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Developing a Scientific Basis for Sustainable Management of Tropical Forest Watersheds

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Top: A giant Dipterocarp tree of the Paunglaung forest watershed
Middle: Scenic view of the Paunglaung forest watershed from the Paunglaung river
Bottom: Annual diameter growth responses to different competition intensities at different initial diameters

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Developing a Scientific Basis for Sustainable Management of Tropical Forest Watersheds: Case Studies from Myanmar

A dissertation to obtain the degree of Doctor at the
Faculty of the Forest Science and Forest Ecology,
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1. Introduction

1.1. Biophysical and geographical descriptions of Myanmar

Myanmar is a country situated in continental Southeast Asia, between 10° N and 29° N latitude and 92° E and 101° E longitude. Covering an area of 676,577 km^2, the country extends at most for 936 km from east to west and for 2,051 km from north to south. International boundaries are shared with China in the north, with Laos and Thailand in the east, and with Bangladesh and India in the west. The southern parts of the country are bordering along the coast of the Bay of Bengal and the Andaman Sea. Topographically, Myanmar can roughly be divided into three parts - the western hills region, the central valley region, and the eastern hills region. The general profile of the country rises from the sea level along the southern coasts to the snow-capped mountains towering with a highest elevation of around 6000 m in the northern tip of the country near the Chinese border. The country can be described as hilly and mountainous because most parts of the country are situated on high lands. Myanmar is drained by three main river systems namely the Ayeyarwaddy, Sittaung and Thanlwin, all of which originate in the north and flow into the sea in the south.

Myanmar typically features a tropical monsoon climate. The climate in some parts of the country is locally modified by the topography, however. Over most parts of Myanmar, there are three well-defined seasons: the rainy season (mid-May to October), the cold season (November to January) and the hot season (February to Mid-May). Nonetheless, the rainfall patterns and temperature distributions are quite diverse throughout the country. The coastal regions receive more than 5000 mm of annual rainfall whereas the central part of Myanmar has an annual rainfall of less than 1000 mm. In addition, the average highest