if T_GirthMax[Tree]<T_GirthMinforTapping_cm then 0 else
if mod(time,int(T_RestDaysperTappingDay+1)) = 1 then 1 else 0

where

T_Tap_at_all = whether trees are being tapped or not
T_Panel_Quality = tapping panel quality, especially whether the renewed bark is suitable or unsuitable for tapping
T_GirthMinforTapping = the minimum girth at which rubber trees can be tapped (>45cm)
T_RestDaysperTappingDay = depends on tapping systems used in the particular year (i.e. alternate days, once in three days etc).

6.3.1.2 Trees tapped latex stock (*T Tapped Latex*)

The amount of latex stock (*T Tapped Latex* stock) is influenced by the number of converters, namely *Cum Latex Y kg per ha, Cum Latex Y kg per tree, T TreeperHa and Areaper Tree*, where:

Cum Latex Y kg per ha= cumulative latex yield ha^{-1}

Cum Latex Y kg per tree = cumulative latex yield $tree^{-1}$ $tapping^{-1}$

T TreeperHa = total number of trees ha^{-1}

Areaper Tree = the area occupied by a single tree

The relationships of the above converters are expressed as follows;

*Cum Latex Y kg per ha = 10000*T_Tapped_Latex*

$$CumLatex\,Y\,kg\;per\,tree = \frac{Cum\,Latex\;\,Y\,kg\;per\,ha}{T\;Treesperha}$$

T TreeperHa = *Total number of trees per hectare*

$$Area\ per\ tree = \frac{10000\,m^2}{T\ Treeperha}$$

6.3.1.3 Total Tapping Days Stock (*T Tot TappingDays*)

This stock accumulates the total tapping days carried out during a particular simulation period. *T Tot TappingDays* influences the total production of latex per hectare per day of work (*T Latexkg per ha per DayofWork*).

The relationship is expressed as follows:

if T_TotTappingDays[Tree]>0 then

$$T\ Latex\,kg\ per\ ha\ per\ DayofWork = T\ Tapped\ Latex\ x\left[\frac{10000}{T\ TotTappingDays}\Big/ T\ TappDOW\right]$$

else 0

where

10000 = 10,000 m^2 in 1 hectare

T Tapped Latex = Amount of tree tapped latex produced

T TotTappingDays = Total tapping days

T TappDOW = Number of trees tapped in a particular working day

6.3.1.4 Expected Returns to Labour Stock (*ExpRetToLab*)

Calculating the wage rate based on a Net Present Value of the crop of zero leads to a proxy for 'returns to labour'. This converts the 'surplus' to a wage after accounting for purchased inputs and discounting for the cost of capital. Where returns to labour exceed the average daily wage rate, individuals with their own land will prefer this activity to off-farm activities. Returns to labour valued at private prices (private prices are the prices that households and firms actually face) can be viewed as a primary indicator of profitability for smallholders' production (Suseno *et al.*, 2004).

This stock is controlled by a *ChExpRettoLabour* flow which is governed by other converters, namely *T TapThisTrees, T ExpRetThresh, T MemExpY, T Recovery Exp and Today RettoLab.*

1. *ChExpRettoLabour* = change of expected returns to labour
2. *ExpRetto Lab* = expected returns to labour
3. *T ExpRetThresh* = threshold value of expected return to labour
4. *T MemExpY* = The extent to which a farmer remembers the previous yield (latex yield) of his crop, and uses this as a basis for his expectation of future yields: values from 0 - 1. 0 = he remembers fully, 1 = he forgets fully (see equation).
5. *T TapThisTrees* = option to tap the trees or not acts as a switch to run the simulation (tap = 1 not tap = 0)

The equations for this stock are written as:

if T_TappingDay?[Tree] = 0 then 0 else (? means tree is tapped or not)

if TodayRettoLab[Tree]> 0 then

(1-T_MemExpY)*(TodayRettoLab[Tree] - ExpRetToLab[Tree])

else (T_RecoveryExp)*T_ExpRetThresh

6.3.2 The Tapping Panel Sub-model

The tapping panel quality also plays an important role in rubber production. This is because a poor tapping panel reduces rubber yield, as tapping cannot be carried out properly. The overall features of the Tapping Sub-model are shown in Figure 6.7.

There are three stocks contained within this sub-module, namely *T PanelAlreadyInitiated, T Panel Available* and *T SecTimePanel Available.*

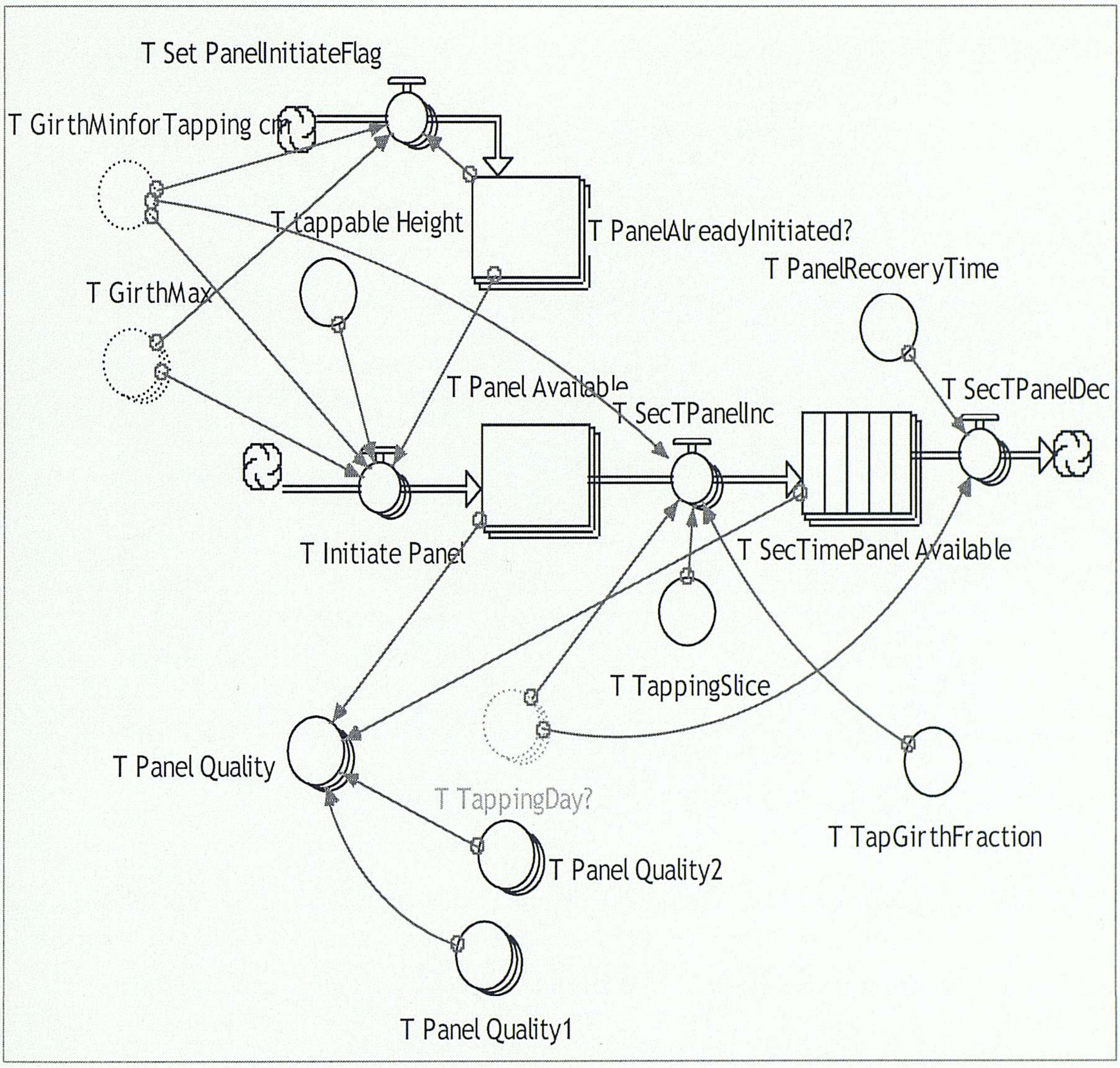


Figure 6.7: The Tapping Panel Sub-model

6.3.2.1 *T PanelAlreadyInitiated* Stock

T PanelAlreadyInitiated Stock is the initial stock of active tapping panels and is controlled by the *T SetPanelInitiateFlag* which acts as a switch to run this sub-module.

The equation for *T SetPanelInitiateFlag* is written as follows.

if *T_PanelAlreadyInitiated?[Tree]* = 0 and

T_GirthMax[Tree] > *T_GirthMinforTapping_*cm then 1 else 0.

6.322 *T Panel Available* Stock

The available tree tapping panel (*T Panel Available*) Stock is controlled by the tapping panel quality *T Panel Quality* converter. *T Panel Quality* is governed by two other converters, namely *T Panel Quality1* and *T Panel Quality2.* Their (stock and converters) relationship is expressed in the equations below:

If T_Panel_Available[Tree]>0 then T_Panel_Quality1[Tree]

else if T_SecTimePanel_Available[Tree]>0 then

T_Panel_Quality2[Tree]

else 0.

6.3.2.3 *T SecTimePanelAvailable* Stock

T PanelSecPanel Available Stock refers to the renewed panel of bark that had previously been tapped in the first round (virgin panel), as illustrated in Figure 6.8.

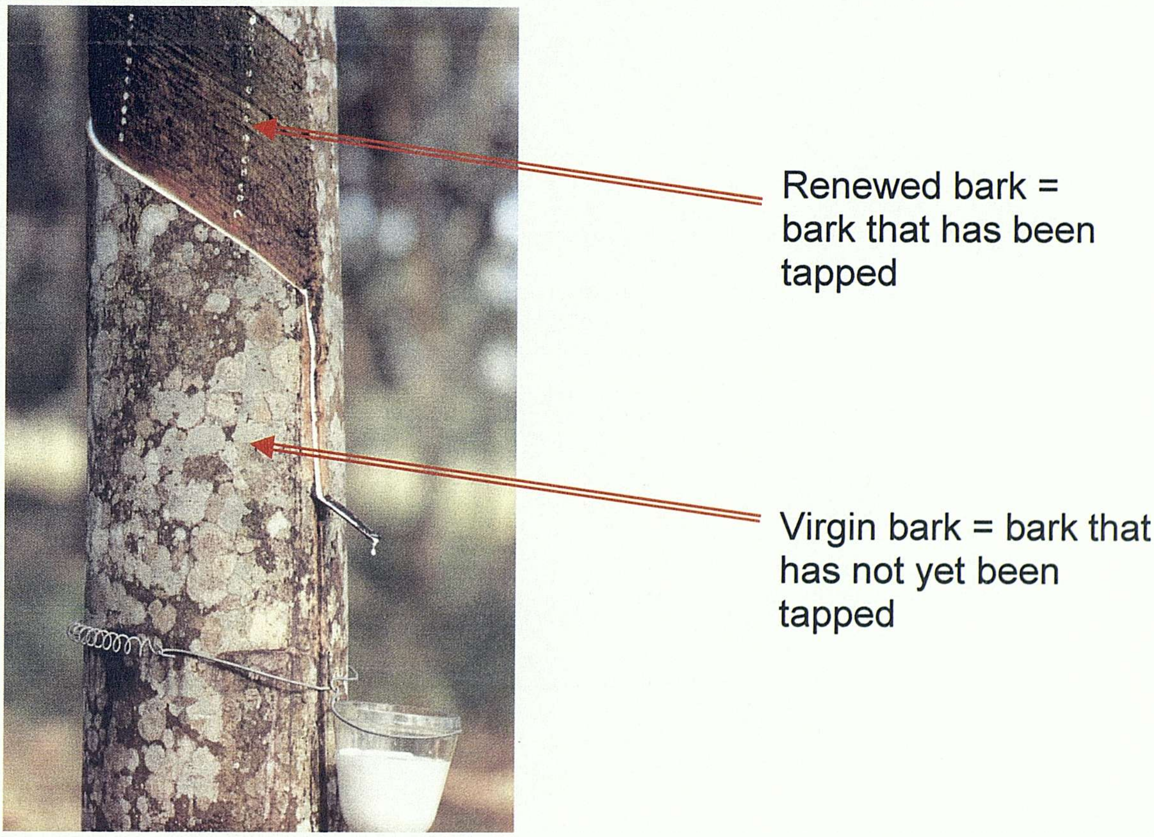


Figure 6.8: Illustration of virgin bark and renewed bark on the tapping panel

This stock is controlled by *T_SecTPanelInc* flow, which is ruled by other converters and expressed as:

T SecTimePanelAvailable = T_TappingDay*T_TappingSlice*
T_GirthMinforTapping_cm*T_TapGirthFraction

Where

T_TappingSlice = the thickness of the bark (in mm) that is removed during tapping

T_GirthMinforTapping_cm = the minimum girth of tapping (>45cm)

T_TapGirthFraction = refers to length of tapping cut (in this model, the cut is a half spiral, i.e. where only half of the circumference is tapped)

T SecTimePanelAvailable Stock is also controlled by *TSecTPanelDec* flow, which is governed by *T PanelRecoveryTime*

T PanelRecoveryTime = the time taken for the tapping panel to fully recover (renewed bark) in time for tapping a second time

6.4 Conclusions

Rubber trees differ from other trees as they produce rubber as a product during the rotation as well as rubber wood after a certain period of tapping (i.e. after 20 years). The tapping model deals with the essential parameters involved in tapping works such as tree stem diameter, total tapping days, tapped latex and expected returns to labour. It also includes other important factors that control the production of rubber such as the density of trees per unit area, tapping rest days and other factors. The user also can calculate the yield of rubber (i.e. kg $tapping^{-1}$) that can be expected during the simulation period.

The tapping panel model influences the tapping work by controlling the availability of tapping panels and the amount bark area left for tapping i.e. tapping panel quality. The lower the index given to the quality of the panel, the lower the yield of rubber. Once both the Tapping model and the Tapping Panel models have been linked to the economics sub-model of WaNuLCAS, users are in a position to calculate the economic returns (i.e. Net Present Value, Internal Rate of Returns etc.) from different options of intercropping in rubber agroforestry systems.

CHAPTER 7

MODEL VALIDATION

7.1 Introduction

Models need to be validated before they can be used to simulate a particular system and should not be used until they have been tested and shown to be fit for purpose. Since models have always been developed for a specific purpose, there is no perfect model that will fit any crop (Moorby, 1985). Ljung and Glad (1994) warn that we should always be sceptical of models and to be mindful of the following fallacies:

- "Don't fall in love with your model". Even when a considerable amount of work has been done to develop the model, we have to remember that the system is most important – not the model.

- “Forcing reality to fit the model is possible”. We must always be ready to develop and modify a model to include new facts and observations. Many important scientific discoveries have their basis in facts that conflict with accepted models.
- “Be aware of the model’s (lack of) accuracy”. It is necessary to keep in mind the degree of accuracy in the model and the level of approximation when the simulation results are interpreted. This is particularly important when the model contains estimated parameters.

7.2 Validation

Deciding if a certain model is effective is called model validation (Ljung and Glad, 1994). According to Rykiel (1996), validation means having a better understanding of a process that results in an explicit statement about the behaviour of a model. Validation is a demonstration that a model works within its domain of applicability and possesses a satisfactory range of accuracy consistent with the intended application of the model.

Validation demonstrates that a model meets some specified performance standard under specific conditions (e.g. a growth pattern under different planting densities, etc). It may also be useful to work with several models for the same system as a single model has a limited domain of validity (Rykiel, 1996). A test based on comparing simulated and observed information is generally used and included in validation process. Beside tests and other statistical measures, Loague and Green (1991) emphasise that graphical displays can be useful for showing trends and distribution patterns gained from the output of the simulation.

In this section, both the results of statistical analyses and graphical methods are used as part of the validation process. The statistical analyses are based on mathematical expressions in Table 4.1 (Chapter 4) while graphical displays are shown as one-to-one line graphs.

7.3 Aims and objectives

As WaNuLCAS has not been validated for all crops (van Noordwijk and Lusiana, 1999), the work in this chapter aims to validate the output of the improved WaNuLCAS model, especially for growth (girth) and rubber production in rubber tree systems ***based on default parameter values*** proposed (van Noordwijk *et al.*, 2004) as shown in Table 8. Simulations were made based on Class I soil classification to represent the largest soil class that is planted with rubber in Malaysia (Wong, 1978). Agroforestry zones are given fertiliser based on RRIM fertiliser recommendations (Nor, 1995). The model was run based on the Malaysia's average annual rainfall of 2500 mm.

The objectives of this work are to:

1. test whether the two sub-models described in Chapter 6 work well after they are linked into the current WaNuLCAS model;
2. assess whether the model is correctly transformed using the mathematical expressions/equations and that the programming logic is correct. This can be checked from the

output from the model (e.g. tapping should start after the trees reach >45 cm in girth, etc.)

3. evaluate the performance of the model to simulate the growth of rubber (girth, above ground biomass, leaf and twig and wood volume)
4. evaluate the performance of the model to predict the production of rubber;
5. compare the output of the simulation against the observed data using relevant statistical analyses.

7.4 Default parameter values for modelling.

The default values that are used in this modelling work are based on research data collected by the author and ICRAF (International Centre for Research in Agroforestry), South East Asia as reported by van Noordwijk *et al.* (2004). The output of the model from the default values was then compared with observed data in order to make adjustments to run the model in the future, as this developed model has not been validated before. Table 7.1 shows default parameters based on van Noordwijk and Lusiana (1999) and van Noordwijk *et al.* (2004).

Definitions of these terms are as follows:

Length of vegetative cycle = duration (days) of initial period before first flowering

Length of generative cycle = duration (days) of flowering to fruit ripeness cycle

Initial stage = tree growth stage at the start of simulation

Stage after pruning = growth stage to the point where the trees have been pruned

Maximum growth rate = maximum growth rate at full canopy closure

Fraction of growth reserve = fraction of tree carbohydrate reserves converted to biomass during growth stage

Leaf weight ratio = leaf to dry weight per unit shoot dry weight

Specific leaf area = tree leaf surface area per unit leaf dry weight

Water for dry matter production = amount of water needed per unit of dry matter

Light intensity affecting tree growth = relative light intensity at which shading starts to affect tree growth

Extinction light coefficient = the efficiency of tree foliage in absorbing light

Table 7.1: Default parameter values for modelling

	Parameters	Units	Hevea
Growth Stage	Length of vegetative cycle	days	1825
	Length of generative cycle	days	150
	Earliest day to flower in a year	Julian day	60
	Latest day to flower in a year	Julian day	84
	Initial stage	[]	0.25
	Stage after pruning	[]	0.2
Growth	Max. growth rate	kg m^{-2}	0.0067
	Fraction of growth reserve	[]	0.05
	Leaf weight ratio	[]	0.3704
	Specific leaf area	$m^2 kg^{-1}$	11.3
	Water for dry matter production	l kg^{-1}	300
Canopy	Max. canopy height above bare stem	m	7.4
	Ratio between canopy radius and height	[]	0.475
	Max. canopy radius	m	3.515
	Maximum leaf area index	[]	5
	Ratio leaf area index min. and max.	[]	0.5
Light capture	Light intensity affecting tree growth	[]	0.7
	Extinction light coefficient	[]	0.7
Rain interception	Rainfall water stored at leaf surface	mm	1
Tree Water	Plant potential for max. transpiration	cm	-5000
	Plant potential for min. transpiration	cm	-15000
Allometric Branching (Above Ground)	Intercept for total biomass equation	kg	0.0660
	Power for total biomass equation	cm^{-1}	2.6200
	Intercept for branch biomass equation	kg	0.0412
	Power for branch biomass equation	cm^{-1}	2.9825
	Intercept for Leaf&twig biomass equation	kg	0.0244
	Power for Leaf&twig biomass equation	cm^{-1}	2.62
	Intercept for litterfall equation	kg	0.0014
	Power for litterfall equation	cm^{-1}	3.0039
	Wood density	kg m^{-3}	600

7.5 Results and validation

The model was run to represent a 20 year rotation of the economic life of rubber, based on a planting density of 400 trees ha^{-1}, on soil types similar to the experimental sites used to generate the original data.

The results of the simulation are shown below.

7.5.1 Growth (girth) increments

Yield of rubber is positively correlated with girth (Paardekooper, 1989) but the trees must reach a certain minimum girth (>45cm) before they are ready for tapping. Prolongation of the immaturity period (the period before tapping starts) will therefore be uneconomic as there are no returns from the rubber plantation during this time. Figure 7.1 compares the observed and simulated data for rubber growth using one-to-one line graph; the statistical results for the simulation are given in Table 7.3.

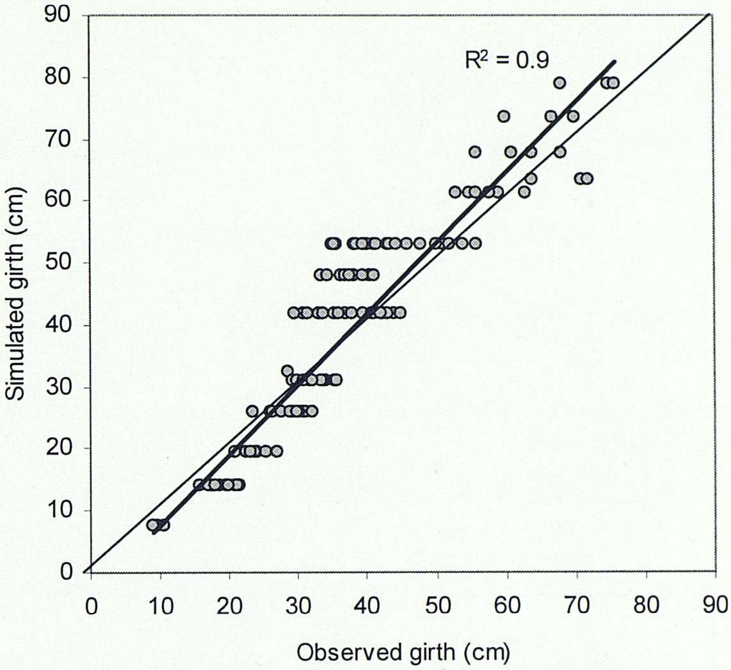


Figure 7.1: Observed versus simulated results for tree growth (girth) for range of rubber clones from Malaysia and Indonesia

(Source: IPGM, 1995; IPGM, 1996; IPGM, 1997; CMU, 1998; CMU, 1999; CMU 2000; CMU, 2001; BPM, 2002; RRIM, 1998 and MRB, 2003a).

(Clones: RRIM 600, PB 260, PR255, PR261, PM10, RRIM 901)

The results demonstrate that the model predicts the girth of rubber trees with high correlation (R^2 = 0.90), agreeing closely with the results from the *Hevea Version 1.0* static growth *(GR)* sub model (R^2 = 0.92). The 1:1 graph (Figure 7.1) tends to underestimate growth during the immaturity period, but overestimates growth after tapping starts.

Apart from reasons given in Chapter 5 (e.g. type of planting material, weather conditions, etc.), another possible reason could be genetic differences from the default values between rubber clones that affect their early development. Based on the clone characteristics reported in the RRIM Planting Recommendations (RRIM, 1980; 1995; 1998; MRB 2003a), most of the rubber clones (i.e. 'default' clones) involved here (including the First Class clones e.g. GT1, RRIM600, PR255, PR261, PB217, RRIM901, PB260, etc.), have different levels of vigour due to their genetic characteristics, and are ranked as above average (3 – 4 out of 5, the index values being 5 = very good, 4 = good, 3 = average, 2 = below average and 1 = poor). This also could due to the stocks used for the grafted scions.

Figure 7.1 shows overestimation of growth after tapping commences, as it would be expected that girth increments would be slower in tapped trees. Different clones also show variable responses to tapping, especially if their bark is shaved during tapping, and appears to be under strong genetic control. This phenomenon is inherit also from their genetic characteristics (RRIM, 1980; 1995; 1998; MRB 2003a).

7.5.2 Rubber yields

The accumulated yields of rubber over 7300 days (20 years) of simulation are shown in Figure 7.2. Yields are expressed in kg and are based on a standard density of 400 trees ha^{-1}. Simulation was based on normal tapping techniques, using the excision method, tapped with half spiral (S/2) on alternate days (d/2).

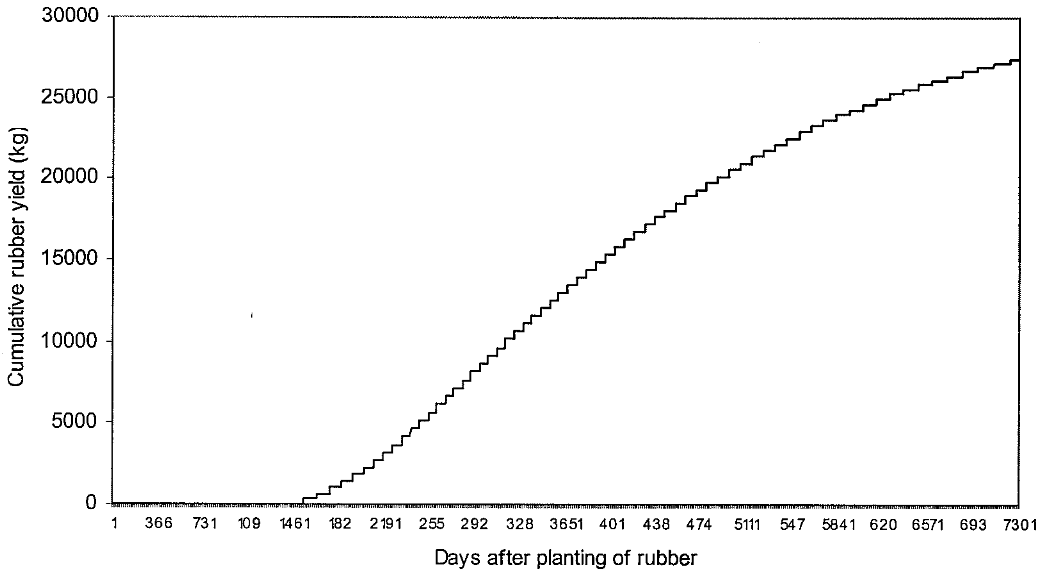


Figure 7.2: Simulated accumulated yields of rubber (kg) during a 20- year growth cycle, planted at 400 trees ha^{-1}

Figure 38 shows that the production of rubber starts between four and four and a half years after planting (1463 days), agreeing with Paardekooper (1989), who also reported that well-grown rubber transplants reach 45 cm girth at this age.

Cumulative production of rubber increases exponentially over time, showing a close correlation with the data from Malaysia and Indonesia field experiments (Figure 7.3).The one-to-one line graph for observed and simulated accumulated yield (kg ha^{-1}) gave a high correlation coefficient (R^2) of 0.97, suggesting that the model was competent to predict the yield of rubber clones including GT1, RRIM600, PB260, PM10, PR261, PR255 and PB217. The statistical results for accumulated yield are shown in Table 7.3.

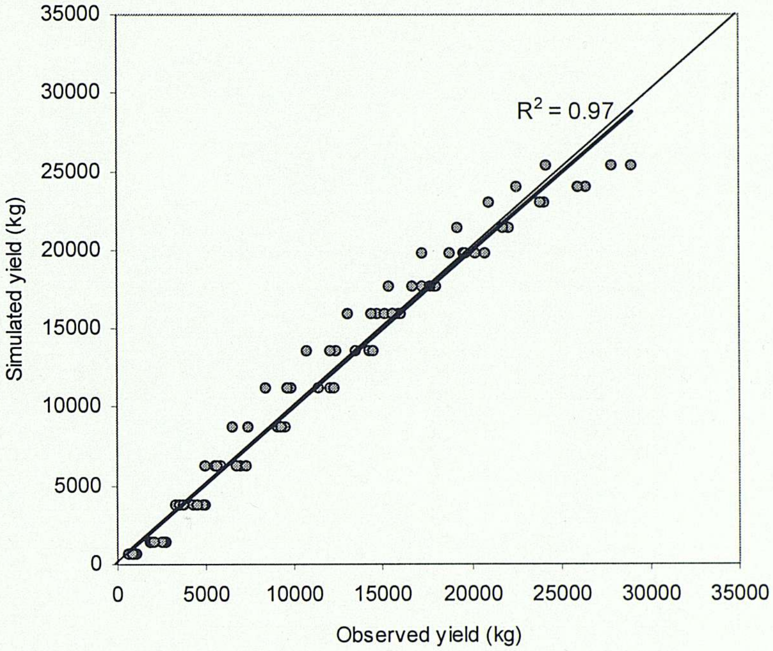


Figure 7.3: Observed versus simulated accumulated rubber yields per hectare over a rotation of 20 years.

(Source: IPGM, 1995; IPGM, 1996; IPGM, 1997; CMU, 1998; CMU, 1999; CMU 2000; CMU, 2001; BPM, 2002; RRIM, 1998 and MRB, 2003a). (Clones: RRIM 600, PB 260, PR255, PR261, PM10, RRIM 901)

7.5.3 Above-ground biomass (T BiomAG)

The observed and simulated results for above ground biomass production (T BiomAG = stem and branches) are shown in Figure 7.4. Although there is a good relationship (R^2=0.87) between observed and simulated values, there is a overall tendency of the model to underestimate the above ground biomass, probably due to inability of the model to adequately describe the morphology and branching characteristics in observed trees since the model uses default values that rely on a fixed ratio between canopy radius and height (a/b) and the maximum canopy radius (c) to describe the shape of individual trees (Table 7.1 and Figure 7.5).

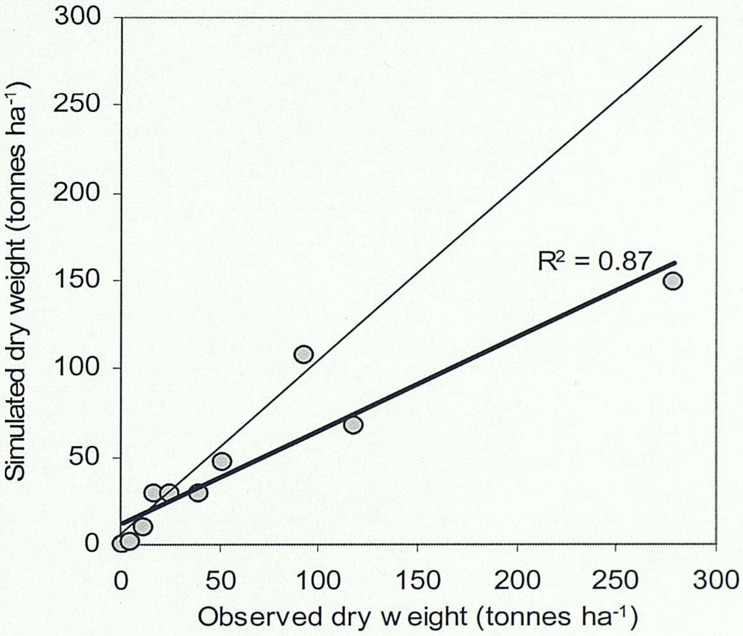


Figure 7.4: The observed and simulated above-ground (AG) biomass (Observed data are from GT1, RRIM501, PB86, LCB1320 and Tjir1 clones) (Watson, 1989a)

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Figure 7.6 illustrates some shapes a few examples of rubber tree out of hundreds shapes found in rubber plantations. The statistical results for AG Biomass are shown in Table 7.3.

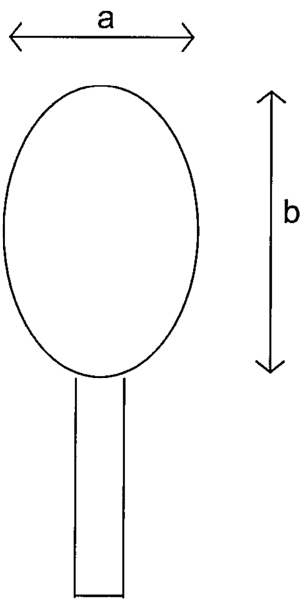
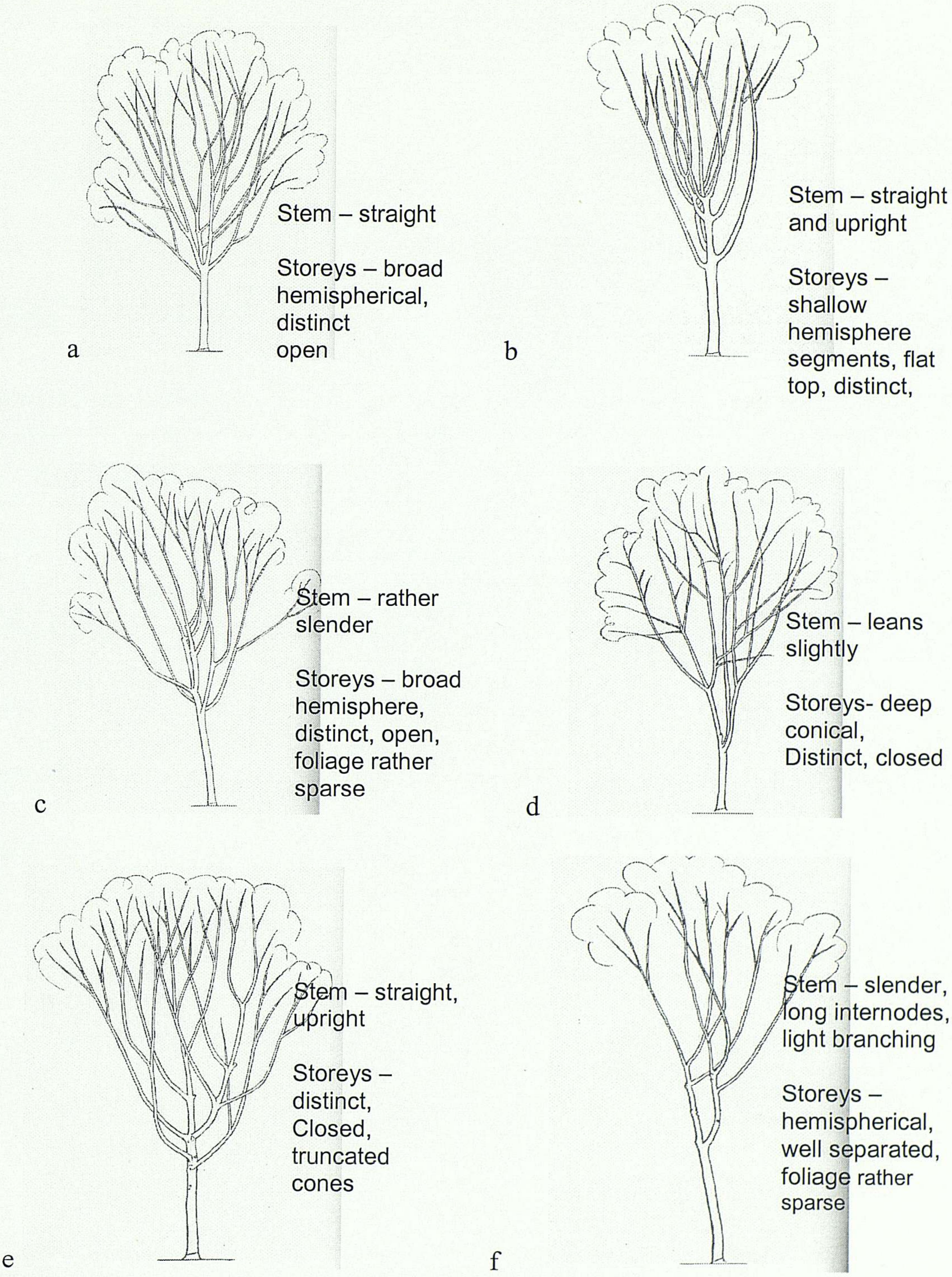


Figure 7.5: General assumption of tree form used in the simulation model



a

Stem – straight

Storeys – broad hemispherical, distinct open

b

Stem – straight and upright

Storeys – shallow hemisphere segments, flat top, distinct,

c

Stem – rather slender

Storeys – broad hemisphere, distinct, open, foliage rather sparse

d

Stem – leans slightly

Storeys- deep conical, Distinct, closed

e

Stem – straight, upright

Storeys – distinct, Closed, truncated cones

f

Stem – slender, long internodes, light branching

Storeys – hemispherical, well separated, foliage rather sparse

Figure 7.6: Example of tree shapes in rubber plantations

(Source: Ford, 1940; Mann and Sharp, 1933; RRIM, 1997)

7.5.4 Leaf and twig biomass (T Lf twig)

The observed and simulated results for leaf and twig biomass production are shown in Figure 7.7 (statistical analysis results in Table 7.3). There is a correlation (R^2) of 0.60 between observed and simulated values in this model, but a tendency to overestimate production in older trees.

The reason for this overestimation is probably the difficulty of the model to describe the branching patterns of trees correctly, as different clones have different branching patterns, influencing the proportion of leaves and twigs.

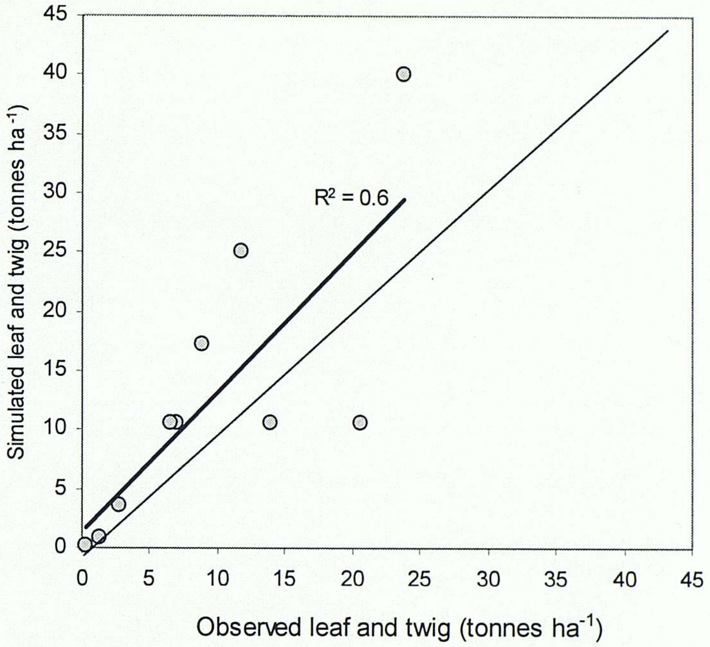


Figure 7.7: The observed vs simulated results for leaf & twig of rubber tree (Clones: RRIM501, PB 86, GT1, LCB 1320 and Tjir 1)(Watson, 1989a)

7.5.5 Wood production (*T Wood*)

Since 1998, the export of rubber wood or '*Heveawood*' products has surpassed that of raw rubber (MRB, 2003b). In 2002, the export of wood products, 70% of which was furniture, amounted to RM4.86 billion (US$1.3 billion) while that of raw rubber was only RM2.35 billion (US$0.62 billion). These figures indicate that the rubber wood industry has become an important role to the Malaysian rubber industry.

As the Malaysian government is taking various steps to encourage investment in the upstream and downstream sectors of the rubber industry (e.g. by promoting the best clones for wood production, rubber wood properties, etc.), it is expected that the rubber wood industry will expand in the future.

The following simulation work attempts to predict the amount of rubber wood produced in plantations of 400 trees ha^{-1}. The results are than compared with the observed data from the latest clones (known as latex timber clones - LTC) which were introduced by the Malaysian Rubber Board in it latest planting recommendations to the Malaysian rubber industry. LTC are clones produced by breeding latex clones (LC) with clones with high quantity of wood. As a result, they are able to produce high latex yield as well as high rubber wood volume (MRB, 2003b). Using the default values assumed in Table 7.1, the model predicts wood volumes of rubber trees poorly, ranging from -45.8% to +56.3% from the 19 clones listed below (Table 7.2) of observed values, depending on the clones.

Table 7.2: The results of difference between observed and simulated results of wood weight

	Clone	Observed (tonnes ha^{-1})	Simulated (tonnes ha^{-1})	% difference
1	RRIM2014	532	232.3	56.3
2	RRIM2008	528	232.3	56.0
3	RRIM2015	520	232.3	55.3
4	PB260	516	232.3	55.0
5	RRIM2016	512	232.3	54.6
6	RRIM2024	504	232.3	53.9
7	RRIM911	460	232.3	49.5
8	RRIM2026	444	232.3	47.7
9	RRIM2027	520	274.7	47.2
10	RRIM2020	400	232.3	41.9
11	RRIM2001	492	297.2	39.6
12	RRIM2002	440	297.2	32.5
13	RRIM2023	324	232.3	28.3
14	RRIM921	504	396.6	21.3
15	RRIM929	480	378.1	21.2
16	RRIM908	408	396.6	2.8
17	RRIM936	296	358.7	-21.2
18	RRIM928	296	378.1	-27.7
19	RRIM2009	272	396.6	-45.8
	Average	444.6	287.0	34.9

Note: The observed and simulated tree wood (tonnes ha^{-1}) for different clones of 14 year-old rubber trees (except RRIM2027-16 years; RRIM2001,RRIM2002-17years; RRIM936, PB260 – 20 years; RRIM928, RRIM929 - 21 years; RRIM2001, RRIM908, RRIM911 and RRIM921 - 22 years old)

(Observed data source: MRB, 2003b)

Based on the results in Table 7.2 (statistical results in Table 7.3), the model's ability to predict the wood volume is shown below.

Difference (%)	**Clones (RRIM)**
< 10	908,936,928,2009
10 – 20	-
20 – 30	929,921,2023
30 – 40	2001,2002
> 40	2014,2008,2015,2027,2016,2024, 911,2026,2020 and PB260

These large differences in wood volume between clones can be explained by their different morphologies (i.e. poor, average or vigorous trunk boles, and light, average or heavy branching patterns).

Different wood densities between clones could also result in the large differences in wood volume.

It was reported that the density of rubber wood ranged from 560 to 650 kg m^3 (MTIB, 1982), while Soewarsono (1990) reported that the density of rubber wood ranged from 550 to 700 kg m^3 depending on ages and clones of rubber.

7.6 Discussions and conclusions

Model validation statistics for girth, yield, above ground biomass, leaf and twig and wood production are given in Table 7.3. The results of simulation show the model runs smoothly, producing satisfactory graph and table outputs. The outputs show a logical increment curves for growth and yield against time for each parameter simulated. This indicates that the inter-relationships between the building blocks (stock, converter, flow and connectors) work well. The model was able to read the 'linked' parameters for trees and crops from Microsoft EXCEL database after changes of values (i.e. changes in values in Microsoft EXCEL can be read by STELLA) have been made.

Table 7.3: The statistical results of model efficiency relating to girth, yield, above ground biomass, leaf and twig and wood production

Parameters	Girth	Yield	Above ground biomass	Leaf & twig	Wood production
n	157	82	10	10	19
ME	13.6 (cm)	3759 (kg ha^{-1})	130.5 (tonnes ha^{-1})	9.66 (tonnes ha^{-1})	299.7 (tonnes ha^{-1})
RMSE	17.9	11.32	69.95	83.40	46.58
CD	0.73	1.01	2.69	0.40	4.07
EF	0.83	0.97	0.70	-0.15	-4.90
CRM	-0.04	0.00	0.22	-0.33	0.35
R^2	0.90	0.97	0.87	0.60	35.4*

* average difference between simulated and observed values
ME - Maximum Error (single greatest error between observed and predicted value)
RMSE - Root Mean Square Error
CD - Coefficient of Determination (expresses the ratio of scatter values of predicted and the scatter values of observed points)
EF - Modelling Efficiency (negative values indicate that the mean of observed values is a better estimate than the simulation)
CRM - Coefficient of Residual Mass (positive values indicate a tendency to underestimate the observed, negative ones indicate a tendency to overestimate
R^2 - correlation coefficient
n – the number of observations or data sets

Although one would hope to have values of ME, RMSE, CD, EF and CRM as close as possible to 0.0, 0.0, 1.0, 1.0 and 0.0, respectively to achieve the 'perfect' model (Loague and Green,1991), the developed model here is capable of simulating the girth, yield and above ground biomass with the modelling efficiency (EF) of 0.83, 0.97 and 0.70 respectively.

The model also produced a good fit with the observed data, giving high R^2 values for girth (0.90), yield (0.98), above ground biomass (0.87) and leaf and twig biomass (0.60). However, it seriously overestimates the result of leaf and twig and underestimates wood production with an EF value of -1.5 and -4.9 respectively, indicating that the mean observed values give a better result than simulated values. The reasons of overestimation of leaf and twig and underestimation of wood could due to the many default values (Table 7.1) of canopy and allometric branching that may direct dry matter production towards leaf and twig than wood. Extinction coefficient of 0.70 is also for dense tree canopy.

In reality there is no clear method of 'designing' trees in modelling (van Noordwijk and Mulia, 2002) can be made unless we have sufficient background data with all empirical equations for all clones. The results show that the model may not be suitable for prediction wood production.

To improve the efficiency of the model, it is suggest that the default values for all parameters should be based on a particular clone to be simulated or one set of parameters for one clone. Although it is difficult and time consuming to carry out for all clones, the work could start with two or three recommended clones for rubber plantations.

MODEL APPLICATION

8.1 Introduction

The growth, production and viability of the rubber agroforestry system varies according to its environment and the superimposed management system. The results from various management manipulations (i.e. planting densities, intercropping, etc.) can be seen from the output of the model. In this chapter, the improved WaNuLCAS model was used not only to simulate the growth and production of rubber, but also to carry out an economic analysis in order to forecast outputs such as NPV (net present value), IRR (internal rate of return), BCR (benefit-cost ratio) and AE (annual equivalent) in different rubber agroforestry options.

The objectives of this work are to;

1. predict the effect of planting density on the growth (girth) of rubber and rubber production;
2. simulate the effect of canopy shading on agricultural crops grown as an intercrop with rubber;

3. carry out economic analyses on different rubber agroforestry options.

The parameters used for this modelling work are shown in Table 7.1 (Chapter 7, section 7.4) of the previous chapter.

8.2 Definitions of economic parameters NPV, IRR, BCR and AE

The net present value (NPV)

The net present value (NPV) is simply the present value (PV) of its net benefit stream (Perkins, 1996). This is obtained by discounting the stream of net benefit produced by the project in future (in this case rubber agroforestry options over a lifetime of 20 years), back to its value at the chosen base period, usually the present. The NPV formula is:

$$NPV = \sum_{t=0}^{n} \frac{(B_t - C_t)}{(1+r)^t}$$

where

B_t = *project benefits in period t*

C_t = *project costs in period t*

r = *the appropriate financial or economic discount rate*

n = *the number of years for which the project will operate*

The project is viable when the NPV ≥ 0

The internal rate of return (IRR)

Another criterion commonly used to assess the viability of a particular project is the internal rate of return (IRR). This is the discount rate that, if used to discount a project's costs and benefits, will just make the project's net present value equal to zero.

Thus, the internal rate of return is the discount rate, *r** at which:

$$NPV = \sum_{t=0}^{n} \frac{(B_t - C_t)}{(1+r^*)^t} = 0$$

Since the internal rate of return is the discount rate internal to the project, its calculation does not depend on prior selection of a discount rate. A project's internal rate of return can therefore be thought of as the discount rate at which it would be just worthwhile doing the project. For a financial analysis, it would be the maximum interest rate that the project could afford to pay on its funds and still recover all its investment and operating cost.

The benefit cost ratio (BCR)

Another criterion that can be used to evaluate the viability of rubber agroforestry options is the benefit to cost ratio (BCR). The BCR is defined as the ratio of the sum of the project's discounted benefit to the sum of its discounted investment and operating costs.

This can be expressed mathematically as:

$$BCR = \frac{\sum_{t=0}^{n} \frac{B_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}}$$

A project should be accepted if its BCR is greater than or equal to 1, that is, if its discounted benefits exceed its discounted costs (Perkins, 1996).

The annual equivalent (AE) method

The annual equivalent method is a means of comparing two or more options by calculating how much each would cost using a series of equal annual payments.

The annual equivalent method is expressed as:

$$AE = \frac{\text{Net Present Value of the Cash Flow}}{\text{The annuity factor to evaluate the Present Value}}$$

The annuity factor is the sum of all discount factors for the duration of the project. The best of the AE options would be the logical one to invest in.

The work described below attempts to carry economic analyses on three rubber production growing systems;

- rubber production planted as monocrop at different tree planting densities, using a 20 year rotation
- rubber production followed by wood extraction and utilisation after 20 years under different planting densities
- rubber production with an intercrop (maize), followed by wood extraction.

8.3 The effect of planting density on growth (girth) of rubber

The model was run to represent 20 years (7,300 days) from the day of planting, i.e. one cycle of the normal economic life of rubber trees before felling and replanting. The model is run with the density of 400, 600 and 800 trees ha^{-1}. These planting densities were selected on the basis of a survey of smallholdings carried out in Malaysia by Webster (1989), who reported that independent smallholdings normally planted a minimum of 400 trees ha^{-1} in order to achieve an appropriate girthing rate for tapping (i.e. >45 cm) after four years of planting. Sepian (1980) suggested that the initial planting density should be at least 600 trees ha^{-1} for smallholdings in order to reduce the risk of casualties due to root diseases, wind damage and other causes. Finally, the higher density of 800 trees ha^{-1} is based on proposals by the Malaysian Rubber Board (MRB, 2003) as an option to increase the quantity of rubber wood for rubber-wood based industries in Malaysia.

The simulation results from the improved WaNuLCAS model (based on default values in Table 7.1 (Chapter 7, section 7.4) for the three different planting densities (400, 600, 800 trees ha $^{-1}$) is shown below (Figure 8.1). These show a negative relationship between tree density and tree girth, with the highest girthing rates gained from low densities of 400 trees ha^{-1} and the lowest girthing rates from the highest densities (800 trees ha^{-1}). Lower planting densities therefore appear to be more beneficial, due to less competition for resources (i.e. nutrients, light, water, space) between trees compared with the higher densities of rubber trees, thus allowing for earlier tapping from the larger individuals.

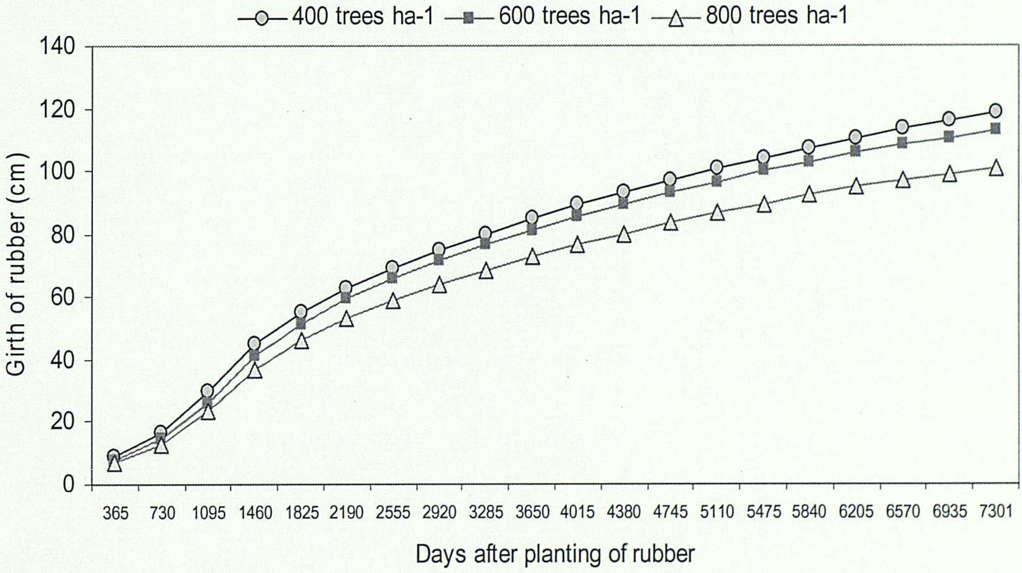


Figure 8.1: The effect of planting density (trees ha-1) on the girth (cm) of rubber over a 20-year rotation

The model predicts rubber trees can be tapped (>45cm girth) after at about 4, 5 and 6 years after planting at densities of 400, 600 and 800 trees ha^{-1}, respectively. These results agree with Ng *et al.* (1987), who reported that rubber trees (clones RRIM 701 and RRIM 600) planted at lower densities (211 trees ha^{-1}; 297 trees ha^{-1} and 399 trees ha^{-1}) took only four years to reach 98% to 100% tappability (the condition where the trees reached the minimum girth for tapping (> 45 cm) measured at 160 cm above ground.

8.4 The effect of planting density on rubber production

The simulated results for cumulative yields over a 20 year rotation are shown in Figure 8.2 below.

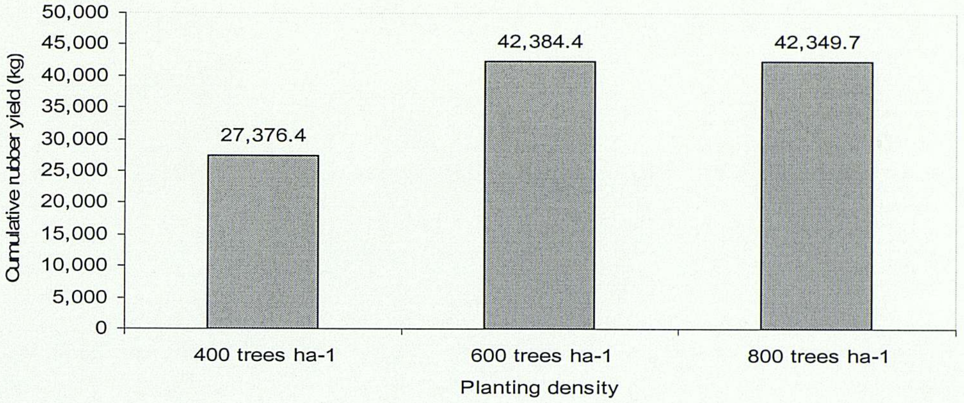


Figure 8.2: Simulated results for cumulative rubber yield (kg) over a 20-year rotation for different tree planting densities (trees ha^{-1})

The output indicates that the highest cumulative rubber yield (42,384.4 kg or 42.38 tonnes) is gained from 600 trees ha^{-1}, a marginal difference between 800 trees ha^{-1} (42,349.7 kg or 42.35 tonnes). The lowest cumulative rubber yield is gained from 400 trees ha^{-1} (27,376.4 kg or 27.38 tonnes). The results indicate that 600 trees ha^{-1} could represent the optimum planting density as it produces the highest cumulative yield. These results agree with Webster (1989) who recommended appropriate planting densities of 500 – 600 trees ha^{-1}.

8.5 Economic aspects of rubber production planted as a monocrop at different planting densities

This option considers the extent to which extraction of rubber from plantations at different densities (400, 600, 800 trees ha^{-1}) influences returns on investment and its viability to rubber smallholders. The assumptions here are as follows:

- numbers of trees are constant up to the period of felling;
- the alternate daily tapping system is used (normal tapping system);
- the price of rubber is based on SMR20 (the Standard Malaysian Rubber grade commonly produced by smallholders), assuming a price range for sensitivity analysis purposes from RM 2.10 kg^{-1} (US\$0.58 kg^{-1}) to RM4.70 kg^{-1} (US\$1.30 kg^{-1}). The lowest price (US\$2.10) is based on the lowest SMR20 price recorded (2001) and RM4.70 on the current SMR20 price (MRB, 2005).
- discounting factors of 8%, 10% and 12% are assumed as an approximation of capital borrowing in Malaysia (MRB, 2003b).

The sensitivity analyses are based on the simulated yearly yield of rubber under different planting densities (Table 8.1). The effects on economic returns using sensitivity analyses for NPV, IRR, BCR and AE for different planting densities and different rubber prices are shown in Table 8.2.

Details of planting and tapping costs for smallholders (RM ha^{-1}) are shown in Appendix 2, 3 and 4 and are based on Abdullah and Ismail (1991), Ahmad and Abdullah (1994), Teh (2004) and Pang (2005). Planting (i.e. land clearing, ploughing, planting etc) and maintenance costs for planting rubber vary from the initial time of planting up to tapping, with an average of about RM5400 - 7900 (US$1420 - 2080) .

Table 8.1: Simulated annual yields of rubber over 20-year rotation period

Age of rubber (year)	Yield of rubber (kg ha^{-1})		
	Density (trees ha^{-1})		
	400	600	800
1	-	-	-
2	-	-	-
3	-	-	-
4	-	-	-
5	294*	-	-
6	1113	505*	-
7	2284	3367	684*
8	2468	4745	5610
9	2495	4122	4775
10	2466	4053	4085
11	2445	3972	4006
12	2285	3871	3909
13	1793	3221	3260
14	2142	3110	3162
15	1617	2486	2544
16	1516	2373	2437
17	1058	1770	2301
18	1295	1694	1678
19	1102	1574	1467
20	1003	1520	1286
Total	27,376	43,384	42,349

*Note: * Tapping starts*

Table 8.2: The results of the sensitivity analyses for NPV(RM), IRR, BCR and AE at different discount rates, planting densities and rubber prices for 20-year rotation period

	SMR20 Price (RM)	Discount at 8%			Discount at 10%			Discount at 12%		
		Planting density (trees ha^{-1})			Planting density (trees ha^{-1})			Planting density (trees ha^{-1})		
		400	600	800	400	600	800	400	600	800
NPV	4.70	31,975	50,556	45,874	25,578	40,502	36,182	20,534	32,579	28,584
IRR		0.405	0.434	0.361	0.405	0.434	0.361	0.405	0.434	0.361
BCR		1.50	1.60	1.42	1.41	1.50	1.31	1.32	1.40	1.19
AE		3,015	4,962	4,503	2,731	4,526	4,043	2,454	4,091	3,590
NPV	3.80	21,773	34,951	31,089	17,208	27,754	24192	13,613	22,088	18792
IRR		0.342	0.373	0.309	0.342	0.373	0.309	0.342	0.373	0.309
BCR		1.02	1.10	0.96	0.95	1.02	0.87	0.87	0.94	0.77
AE		2,053.4	3,430.6	3,052	1,837	3,101	2,703	1,627	2,774	2,360
NPV	2.10	2,503	5,474.0	3,162.6	1,398.0	3,674.9	1,544.1	539.5	2,272.5	294.4
IRR		0.136	0.168	0.126	0.136	0.168	0.126	0.136	0.168	0.126
BCR		0.12	0.16	0.08	0.08	0.12	0.03	0.03	0.07	0.02
AE		236.1	537.3	310.4	149.3	410.6	172.5	64.5	285.4	37.0

Note: i. The value of NPV and AE is in Malaysian Ringgit (RM): 1US$ = RM3.7 (Jan 2006)
ii. The value for IRR is expressed as a fraction. For example, 0.304 is equivalent to 30.4 %
iii. Returns are prices per hectare

The results from Table 8.2 show that rubber planted at 600 trees ha^{-1} gives the highest returns compared with densities of 400 and 800 trees ha^{-1}. For a SMR20 (Standard Malaysian Rubber Grade) product priced at RM4.70 (US$1.30), this option is viable with an NPV of RM50,556, an IRR of 43.4%, BCR of 1.60 and AE value of RM4,962 at a discount rate of 8%.

This density is not viable at all discount rates and SMR20 price of RM2.10. This density also not viable at SMR20 price of RM3.80 at discount rate of 12% as BCR is 0.94.

For rubber planted at 800 trees ha^{-1}, the enterprise is viable at the highest price of SMR20 (RM4.70 kg^{-1}) at all discount rates. However this option is not viable when the price of rubber falls to RM3.80 kg^{-1} as the BCR is <1, irrespective of discount rate. The option of planting at 400 trees ha^{-1} is also unviable at RM3.80 and below, with the BCR <1 except at a discount rate of 8%.

In conclusion, rubber trees planted at 600 trees ha^{-1} delivered the highest economic returns compared with 400 trees ha^{-1} and 800 trees ha^{-1}. Further increases above this optimum will result in lower viability of the rubber plantation due to the delay in tapping, with consequently less rubber extracted. As a result, it influences the returns as it reduces the NPV, IRR, BCR as well as the AE. All three planting densities options are viable at a favourable price of RM4.70 kg^{-1} for all discount rates, but at the low price of RM2.10 kg^{-1}, no option is viable.

8.6 Rubber planted as monocrop, followed by wood extraction

After a 20-year period of rubber extraction, smallholders are advised to sell their rubber wood as a by-product. This option is part of an approach to improve the productivity of smallholders, since it is common practice to clear and burn the tree crop after felling and before replanting is commenced. In this case, densities of 400, 600 and 800 trees ha^{-1} are again considered for the purposes of economic analysis.

From the output of the model, wood production of 341.4, 464.8 and 468.7 tonnes ha^{-1} respectively are calculated for these planting densities (Figure 8.3). There is only a marginal difference of 3.9 tonnes ha^{-1} between densities 600 and 800 trees ha^{-1}. The difference between the lowest (400 trees ha^{-1}) and the highest (800 trees ha^{-1}) density is more substantial at 127.3 tonnes or about 27 %.

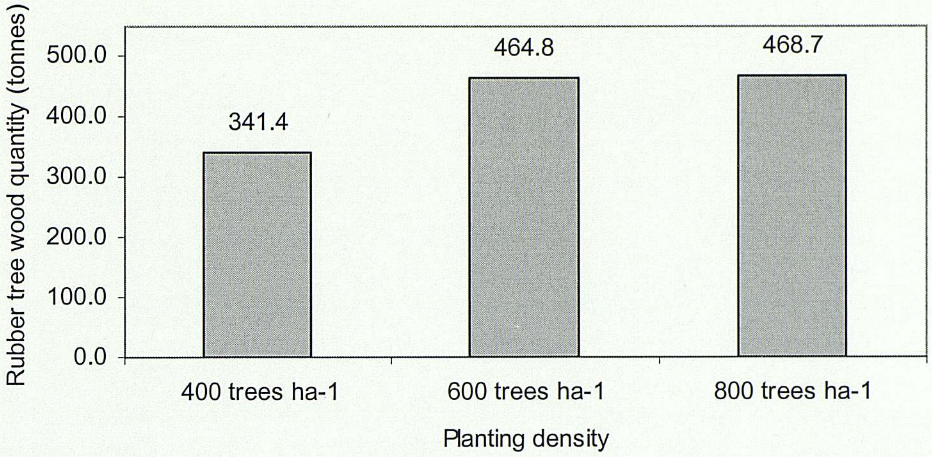


Figure 8.3: Simulation of rubber tree wood production (tonnes) for different planting densities after a 20-year rotation

Table 8.3 shows the results of sensitivity analyses based on the SMR price range used above (RM2.10, RM3.80 and RM4.70) and current rubber wood log price (RM105 tonne^{-1}) at different discount rates (8%, 10% and 12%).

Table 8.3: The results of the sensitivity analyses for NPV (RM), IRR, BCR and AE at different discount rates, different planting densities and at the current rubber wood log price

		Discount at 8%			Discount at 10%			Discount at 12%		
	SMR20 Price (RM)	Planting density (trees ha^{-1})			Planting density (trees ha^{-1})			Planting density (trees ha^{-1})		
		400	600	800	400	600	800	400	600	800
NPV	4.70	37,102	57,536	52,913	29,130	45,339	41,058	23011	35,952	31,985
IRR		0.406	0.436	0.364	0.406	0.436	0.364	0.406	0.436	0.364
BCR		1.55	1.64	1.48	1.46	1.54	1.37	1.37	1.44	1.25
AE		3,499	5,647	5,194	3,111	5,066	4,588	2,751	4,515	4,017
NPV	3.80	26,900	41,931	38,128	20,760	32,591	29,069	16,090	25,461	22,193
IRR		0.345	0.376	0.313	0.345	0.376	0.313	0.345	0.376	0.313
BCR		1.13	1.19	1.06	1.04	1.10	0.96	0.95	1.01	0.86
AE		2,537	4,116	3,742	2,217	3,642	3,248	1923	3,198	2,787
NPV	2.10	7,630	12,454	10,,202	4,950	8,511	6,421	3,017	5,645	3,696
IRR		0.174	0.198	0.164	0.174	0.198	0.164	0.174	0.198	0.164
BCR		0.32	0.34	0.27	0.25	0.27	0.20	0.18	0.20	0.12
AE		719.6	1,222	1,001	528.6	951.1	717.5	360.6	709.0	464.1

** Rubber wood log price is based on statistics from the MRB (2005)*

These results indicate that the option of selling rubber wood after a 20-year rotation slightly improves the viability of rubber plantations. The maximum revenue is gained from densities of 600 trees ha^{-1} for a combined price of SMR20 at RM4.70 and RM105.00 tonne^{-1} for rubber wood logs. At a discount rate of 8%, this gives an NPV of RM57,536, an IRR of 43.6%, and the BCR of 1.64 resulting in the AE of RM5,647.

At the rubber price (SMR20 = RM3.80 kg^{-1}) and rubber wood log price of RM105 tonne^{-1}, the options of planting rubber at densities of 600 ha^{-1} are still viable up to discount rates of 12% as they produce an IRR value above the discount rates (37.6%) as well as BCRs of >1.

On the other hand, if the SMR20 price falls to RM2.10 kg^{-1}, no option is viable at any discount rates.

8.7 Rubber production intercropped with maize, followed by wood extraction

Besides maintenance activities, (i.e. weeding, manuring, pest and disease control, etc.) during the immature period of rubber trees, smallholders are strongly encouraged to carry out intercropping as this provides an early income prior to tapping. Normally, intercropping can be carried out 3-4 years before shading from the rubber trees become limiting. Maize was chosen as this crop is one of the important food crops in the region and one of the easiest to market.

As an agroforestry modelling interface, WaNuLCAS is able to simulate tree : agricultural crop interactions particularly in terms of resource capture (above and below ground) from the component species, based on their leaf area index and root length density (van Noordwijk *et al*., 2004).

In this application, it is assumed that two crops of maize are planted in a year (60 and 210 days after planting of rubber), up to the first tapping.

The general layout of the agroforestry zones used in the model is illustrated in Figure 8.4. These are spatially divided into Zones 1- 4 by WaNuLCAS, representing half of the total agroforestry zone between rows of trees. Zone1 is allocated only to the trees (rubber) and Zones 2 - 4 for the crops (maize). The designated agroforestry zones for the different planting densities adopted in this modelling work are shown below (Table 8.4).

Table 8.4: Designated agroforestry zones used in the WaNuLCAS model.

Density of rubber	Rubber planting distance	Zone 1	Zone 2	Zone 3	Zone 4
400 ha^{-1}	10.0m x 2.5m	0.5m	1.0m	1.0m	2.5m
600 ha^{-1}	6.0m x 2.8m	0.5m	1.0m	1.0m	0.5m
800 ha^{-1}	4.0m x 3.1m	0.5m	0.5m	0.5m	0.5m

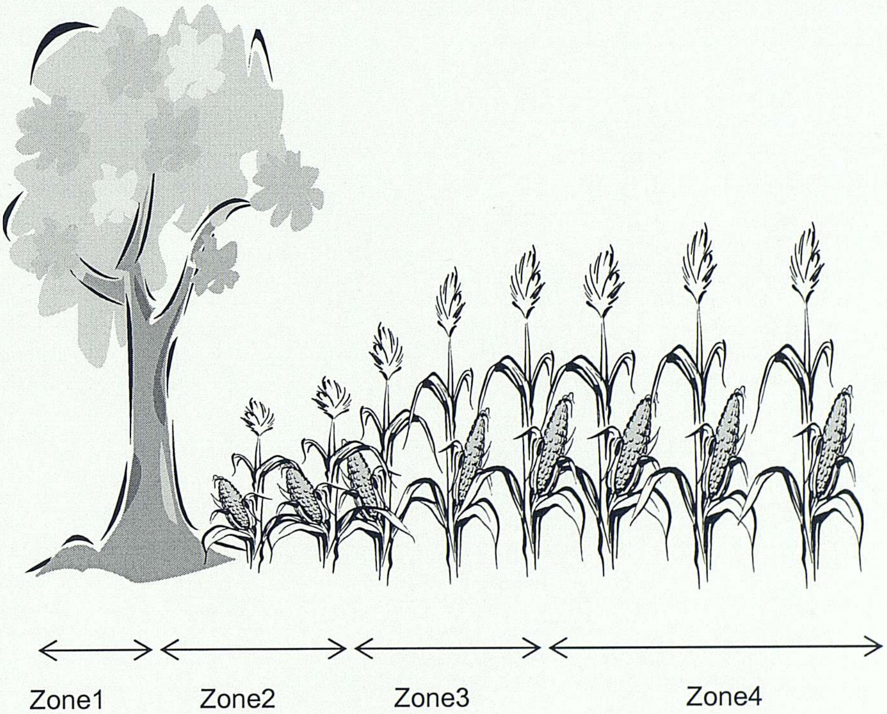


Figure 8.4: Designated rubber agroforestry zones used in the WaNuLCAS model to determine resource capture.

Note:

- *In WaNulCAS, the zone is represented as half of the total agroforestry zone between rows of trees and biomass is measured in kg m^2*
- *Model users are not allowed to enter the value of 0 in any agroforestry zone as the model may 'crash' or could not run the simulation*

The simulated maize yields intercropped with rubber during its immaturity period begin to decline after the second year of planting of rubber (Table 8.5).

Table 8.5: Simulated average maize yields (tonne ha^{-1}) for different ages of rubber, prior to tapping, and different plantation densities. Yields are for two crops per year are combined

Age of rubber	Rubber densities (trees ha^{-1})		
	400	600	800
1	11.9	7.9	6.6
2	11.9	7.9	6.6
3	7.0	6.5	5.4
4	2.9	0.2	0.1
5	-	0.1	0.1
6	-	-	0.1

Yields fell from 11.9 to 2.9 tonnes ha^{-1} at densities of 400 trees ha^{-1}, 7.9 to 0.1 tonnes ha^{-1} at 600 trees ha^{-1} and 6.6 to 0.1 tonnes ha^{-1} at 800 trees ha^{-1} after four years. This demonstrates the ability of the model to simulate shading effects from rubber trees canopy on the maize crop, corresponding to simulated results, which measure the expansion of the canopy radius (Figure 8.5).

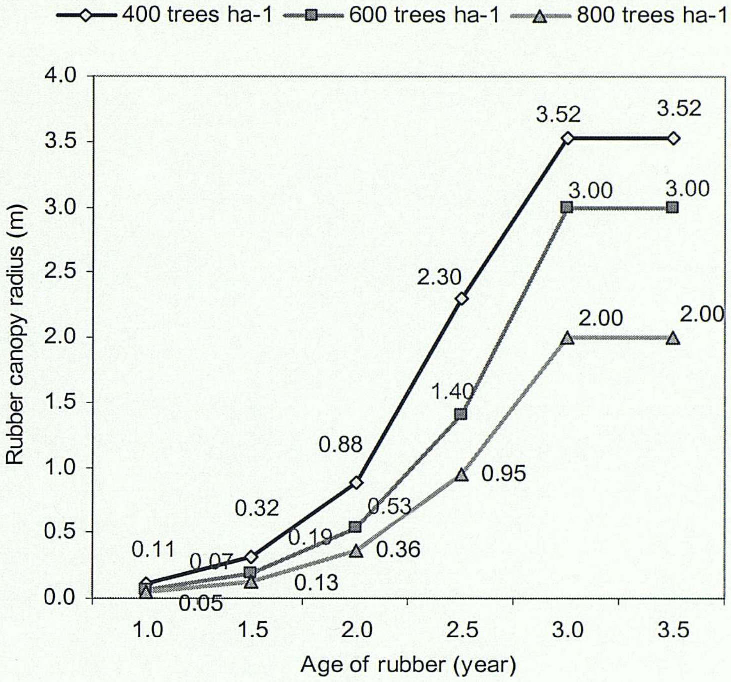


Figure 8.5: Simulated expansion of the rubber tree canopy over the first three and a half years of plantation establishment.

At a density of 400 trees ha^{-1}, from a radius of 0.11 m at the end of the first year, the canopy expands to nearly 2.3 m at two and a half years, reaching a maximum of 3.52 m at three years of age. For higher densities (600 and 800 trees ha^{-1}), the canopy radius reaches 3.0 and 2.0 m respectively at age three. The model also predicts that maize yields are the most affected in agroforestry Zone 2, due to above and below ground competition with the rubber trees, and least affected in Zone 4.

The average maize yields (kg m^{-2}) (before tapping starts) for the different rubber agroforestry zones are shown in Figure 8.6.

Results show that an average annual maize yields prior to tapping in Zone 2 are 0.71, 0.66, 0.49 kg m^{-2} for 400, 600 and 800 trees ha^{-1} respectively compared with Zone 3 (0.86, 0.79 and 0.54 kg m^{-2} for 400, 600 and 800 trees ha^{-1} respectively) and Zone 4 (1.21, 0.79 and 0.57 kg m^{-2} 400, 600 and 800 trees ha^{-1} respectively).

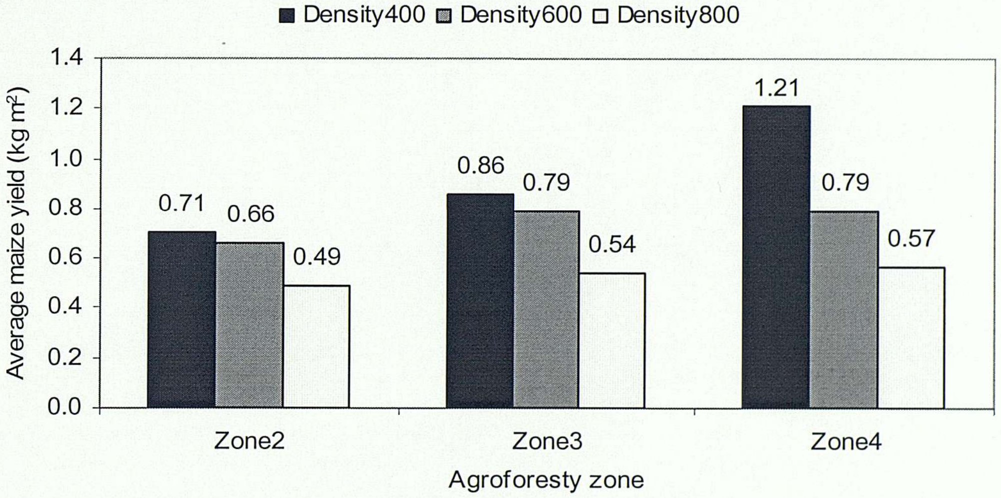


Figure 8.6: Average annual maize yields (kg m^{-2}) in different agroforestry zones during the immaturity period of rubber

Apart from shading by the rubber canopy, the maize crop is also affected by below ground competition for nutrients and water.

The partitioning of this competition can be seen from the simulation of ‘factors affecting crop growth’, which is the default output of WaNuLCAS (van Noordwijk *et al.*, 2004). If the growth of a crop is limited by water, nutrients or light (represented by *CW_PosGrow* – (the effect of water stress on crop growth), *C_NPosGrow[N,P]* (the effect of nutrient limitation on crop growth) and *Light_CRelCap* (the effect of light capture limitation on crop growth) the value will be 0 or close to zero. Values of 1 imply no limitations. The *CW_PosGrow*, *C_NPosGrow[N,P]* and *Light_CRelCap* can be found in the *crop growth sub-model* in WaNuLCAS.

The degree of competition from above ground (AG) (i.e. canopy) and below ground (BG) (i.e. nutrients and water) on the loss of maize yield can be estimated by calculating the number of days that crop (maize) is stressed by AG or BG divided by the total number of cropping days (Lusiana and Khasanah, 2005). The relative amount of competition (*RComp*) in percent (%) from AG for densities of 400, 600 and 800 trees ha^{-1} for different ages of rubber are shown in Figures 8.7a, 8.7b and 8.7c respectively.

RComp for 400 trees ha^{-1}can be expressed as follows:

$$RComp(\%) = 40.91 + \frac{63.95}{1 + exp^{-\left[\frac{RAge - 4.357}{0.621}\right]}} \qquad R^2 = 0.99$$

RComp for 600 trees ha^{-1} can be estimated as:

$$RComp(\%) = 45.78 + \frac{48.33}{1 + exp^{-\left[\frac{RAge - 2.677}{0.4003}\right]}} \qquad R^2 = 1.0$$

RComp for 800 trees ha^{-1} can be calculated as:

$$RComp(\%) = 38.12 + \frac{39.93}{1 + exp^{-\left[\frac{RAge - 2.414}{0.2856}\right]}} \qquad R^2 = 1.0$$

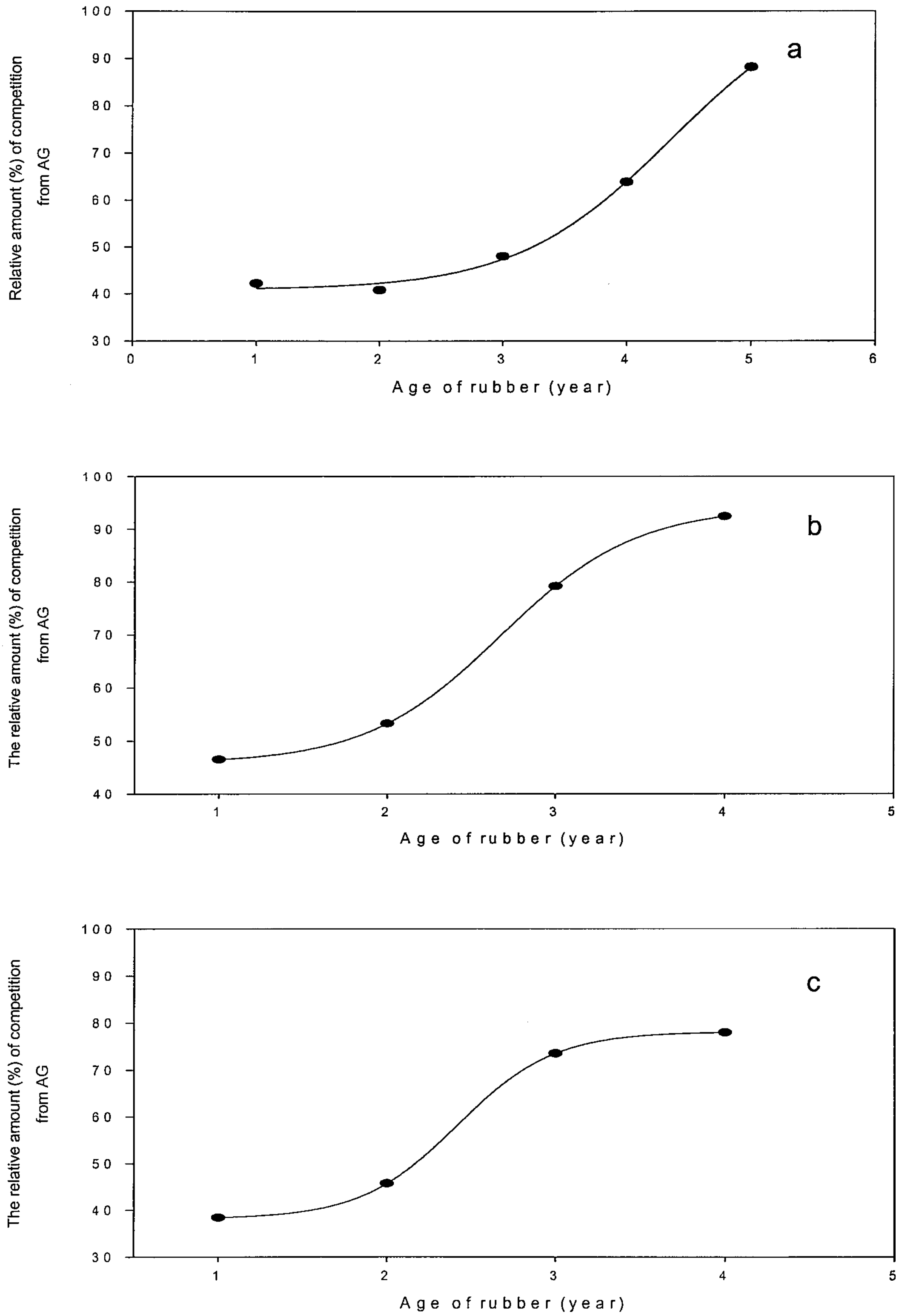


Figure 8.7: The relationship between age of rubber and the relative amount (%) of competition from AG for density of 400 (8.7a), 600 (8.7b) and 800 (8.7c) trees ha^{-1}

Results from Figure 8.7a, 8.7b and 8.7c show that the relative amounts (in percent) of competition from AG is about 40% in the first year and steadily increased up to 70% in fourth year for a density of 400 trees ha^{-1}. However, for densities of 600 and 800 trees ha^{-1}, the magnitude of competition from AG increases up to 80 to 90% in fourth year after planting once canopy reached to the maximum size. Results from the simulation also show marginal effects of competition by maize on rubber growth and production. The difference in rubber tree girth and accumulated yield of rubber planted with and without intercropping with maize are shown in Figures 8.8 and 8.9.

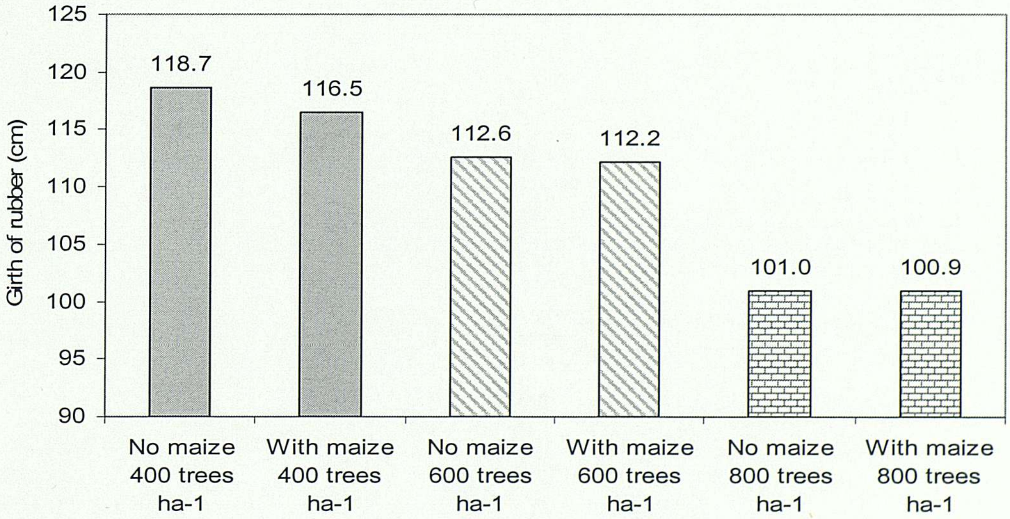


Figure 8.8: Differences in girth of rubber at 20 years) with and without maize intercropping in the period prior to tapping

Figure 8.8 shows there is not much difference in girth between rubber planted without maize and with maize after a 20-year rotation, with only a 2.1, 0.4 and 0.1 cm difference for rubber planting at 400, 600 and 800 trees ha^{-1}, respectively. These results agree with Watson (1989a) who reported that given appropriate inputs, satisfactory yields of maize, soybean, mungbeans could be obtained without harming girth development of rubber trees.

Simulations also show that intercropping with maize reduces the yield of rubber by small amounts (Figure 8.9). The results indicate that at 400 trees ha^{-1} there is 1,924 kg or 7% reduction in the yield of rubber planted with maize. On the other hand, there are only 350 kg difference for rubber planted at density of 600 trees ha^{-1} and 297 kg for rubber planted at 800 trees ha^{-1}, reductions of <1%, due to the lesser areas planted with maize. The designated areas of maize assumed in this modelling approach were 90%, 60% and 50% for 400, 600 and 800 trees ha^{-1} of the total agroforestry area respectively.

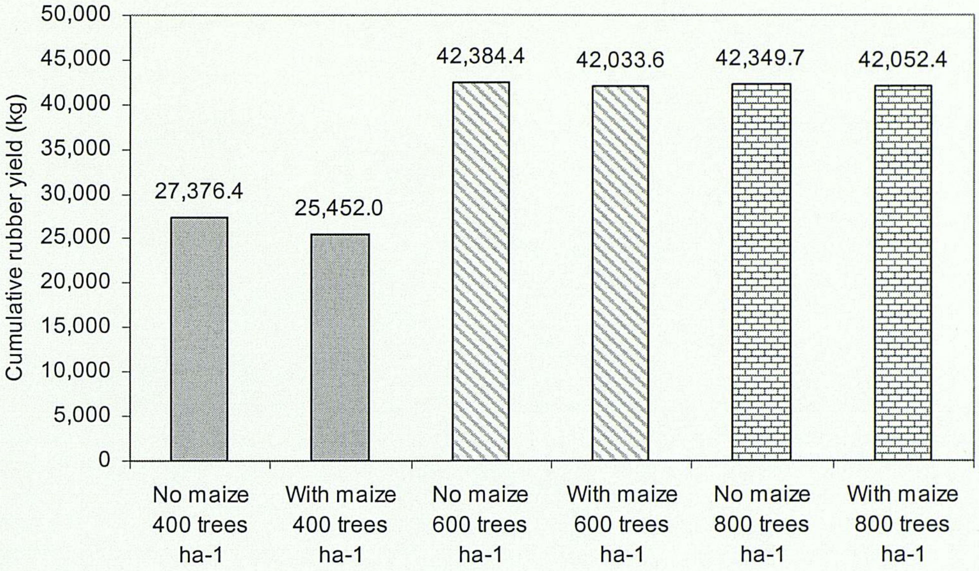


Figure 8.9: Differences in cumulative yield of rubber at 20 years, with and without maize intercropping cropping prior to the tapping period.

In order to compare the efficiency of the rubber:maize intercropping system, it is necessary to compare outputs of the control components, namely pure rubber monocrops, dealt with earlier, and pure maize cultivation. An economic sensitivity analysis was therefore carried out for two situations: a) the agroforestry option of rubber intercropped with maize (up to first tapping), followed by wood extraction at 20 years (Table 8.6a), and b) sole maize (Table 8.6b).

Table 8.6a shows that the rubber: maize intercrop system improved the NPV, IRR, BCR and the AE for all planting densities, at all SMR20 prices and all discount rates compared with rubber monocropping (Table 8.3).

The highest economic gains occurred at a density of 600 trees ha^{-1} and the lowest discount rate of 8%, where intercropping improved the NPV from RM57,536 to RM59,091, the IRR from 43.6% to 49.7%, the BCR from 1.64 to 1.69 and the AE from RM5,647 to RM5,800 at the SMR20 price of RM4.70 .

At the SMR20 prices of RM3.80, all options were still viable except 800 trees ha^{-1} at the discount rate of 12%. However, at RM2.10 all options are unviable.

Table 8.6a: Results of the sensitivity analyses for NPV (RM), IRR, BCR and AE at different discount rates and planting densities for rubber intercropped with maize up to tapping maturity, and followed by wood log extraction at 20 years.

	SMR20 Price (RM)	Discount at 8%			Discount at 10%			Discount at 12%		
		Planting density (trees ha^{-1})			Planting density (trees ha^{-1})			Planting density (trees ha^{-1})		
		400	600	800	400	600	800	400	600	800
NPV	4.70	39,406	59,091	5,4214	31353	46,839	4,2314	25,158	37,402	33,199
IRR		0.536	0.497	0.397	0.536	0.497	0.397	0.536	0.497	0.397
BCR		1.65	1.69	1.52	1.57	1.60	1.42	1.49	1.51	1.30
AE		3,716	5,800	5,321	3,348	5,234	4,728	3,007	4697.1	4,169
NPV	3.80	29,204	43,485	39,429	22,983	34,091	30,324	18,237	26,911	23,406
IRR		0.467	0.434	0.345	0.467	0.434	0.345	0.467	0.434	0.345
BCR		1.22	1.24	1.10	1.15	1.16	1.01	1.08	1.08	0.91
AE		2,754	4,268	3,870	2,454	3,809	3,389	2,180	3,380	2,939
NPV	2.10	9,934	14,009	11503	7,173	10,012	7,677	5164	7,096	4,909
IRR		0.256	0.238	0.186	0.256	0.238	0.186	0.256	0.238	0.186
BCR		0.42	0.39	0.31	0.36	0.33	0.24	0.31	0.27	0.17
AE		936.9	1,375	1,129	766.0	1,119	857.8	617.3	891.1	616.5

Table 8.6b: Results of the sensitivity analyses for NPV(RM), IRR, BCR and AE at different discount rates for the maize monocropping option

	Discount at 8%	Discount at 10%	Discount at 12%
NPV	11,743	9,776	8213
IRR	0.686	0.686	0.686
BCR	1.16	1.10	1.03
AE	1,107	1,044	981.7

Note:

- *The sensitivity analyses for maize is based on annual yields of different densities of rubber (Table 8.4)*
- *The simulated yield for sole maize is 13.0 tonnes ha^{-1} for 2 seasons year^{-1}*
- *It is assumed that only 70% of total maize is marketable (good grade) and the other 30% is low grade (based on MARDI, 1996)*
- *Costing of the maize project is based on MARDI (1996) , Eusof et al.(1996), Eusof and Salleh (2001), Teh (2004) and Pang (2005).*
  (Costing of maize project is shown in Appendix 5)

The results also show that planting rubber at densities of 400 - 800 trees ha^{-1} are still viable at an SMR20 price of RM3.80, even at discount rates of 10%, which is not the case for rubber monocropping. This confirms that intercropping rubber with maize during the immaturity period followed by wood extraction at the end of the rotation is capable of improving the economic viability of the system at higher discount rates (10% and 12%).

In comparison with some agroforestry options (Tables 8.2 and 8.3), monocropping with maize (Table 8.6b) is viable at all discount rates. While the sole maize option was still viable at 12%, planting rubber at all densities at the SMR20 price of RM2.10 are not profitable, even at the 8% discount rate.

8.8 The effect of canopy radius on yield of maize

As the rubber crop grows, canopy expansion will affect the growth of maize beneath. This was modelled by changing the default value of 3.5 m (maximum canopy radius) for the canopy radius from 3.5 m to 7.0 m (e.g. RRIM937 clone) to represent different rates of expansion for different rubber tree clones or canopy shapes.

Figure 8.10 compares the effect of final canopy radii (3.5m and 7.0 m) on maize yield (tonnes ha^{-1}) for different ages of rubber.

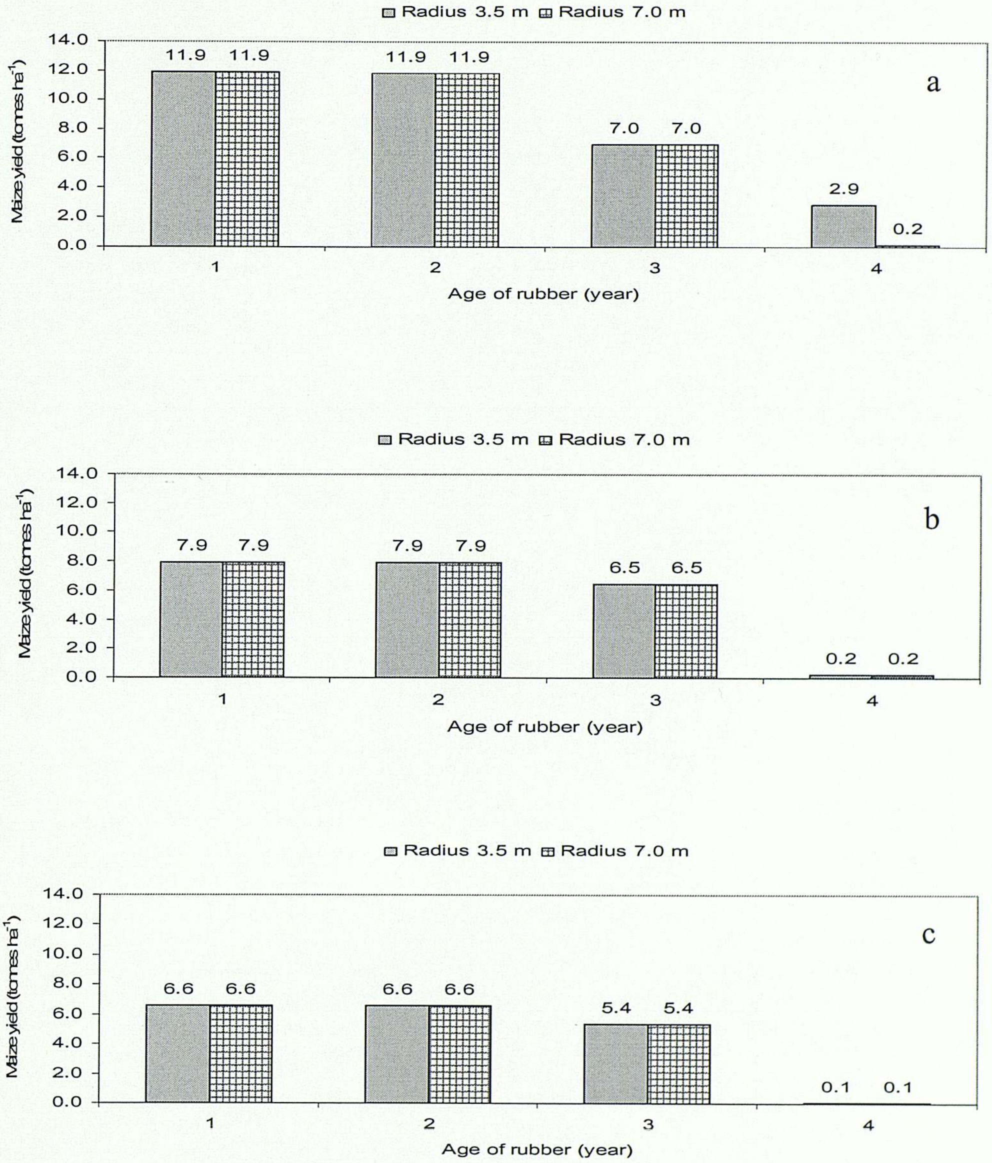


Figure 8.10: Simulated effects of rubber tree canopy radius (m) on yields of maize (tonnes ha^{-1}) at different ages and planting densities (8.10a – 400 trees ha^{-1}; 8.10b – 600 trees ha^{-1}; 8.10c – 800 trees ha^{-1})

As expected, the simulation shows that trees of wider canopy radius give lower maize yields. The yield of maize intercropped with 400 trees ha^{-1} of rubber drops from 11.9 to 2.9 tonnes ha^{-1} in year four for 3.5 m canopy radius and from 11.9 to 0.2 tonnes ha^{-1} for a 7.0 m canopy radius (Figure 8.10a). However at the highest densities (600 and 800 trees ha^{-1}), simulation results shows there is no difference in the simulated yields between all canopy sizes (3.5 and 7.0 m) at four years after planting as a result of full canopy closure gained from 600 and 800 trees ha^{-1} at this stage.

CHAPTER 9

SUMMARY AND CONCLUSIONS

Model Development

This study was undertaken with the aim of developing a model able to simulate the growth and production of rubber under different environmental conditions, as well as different rubber agroforestry options. The development of simple static model, using empirical equations from related rubber literature, was compiled as *Hevea Version 1.0* using Microsoft EXCEL. This was developed primarily as a *precursor* but was able to simulate crop growth with acceptable modelling efficiencies (EF) of 0.87 for girth and 0.97 for rubber production. Although few parameters were involved in developing this model, it still has advantages such as ease of construction and it is easy to understand, especially for beginners.

As several factors were not included in the simple model, such as the effect of planting density on growth and yield of rubber and the effect of shade on crops planted underneath, attempts were made to develop a dynamic model that is able to incorporate these different options of the rubber agroforestry system. These included the development of the tapping and tapping panel-sub models. Both sub-models were then linked to an existing agroforestry model namely WaNuLCAS (Water, Nutrient, Light Capture in Agroforestry Systems), built in the STELLA modelling environment.

Model validation

Throughout the validation process, the improved WaNuLCAS model was run without programming difficulties and was satisfactorily linked to STELLA Research Environment Software and Microsoft EXCEL. The model predicts with modelling efficiencies (EF) of 0.83, 0.97 and 0.70 the girth, rubber production and above-ground biomass respectively. However, the EF of *Hevea Version 1.0* was slightly better in predicting the girth increments (0.87) than the improved WaNuLCAS model. This could be because the former uses an index value (e.g. site index, clone index) for different clones, as proposed by Malaysian Rubber Board in their Planting Recommendations.

In these recommendations, growers are advised to plant rubber clones in suitable area to avoid the risk of certain diseases that affect growth. This is not the case of improved WaNulCAS where growth of rubber was calculated on the basis of the growth rate day^{-1}, without using any adjustment for clones, therefore slightly reducing the EF of the model.

Significant improvements were seen from the output of the simulation, as the dynamic model improved the tendency for overestimation (negative CRM) from -0.05 to -0.04 for girth and -0.14 to 0.0 for rubber production. However, the negative values of EF for the leaf and twig (-0.15) and wood production (-4.9) indicate that the average value results for leaves and twig and wood production is still more accurate than the simulated results. Good correlations were also gained between simulation results and observed data with R^2 values for girth, yield, total above-ground biomass, and leaf and twig biomass of 0.90, 0.97, 0.87 and 0.60 respectively.

Estimates of wood production varied from -45.8 to 56.3 % difference in wood quantity (kg ha^{-1}) over observed data, depending on the clone selected. The model predicts a <10% difference for clones RRIM908, RRIM936, RRIM928, RRIM2009; 20 - 30% differences for RRIM929, RRIM921, RRIM2023; 30 – 40% differences for

RRIM2001, RRIM2002 and a >40% difference for clones RRIM911, RRIM2008, RRIM2014, RRIM2015, RRIM 2016, RRIM2020, RRIM2024, RRIM2026, RRIM 2027 and PB260. Further improvement of the model is discussed in future recommendation section.

Model application

Effect of planting density (tree ha^{-1})

The model was used to predict the effect of different planting densities (400, 600 and 800 trees ha^{-1}) on growth of rubber trees. Simulations indicated that rubber trees can be tapped (at >45 cm girth) at the ages of about 4, 5 and 6 years at densities of 400, 600 and 800 trees ha^{-1}, respectively. Results showed a negative relationship between girth and the density of planting. Lower density planting produces a more rapid girthing rate, with consequently earlier exploitation. These results can provide important guidelines, allowing rubber planters to select suitable crop densities and to predict when the trees will be ready for tapping.

They also allow budget forecasts to be made. In this case, low planting densities are expected to have a lower maintenance costs and earlier returns than high density planting.

Effect of planting densities on rubber production

A 20-year of simulation of one cycle of the economic life of a rubber plantation showed that the density of 600 trees ha^{-1} gives the highest rubber production, while 400 trees ha^{-1} produced lowest rubber production. This result suggests that 600 trees ha^{-1} represents an optimum as it produces higher yields than either 400 or 800 trees ha^{-1}.

The economic viability of different options of rubber agroforestry system

The model simulations over a 20-year cycle show that trees planted as monocrop at the density of 600 trees ha^{-1} give the highest NPV, IRR, BCR and AE compared with trees planted at the density of 400 and 800 trees ha$^{-1.}$ Nevertheless, the sensitivity analyses reveal that planting rubber as monocrop using the selected range of densities (400, 600 and 800 trees ha^{-1}) will only viable if the price of SMR20 is

RM4.70 or more up to 12% discount rates. At lower SMR20 prices of RM2.10, no option is viable.

Rubber planted as monocrop followed by wood extraction

The simulation showed that trees planted at 800 trees ha^{-1} produced the highest wood volume but that this did not compensate for the lower yields of rubber over the 20-year cycle. However, compared with the alternative of burning rubber trees after felling, this option enables smallholders to increase their income as demonstrated by the improved economic indicators of NPV, IRR, BCR and AE. The sale of rubber wood at the end of the rotation makes the option of planting 400 trees ha^{-1} viable at discount rates of 10% at the medium SMR20 price of RM3.80.

Rubber intercropped with maize followed by wood extraction

The sensitivity analyses show much improved viability over the monocropping alternatives of the intercrop system followed by wood extraction. At SMR20 prices of RM3.80 and assuming a rubberwood price of RM 105.00 tonne^{-1}, this option resulted in higher values NPV, IRR, BCR and AE than monocropping. Intercropping rubber with maize makes at option of planting at densities of 400 and 600 and trees ha^{-1} viable at the highest discount rate of 12%.

Effect of rubber tree canopy on maize yields

Simulating intercropping with maize showed that there was no difference in maize yields in the first and second year, but these declined in the third and fourth year. This was due to the shading by the rubber canopy and below ground uptake, as the results closely correspond with the simulated canopy radius as they increased to a maximum of 3.5 m in third year, depending on the final size of the canopy radius.

The relationship between age of rubber (*RAge*) and canopy radius (*CRad of default value – 3.5 m*) of rubber tree can be expressed as follows:

$$CRad = \frac{3.585}{1 + exp^{-\left(\frac{RAge-2.308}{0.2775}\right)}}$$ $(R^2 = 0.99)$ for density of 400 trees ha^{-1}

$$CRad = \frac{3.071}{1 + exp^{-\left(\frac{RAge-2.488}{0.2397}\right)}}$$ $(R^2 = 0.99)$ for density of 600 trees ha^{-1}

$$CRad = \frac{2.047}{1 + exp^{-\left(\frac{RAge-2.480}{0.2441}\right)}}$$ $(R^2 = 0.83)$ for density of 800 trees ha^{-1}

Where *CRad* is in meter and *RAge* in year.

The model predicts that the wider the tree canopy, the more it affects the yield of maize: thus, a 3.5 m canopy radius has the least affect on yield, resulting in a 75 % reduction in yield in the fourth year for 400 trees ha^{-1}. However, yields fell to nearly 98% if planted under rubber canopies of 7.0 m radius (400 trees ha^{-1}). The effect of shading is markedly increased at 600 and 800 trees ha^{-1}, with maize yields falling from 7.9 to 0.2 tonnes ha^{-1} and from 6.6 to 0.1 tonnes ha^{-1} respectively for canopy radius of both 3.5 and 7.0 m.

The model simulation shows that maize yields closest to the tree rows (Zone 2), as expected, the most affected by tree proximity, while the least affected was maize planted in Zone 4. Simulation also showed that competition for water and nutrients (nitrogen and phosphorus) also causes the reduction in yield of rubber. Overall, the simulations results show that intercropping with maize has little effect on growth of rubber trees as the reduction in girthing rates were only 2.1, 0.4 and 0.1 cm for rubber planted at 400, 600 and 800 trees ha^{-1}, respectively.

This result agrees with Prawit *et al.* (1975) and Watson (1989) who reported that at three years after planting, the growing of intercrops did not lead to any loss in growth of rubber. However, results showed that there were about 7, 0.8 and 0.7% reduction in rubber yield after 20-year of simulation for the densities of 400, 600 and 800 trees ha^{-1} respectively.

Future recommendations

Although the developed model shows good ability to predict growth and rubber production under different rubber agroforestry options, the efficiency of the model could be further improved by;

a) developing suitable default values based on the particular clone in use, and
b) collecting more empirical data and inputting this into the model.

Although much has been done to calibrate (by sensitivity analysis) the *default values* (Table 7.1, Chapter 7) to be used as *a basis* for simulation for rubber tree, it is suggested that new sets of default values (with similar parameters as in Table 7.1) for each rubber clone is needed. This is because each clone has widely varying characteristics and using one set of parameters for all clones will reduce the efficiency of the model. Although it is difficult and time-consuming to carry out this work for all clones, the priority would be to begin with two or three recommended clones and temporarily to assign other clones of similar growth habit to the most suitable developed models.

More data from destructive sampling is also needed, especially for above-ground biomass (leaf and twig, wood volume, girth, etc.) as this will increase the efficiency of the model through the validation processes.

Based on the output of the WaNuLCAS model, several important factors need to be considered when developing recommendations for rubber smallholders. These include the integration of rubber with other crops, the selection of agroforestry zones, development of novel under crop types, careful clone selection and full exploitation of the rubberwood by-products:

- Integration of rubber with other crops

Simulation shows that intercropping rubber with other crops is capable of improving the economic viability of rubber tree systems as they increase the NPV, IRR, BCR as well as AE. The method of intercropping normally adopted in the first few years prior to tapping could be varied to improve sustainability. For example, in the first two years after planting of rubber, smallholders are encouraged to grow light-demanding intercrops (e.g. maize, groundnuts, etc.)

but after three years, the choices should switch to shade tolerant species that have high economic value (e.g. cocoa). This option is important as smallholders are able to utilise the intercrop area not only for the first few years (during immaturity), about 25% of total economic life of rubber, but also during the remaining 75% to maturity.

- Selection of agroforestry zones

As rubber grows older, the canopy extends in width and begins to shade crops planted beneath or near to them. The nearer the crops are planted to the trees (Zone1), the more the shading effect. Simulation showed that there was no reduction in maize yield in the first and second year after planting, but the impact was huge (>50%) from the third year onwards. Based on this information, smallholders are suggested to grow their crops only in Zones 3 and 4 two years after planting, in order to gain maximum returns from their crops.

- Novel under crops

It is timely to venture into new types of crops that have potential economic value to be integrated with rubber trees. It has been reported that there are about 1,230 potential indigenous species of plants can be found under tropical rainforest (Zakaria and Ali, 1992). These are mostly shade-tolerant species; consist of herbs, medicinal plants, spices as well as aromatic plants, which could be exploited for the benefit of smallholders. Research is needed to explore potential species such as Mengkudu (*Morinda citricola*), Misai kucing (*Orthosipon aristatus*), Hempedu bumi (*Adrographis paniculata*) and Kacip Fatimah (*Labisia pumila*) for medicinal use (Vimala *et al.,* 2002).

Research should also establish the suitability of species to be intercropped with rubber trees. Apart from exhibiting shade-tolerance, they should be relatively non-competitive both above and below ground, partially sharing different soil horizons for water and nutrient uptake.

- Choices of rubber clones

To increase the productivity of the rubber agroforestry system, especially for smallholders using intercropping, narrow-crowned rubber clones will reduce shading of the crop, especially in the years approaching tapping.

Suitable clones recommended are:

- Clones from the RRIM (Rubber Research Institute of Malaysia) Series: RRIM2001, RRIM2009, RRIM2014, RRIM2015, RRIM2020, RRIM2023, RRIM2025 and RRIM2026
- Clones from PB Series (Prang Besar Estate) Series: PB260, PB235, PB350 and PB366

These are chosen for their narrow and light canopy characteristics as described by the Rubber Research Institute of Malaysia (1980, 1997 and 1998), the MRB (2003a) and also Ibrahim and Sulaiman (2003).

- Rubber wood as a by product

The traditional burning rubber trees after felling should now be discouraged as rubber wood can be turned into valuable products (e.g. furniture) after 20-year of rotation. With the current log price of RM105 tonnes^{-1}, this option promises to increase smallholders' incomes.

To sum up, both the static (*Hevea Vesion 1.0*) and the improved WaNuLCAS models appear to be capable of increasing our understanding of how the rubber tree system works, and provide insights into how it can be manipulated to the advantage of smallholders. Although the *Hevea Version 1.0* was developed with fewer parameters, it is robust, is easy to understand and simple to use. The improved WaNuLCAS also helped to develop a deeper understanding of the rubber agroforestry system, including above and below ground interactions. As both of these models have been developed only for a particular purpose, they are not flexible enough to simulate production in all environments and conditions. Therefore, users are advised to use both static and dynamic models as they could complement each other in order to produce good modelling results.

As the prediction for growth in girth (EF = 0.87) is slightly better compared with that of the improved WaNuLCAS model (EF = 0.83), it is suggested that the *Hevea Version 1.0* version is used for this parameter, especially where the index (i.e. clone and site indices) for each clone is known. This is important, as it will provide a more accurate estimate of when the trees will be ready for tapping (>45 cm in girth). However, users of *Hevea Version 1.0* should also use the outputs (i.e. regression equations) derived from improved WaNuLCAS to predict the relationship between the age of rubber (*RAge*) and canopy radius (*CRad*) and also the relative amount of above-ground competition (*RComp*) for different densities. This will provide a basis for future planning if intercropping between rubber and other crops is envisaged.

Note:

(A CD containing files *Hevea Version 1.0*, Wanulcas.xls and Wanulcas.stm is attached - Appendix 6)

REFERENCES

Abdullah, R. and Ismail, A.Z. 1991. Ke arah menggalakkan tumbesaran dan meningkatkan produktivitl pokok getah. Bahagian Khidmat Nasihat. Institut Penyelidikan Getah Malaysia, Kuala Lumpur. pp. 4 - 6

Ahmad, A.B., and Abdullah, R. 1994. Teknologi perladangan dan pemprosesan getah. Institut Penyelidikan Getah Malaysia, Kuala Lumpur. pp. 106 - 108

Ahuja, L.R., Ma, L. and Howell, T.A. 2002. Whole System Integration and Modelling - Essential to Agricultural Science and Technology in the 21st Century. In: *Agricultural System Models in Field Research and Technology Transfer* (eds) Ahuja, L.R., Ma, L. and Howell, T.A. Lewis Publisher. pp. 1 - 8

Balai Penelitian Medan. 2002. Report on yield and growth for recommended rubber clones in Indonesia, Balai Penelitan Karet, Medan, Indonesia. pp. 1 - 3

Boote, K.J, Jones, J.W and Pickering, N.B. 1996. Potential uses and limitations of crop models. *Agronomy Journal* **88**: 704 - 716

Chan, H.Y. and Pushparajah, E .1972. Productivity potentials of *Hevea* on West Malaysian soils. A preliminary assessment. Proceedings of the Rubber Research Institute of Malaya Planters' Conference, Kuala Lumpur 1972. pp. 97 - 125

Chan, H.Y., Soong, N.K., Woo, Y.K. and Tan, T.H. 1972. Manuring in relation to soil series in West Malaysian mature rubber-growing plantations. Proceedings of the Rubber Research Institute of Malaya Planters' Conference, Kuala Lumpur 1972. pp. 127 - 139

Crop Management Unit .1998. Annual Report, Production Development Division, Malaysian Rubber Board. pp. 1 - 20

Crop Management Unit .1999. Annual Report, Production Development Division, Malaysian Rubber Board. pp. 5 - 20

Crop Management Unit .2000. Annual Report, Production Development Division, Malaysian Rubber Board. pp. 5 - 25

Crop Management Unit .2001. Annual Report, Production Development Division, Malaysian Rubber Board. pp. 5 - 25

Eusof, Z., Shah Kobat, R.B. and Meor Hassan, M.Z. 1996. Management of sloping lands for sustainable agriculture in Malaysia (Phase 3). IBSRAM Asialand Network Annual Report. Rubber Research Institute of Malaysia. 39 p.

Eusof, Z., Shah Kobat, R.B. and Meor Hassan, M.Z. 1997. Management of sloping lands for sustainable agriculture in Malaysia (Phase 3). IBSRAM Asialand Network Annual Report. Rubber Research Institute of Malaysia. 17 p.

Eusof, Z., and Salleh, M.A.S. 2001. Management of sloping lands for sustainable agriculture in Malaysia (Phase 4). IWMI Asialand Network Annual Report. Malaysian Rubber Board. 46 p.

Ford, C.E. 1940. The identification of Ceylon clone of *Hevea brasiliensis*. Rubber Research Institute of Ceylon. 98 p.

Gomez, J.B. 1983. Anatomy of Hevea and its influence on latex production. Malaysian Rubber Research and Development Board (MRRDB) Monograph no. 7. 76 p.

Gomez, J.B., Sivanadyan, K., Leong, S.K., and Ghandimathi, H. 1989. The concept of harvest index as applied to Hevea. *Journal of the Rubber Research Institute of Malaysia* **4**: 86 - 92

Grist, P.G. and Menz, K.M .1995. Modelling the economics of *Imperata* control in smallholder rubber plantations. Canberra, CRES, ANU, *Imperata* Project Paper 1995/5.

Grist, P.G., Menz, K.M. and Thomas .1998. Modified BEAM Rubber Agroforestry Models: RRYIELD and RRECON. ACIAR Technical Series, no. 42. 43 p.

Ibrahim, A.G. 2000. A report on rubber-based integrated farming systems. Malaysian Rubber Board. pp. 1 - 5

Ibrahim, A.G. and Sulaiman, Z. 2003. Pertanian integrasi berasaskan getah. Monograf No. 13. Lembaga Getah Malaysia. 45 p.

Institut Penyelidikan Getah Malaysia. 1995. Percubaan Pembajaan. Laporan Sukutahun Unit Pengurusan Tanaman, IPGM Sg Buloh. p. 2

Institut Penyelidikan Getah Malaysia. 1996. Percubaan Pembajaan. Laporan Sukutahun Unit Pengurusan Tanaman, IPGM Sg Buloh. p. 5

Institut Penyelidikan Getah Maiaysia. 1997. Percubaan Pembajaan. Laporan Sukutahun Unit Pengurusan Tanaman, IPGM Sg Buloh. p. 7

International Rubber Research and Development Board .1988. Compte-Rendu du Colloque Exploitation-Physiologie et Amelioration de l'Hevea. Hevea 88 Colloque IRCA/CIRAD, Paris. pp. 85 - 94

Iyer, G.C., Pushparajah, E., Subramaniam, T., Ismail, T. and Simon, D. 1985. Novel Spacing design for Hevea. Proceedings of the Rubber Research Institute of Malaysia Planters' Conference, Kuala Lumpur 1985. pp. 657 - 667

Jacob, J.L., Prevot, J.C, Roussel, D., Lacrotte R., Serres E., d'Auzac, J., Eschbach, J.M. and Omont, H. 1989. Yield limiting factors, latex physiological parameters, latex diagnosis and clonal typology. In: *Physiology of Rubber Tree Latex* (eds) d'Auzac J., Jacob, J.L. and Chrestin, H. CRC Press Inc., Florida. pp. 347 - 381

Jhan, S. 2002. Report on various fertiliser trials in CMU. Crop Management Unit, Malaysian Rubber Board. pp. 1 - 15

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Roberson, M.J., *et al*. 2003. An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy* **18**: 267 - 288

Ljung, L. and Glad, T. 1994. Modelling of dynamic systems. Prentice Hall Information and System Sciences Series. 361 p.

Loague, K. and Green, R.E. 1991. Statistical and graphical methods for evaluating solute transport models: Overview and application. *Journal of Contaminant Hydrology* **7**: 51 - 73

Lusiana, B. and Khasanah, N. 2005. International Centre for Research in Agroforestry (ICRAF) South East Asia, Bogor. Personal Communication

Macandog, M.D. 2002. Policy implications of different land use options for smallholder farms in *Imperata* grasslands. International Symposium on Sustaining Food Security and Managing Natural Resources in Southeast Asia – Challenges for the 21st Century. January 8-11, 2002, Chiang Mai, Thailand, pp.1 - 3

Malaysian Rubber Board .2003a. LGM Planting Recommendations 2003, Monograph No. 7, Malaysian Rubber Board, Ministry of Primary Industries, Malaysia. 24 p.

Malaysian Rubber Board. 2003b. Viability of rubber forest plantation. Monograph No.6, Malaysian Rubber Board, Ministry of Primary Industries, Malaysia. 24 p.

Malaysian Rubber Board. 2004. Malaysian Rubber Statistics 2004. Malaysian Rubber Board, Ministry of Primary Industries, Malaysia. pp. 1 - 5

Malaysian Rubber Board. 2005. Malaysian Rubber Statistics 2005. Malaysian Rubber Board, Ministry of Primary Industries, Malaysia. pp.1 - 5

Malaysian Rubber Research and Development Board .1987. Natural Rubber and Malaysia. Ministry of Primary Industries, Malaysia. pp. 1 - 24

Malaysian Rubber Research and Development Board.1992. Malaysian Rubber In Picture. Ministry of Primary Industries, Malaysia. 26 p.

Malaysian Timber Industries Board. 1982. Malaysian Timbers - rubberwood. Malaysian Forest Service Trade Leaflet No. 58

Mann, C.E.T. and Sharp, C.C.T. 1933. The history and development of clones of Hevea brasiliensis . Planting manual No. 5. Rubber Research Institute of Malaya. 32 p.

MARDI. 1996. Large scale production of grain maize. The Ladang Lambor maize project (ed) C.O. Leong. Special Report. 50 p.

Matthews, R.B. 2002. Crop management. In: *Crop-soil Simulation Model* - Application In Developing Countries (eds) Matthews, R.B. and Stephens W.) CABI Publishing. 277 p.

Matthews, R.B. and Stephens, W .1998. The role of photoperiod in regulating seasonal yield variation in tea (*Camelia sinensis L*). *Experimental Agriculture* **34**: 323 - 340

Moorby, J. 1985. Wheat growth and modelling: Conclusion. In: *Wheat growth and and modelling* (eds) Day, W. and Atkin, R.K. NATO ASI Series, Series A: Life Science Vol.86

Ng, A.P., Leong, W., Hashim, I., Pushparajah, E. and Yoon, P.K. 1987. Current status on effects of planting density on the performance of Hevea brasiliensis. Proceedings of Rubber Growers Conferences 1987. pp. 52 - 85

Ng, A.P., Sepian, A., Ooi, C.B., Leong, W., Lew, H.L. and Yoon, P.K. 1979. Report on various aspects of yield, growth and economics of a density trial. Proceeding of RRIM Planters' Conference 1979. pp. 303 - 321

Nor, M.Y. 1995. RRIM Fertiliser recommendations. Crop Management Unit, Rubber Reseach Institute of Malaysia. Unpublished

Paardekooper, E.C. and Sookmark, S. 1969. Diurnal variations in latex yield and dry rubber content and relation to saturation deficit of air. *Journal of the Rubber Research Institute of Malaysia,* **21**: 241 - 250

Paardekooper, E.C. 1989. Exploitation of the rubber tree. In: *Rubber* (eds) Webster, C.C. and Baulkwill, W.J. Longman Scientific and Technical. pp. 349 – 414

Pang, C.P. 2005. Crop Management Unit. Malaysian Rubber Board, Sg. Buloh.Personal Communication

Parkianathan, S.W., Haridas, G. and d'Auzac, J. 1989. Water relations and latex flow In: *Physiology of Rubber Tree Latex* (eds) d'Auzac J., Jacob, J.L. and Chrestin, H. CRC Press Inc., Florida. pp. 233 - 256

Parton, W.J., Scimel, D.S., Cole, C.V. and Ojima, D. 1987. Analysis of factors controlling soil organic matter levels in Great Plains Grasslands. *Soil Science Society of American Journal* **51**: 1173 - 1179

Parton, W.J., Keown B.M., Kircher, V. and Ojima, D. 1992. CENTURY Users Manual. Colorado State University. I1 - V1.

Perkins, F. 1996. Practical cost benefits analysis. Basic concepts and applications. Macmillan Education Australia Pty Ltd. 396 p.

Pratummintra, S. 2000. Dynamic approach in predicting land production potential for rubber: case study in east and northeast Thailand. PhD Thesis, Universiti Putra Malaysia

Prawit, W., Waiwit, B. and Templeton, J.K. 1975. Girth growth of rubber and interrow management. Rubber Research Centre, Hat Yai, Thailand. Document No. 56

Purnamasari, R., Cacho, O. and Simmons, P. 2002. Management strategies for Indonesian rubber production under yield and price uncertainty: a bioeconomic analysis. *Agroforestry Systems* **54**: 121 - 135

Pushparajah, E. 1983. Problems and potentials for establishing *Hevea* under difficult environment conditions. Planters, Kuala Lumpur 59. pp. 242 - 251

Pusparajah, E.and Yew, F.K. 1977. Management of soils. In: *Soils under Hevea and their management in Peninsular Malaysia.* Rubber Research Institute of Malaysia. pp. 94 - 117

Rinaldi, M, Losavio N and Flagella, Z. 2003. Evaluation and application of OILCROP-SUN model for sun flower in Southern Italy. *Agricultural Systems* **78**: 17 – 30

Rodrigo, V.H.L., Stirling, C.M., Teklehaimanot, Z., and Nugawela, A. 2001. Intercropping with banana to improve fractional interception and radiation-use efficiency of immature rubber plantations. *Field Crop Research* **69**: 237 - 249

Rubber Research Institute of Malaysia. 1980. RRIM Planting Recommendations 1980 - 1982. Planters' Bulletin no. 162. pp. 4 - 22

Rubber Research Institute of Malaysia .1995. LGM Planting recommendations 1995 - 1997. Planters' Bulletin no 224/225

Rubber Research Institute of Malaysia .1997. RRIM 2000 Series Clones. Characteristics and description. Crop Improvement and Protection Division, Rubber Research Institute of Malaysia. 67 p.

Rubber Research Institute of Malaysia .1998. LGM Planting recommendations 1998 - 2000. Planters' Bulletin no 3. pp. 3 - 30

Rykiel, E.J. 1996. Testing ecological models: the meaning of validation. *Ecological Modelling* **90**: 229 - 244

Sepian, A. 1980. Economics of high planting density on rubber smallholdings. Proceedings of the Rubber Research Institute of Malaysia Planters' Conference 1979. pp. 82 - 92

Sethuraj, M.R. 1985. Physiology of growth and latex flow in *Hevea brasiliensis*. Proceedings of the International Rubber Conference Kuala Lumpur 1985, Volume 3

Shorter, R., Lawn, R.J. and Hammer, G.L. 1991. Improving genotype adaptation in crops a role of breeders, physiologies and modellers. *Experimental Agriculture* **27**: 155 - 175

SigmaPlot for Windows. 2001. http://www.sigmaplot.com

Soewarsono, P.H. 1990. Specific gravity of Indonesian woods and its significance for practical use. FRPDC. Forest Department Bogor, Indonesia. 99 p.

STELLA Research Technical Documentation. 1996. High Performance Systems, Inc. Hanover NH. http://www.hps-inc.com/

Stephens, W. and Middleton, T. 2002. Tools to support operational decision making. In: *Crop-soil Simulation Model - Application In Developing Countries* (eds) Matthews, R.B. and Stephens, W. CABI Publishing. 277 p.

Stoorvogel, J.J. 1995. Integration of computer-based models and tools to evaluate alternative land-use scenarios as part of an agricultural system analysis. *Agricultural Systems* **49**: 353 - 367

Suseno, B., Joshi, L., Wibawa, G. and Angeles, M.S.D. 2004. A profitability assessment of smallholder rubber agroforestry systems in Jambi, Sumatra, Indonesia. Manuscript submitted to *Agroforestry Systems*. 1 - 22

Sys, C. 1975. Report of the ad hoc expert consultation on land evaluation, FAO World Soil Resources Report no. 45, Rome. pp. 59 - 79

Teh, A.K. 2004. Crop Management Unit. Malaysian Rubber Board, Sg. Buloh, Personal Communication

Templeton, J.K. 1969. Partitioning of assimilates. *Journal of the Rubber Research Institute of Malaysia* **21**: 259 - 263

Tsuji, G.Y., du Toit, A., Jintrawet, A., Jones, J.W., Bowen, W.T., Ogoshi, R.M., and Uehera, G. 2002. Benefits of models in research and decision support: The IBSNAT experience. In: *Agricultural System Models in Field Research and Technology Transfer* (eds) Ahuja, L.R., Ma, L. and Howell, T.A. Lewis Publisher. pp. 71 - 90

Tupy, J. 1989. Sucrose supply and utilisation for latex production. In: *Physiology of Rubber Tree Latex* (eds) d'Auzac, J., Jacob, J.L. and Chrestin, H. CRC Press Inc., Florida. pp. 179 - 218 van Noordwijk, M. 2004. International Centre for Research in Agroforestry (ICRAF) South East Asia, Bogor. Personal Communication

van Noordwijk, M. and Lusiana, B.1999. WaNulCAS, a model of water, nutrient and light capture in agroforestry systems. *Agroforestry Systems* **43**: 217 - 242

van Noordwijk, M., Lusiana, B. and Khasanah, N. 2004. WaNuLCAS version 3.01. Background on a model of water, nutrient and light capture in agroforestry systems. International Centre for Research in Agroforestry (ICRAF), Bogor, Indonesia. 246 p.

van Noordwjk, M. and Mulia, R. 2002. Functional branch analysis as tool for fractal scaling above and belowground trees for their additive and non-additive properties. *Ecological Modelling* **149**: 41 - 51

Vijayakumar, K.R. Chandrashekar, T.R. and Philip, V. 1989. Agroclimate. In: *Natural Rubber*: Agro management and Crop Processing (eds) George, P.J.and Jacob, C.K. Rubber Research Institute of India, Kottayam. pp. 98 - 115

Vimala, P., Sulaiman, Z. Senami, M. and Shokri, A. 2002. Effect of fertiliser on growth and early yield of *Mengkudu (Morinda citricola)* grown under rubber. Paper presented in MSSS General Meeting, Kangar, Perils. 14 p.

Watson, G.A. 1989a. Nutrition. In: *Rubber* (eds) Webster, C.C. and Baulkwill, W.J. Longman Scientific and Technical. pp. 291 - 348

Watson, G.A. 1989b. Climate and soil. In: *Rubber* (eds) Webster, C.C. and Baulkwill, W.J. Longman Scientific and Technical. pp.125 - 164

Webster C.C. and Paardekooper E.C.1989. The botany of the rubber tree. *In*: *Rubber* (eds) Webster, C.C. and Baulkwill, W.J. Longman Scientific and Technical. pp. 57 - 84

Webster, C.C. 1989. Propagation, planting and pruning. In: *Rubber* (eds) Webster, C.C. and Baulkwill, W.J. Longman Scientific and Technical. pp. 195 - 244

Wong, C.B. 1977. A Toposequence on Granite and its influence on the performance of *Hevea brasiliensis*. Proceeding of the Rubber Research Institute of Malaysia Planters' Conference, Kuala Lumpur 1977. pp. 74 - 83

Wong, C.B. 1978. Distribution and classification of soils under rubber: Soils, management of soils and nutrition of *Hevea*. Rubber Research Institute of Malaysia. pp. 39 - 50

Yew, F.K. 1982. Contribution towards the development of a land evaluation system for *Hevea brasiliensis* Muell. Arg. Cultivation in Peninsular Malaysia. PhD Thesis. University of Gent

Young, C.P.L., and Heath, S.B. 1991. Software for teaching land use studies. 2nd Edition. CTI Centre for Land Use Studies. University of Aberdeen. 62 p.

Young, A., Menz ,K., Muraya, P. and Smith, C. 1998. SCUAF Version 4: A model to estimate soil changes under agriculture, agroforestry and forestry. ACIAR Technical Reports Series no. **44**

Zakaria, M. and Ali, M. 1992. Tumbuhan dan perubatan tradisonal. Penerbit Fajar Bakti, Kuala Lumpur. 168 p.

Zainol, E. 1978. Soil capability and suitability for rubber: *Soils, management of soils and nutrition of Hevea.* Rubber Research Institute of Malaysia. pp. 51 - 63

Appendix 1: Summary of girth data from the Malaysian Rubber Board's experiment to validate the model in this modelling work

TSB. JELAI, BATU KURAU, PERAK.
Slow release fertiliser experiment (AGROBLEN -16:8:9:3)
Clone RRIM 901
Girth at 160 cm

Treatments	Rounds of fertiliser	Year 2 97	Year 3 98	Incr.	Year 4 99	Incr	Year 5 00	Incr.	Cumm Incr.
Control	RISDA compound	12.4	21.4	9.0	33.5	12	38.8	5.3	*26.4*
Agroblen - 75g	4 rounds SRF + 2 rounds compound	12.9	20.6	7.7	30.9	10	36.8	5.9	*23.9*
Agroblen - 100g	4 rounds SRF + 2 rounds compound	12.2	20.1	7.9	28.9	8.8	33.1	4.2	*20.9*
Agroblen - 150g	4 rounds SRF + 2 rounds compound	12.7	21.7	9.0	30.5	8.8	36.6	6.1	*23.9*
Mean		12.6	21.0	8.4	31.0	10.0	36.3	5.4	*23.8*

Compound fertiliser
RISDA
Planting : 15/8/95

SE : 243

RRIMINIS, RANTAU MANIS,

GUA MUSANG, KELANTAN.

Slow release fertiliser experiment

Clone RRIM 901

Girth at 160 cm height.

Planted 1995

Treatments	Rounds of application	**Year 1** 96	**Year 2** 97	**Year 3** 98	**Year 4** 99	**Year 5** 00	Cum. Incr.
FLATFORM							
Ibdu Woodace	2 + 4 conventional	9.2	20.2	31.0	41.8	47.5	38.3
Kokei Field King	2 + 4 conventional	10.0	21.5	31.7	42.4	48.2	38.2
CCM 15	12 rounds	9.7	21.7	33.0	43.1	48.6	38.9
RRIM Mixture	Control	9.5	21.0	32.1	42.2	47.7	38.2
Mean		9.6	21.1	32.0	42.4	48.0	38.4
TERRACE							
Ibdu Woodace	2 + 4 conventional	8.8	19.8	31.7	41.6	46.6	37.8
Kokei Field King	2 + 4 conventional	9.7	19.6	29.2	38.3	42.5	32.8
CCM 15	12 rounds	9.0	19.6	30.3	39.2	44.4	35.4
RRIM Mixture	Control	8.5	19.4	29.7	39.3	44.0	35.5
Mean		9.0	19.6	30.2	39.6	44.4	35.4
Overall mean		*9.3*	*20.4*	*31.1*	*41.0*	*46.2*	*36.9*

'PHOSPHATE' FERTILISER TRIAL

Batu 9, Jalan Trong, Perak

Girth at 160 cm.

Planting 6/95

Treatments	Year 2	Year 3	Year 4	Year 5	Year 6	Increment
Control	17.7	27.8	34.0	39.1	44.3	26.6
CIRP	19.6	30.0	36.7	41.9	44.9	25.3
CHINA	18.5	28.3	34.8	38.4	42.9	24.4
GAFSA	18.8	28.7	35.2	40.0	43.5	24.7
Mean	*18.7*	*28.7*	*35.2*	*39.9*	*43.9*	25.25

* Fertiliser apply as Mix Mag X and Mag Y after 36 month

RRIMINIS Sri Iskandar

Frequency of manuring experiment (UREA)

Clone: RRIM 901

Girth at 160cm

Treatments	Jun-93	Nov-93	May-94	Nov-94	Jun-95	Nov-95	Jun-96
N1 F1	14.2	20.0	28.4	34.3	40.2	44.8	49.1
N1 F2	14.0	20.3	28.3	33.8	40.3	45.1	50.3
N1 F3	14.7	21.2	29.4	34.9	41.4	46.1	50.4
N2 F1	15.2	21.4	29.9	35.5	42.5	47.2	52.2
N2 F2	11.3	16.9	24.7	30.4	36.8	41.1	45.4
N2 F3	14.2	20.2	28.1	33.0	40.3	45.1	50.2
Mean	13.9	20.0	28.1	33.7	40.3	44.9	49.6
Control	10.9	15.8	23.5	29.5	35.5	40.8	46.0

N1	UREA
N2	Mix
F1	1X
F2	2X
F3	4X
Control	None

Planting; 6/92

Appendix 2: Planting and tapping costs for smallholders (RM ha^{-1}) for 400 trees ha^{-1}

Year	Land clearing	Burning & restacking	Terracing & ploughing	Lining	Holing	Planting materials	Planting cost	Disease control	Weeding cost	Manuring cost	Tapping cost	Total Cost
1	700.0	300.0	450.0	100.0	225.0	900.0	450.0		150.0	130.0	0.0	3405.0
2								200.0	150.0	130.0	0.0	480.0
3						90.0	45.0	200.0	150.0	130.0	0.0	615.0
4									150.0	130.0	0.0	280.0
5									75.0	130.0	382.2	587.2
6								200.0	75.0	260.0	1446.9	1981.9
7									75.0	260.0	2969.2	3304.2
8									75.0	260.0	3208.4	3543.4
9								100.0	75.0	260.0	3243.5	3678.5
10									75.0	260.0	3205.8	3540.8
11									75.0	260.0	3178.5	3513.5
12								100.0	75.0	260.0	2970.5	3405.5
13									75.0	260.0	2330.9	2665.9
14									75.0	260.0	2784.6	3119.6
15									75.0	260.0	2102.1	2437.1
16									75.0	260.0	1970.8	2305.8
17									75.0	260.0	1375.4	1710.4
18									75.0	260.0	1683.5	2018.5
19									75.0	260.0	1432.6	1767.6
20									75.0	260.0	1303.9	1638.9

Costing based on Abdullah and Ismail (1991), Ahmad and Abdullah (1994), Teh (2004) and Pang (2005)

Appendix 3: Planting and tapping costs for smallholders (RM ha^{-1}) for 600 trees ha^{-1}

Year	Land clearing	Burning & restacking	Terracing & ploughing	Lining	Holing	Planting materials	Planting cost	Disease control	Weeding cost	Manuring cost	Tapping cost	Total Cost
0	700.0	300.0	450.0	100.0	300.0	1320.0	300.0		200.0	200.0	0.0	3870.0
1								200.0	200.0	200.0	0.0	600.0
2						132.0	30.0	200.0	200.0	200.0	0.0	762.0
3									200.0	200.0	0.0	400.0
4									200.0	200.0	0.0	400.0
5								200.0	100.0	400.0	656.5	1356.5
7									100.0	400.0	4377.1	4877.1
8									100.0	400.0	6168.5	6668.5
9								100.0	100.0	400.0	5358.6	5958.6
10									100.0	400.0	5268.9	5768.9
11									100.0	400.0	5163.6	5663.6
12								100.0	100.0	400.0	5032.3	5632.3
13									100.0	400.0	4187.3	4687.3
14									100.0	400.0	4043.0	4543.0
15									100.0	400.0	3231.8	3731.8
16									100.0	400.0	3084.9	3584.9
17									100.0	400.0	2301.0	2801.0
18									100.0	400.0	2202.2	2702.2
19									100.0	400.0	2046.2	2546.2
20									100.0	400.0	1976.0	2476.0

Appendix 4: Planting and tapping costs for smallholders (RM ha^{-1}) for 800 trees ha^{-1}

Year	Land clearing	Burning & restacking	Terracing & ploughing	Lining	Holing	Planting materials	Planting cost	Disease control	Weeding cost	Manuring cost	Tapping cost	Total Cost
0	700.0	300.0	450.0	100.0	400.0	1760.0	880.0		250.0	150.0		4990.0
1								250.0	250.0	150.0		650.0
2						160.0	40.0	250.0	250.0	150.0		850.0
3									250.0	150.0	0.0	400.0
4									250.0	150.0	0.0	400.0
5								200.0	250.0	150.0	0.0	600.0
7									125.0	240.0	889.2	1254.2
8									125.0	480.0	7293.0	7898.0
9								200.0	125.0	480.0	6207.5	7012.5
10									125.0	480.0	5310.5	5915.5
11									125.0	480.0	5207.8	5812.8
12								200.0	125.0	480.0	5081.7	5886.7
13									125.0	480.0	4238.0	4843.0
14									125.0	480.0	4110.6	4715.6
15									125.0	480.0	3307.2	3912.2
16									125.0	480.0	3168.1	3773.1
17									125.0	480.0	2991.3	3596.3
18									125.0	480.0	2181.4	2786.4
19									125.0	480.0	1907.1	2512.1
20									125.0	480.0	1671.8	18681.3

Appendix 5: Costing of maize project (RM ha $^{-1}$season^{-1})

Item	**Cost (RM)**
Labour cost	
Land preparation	660.00
Lining and holing	180.00
Planting	450.00
Weeding	450.00
Labour for manuring	120.00
Labour for pest control	120.00
Harvesting	360.00
Sub total	**2340.00**
Material cost	
Seed	100.00
Fertiliser	350.00
Herbicide	200.00
Fungicide	80.00
Sub total	**730.00**
TOTAL	**3070.00**

Appendix 6: Starting WaNulCAS

Initiate EXCEL. Open Wanulcas.xls. It will give warning that the file contains macros.

Choose enable macros. This is to make sure the macro built to ease inputting parameters in the model work properly.

Then run STELLA. It will automatically open a blank working model. Close it and open Wanulcas.stm ffrom appropriate directory.

You are now inside the WaNuLCAS the Main Menu of the WaNuLCAS and ready to work.

Please be patient while loading the WaNuLCAS.

To familiarize yourself with WaNulCAS, please try the following exercise:

First, view the model then return to Main Menu

Second, run the model with default parameters

Third, check the of summary input and output of the model

Fourth, modify input parameters and try a new run

Fifth, import output resulting from a new run

A CD containing files *Hevea Version 1.0*, Wanulcas.xls and Wanulcas.stm is attached.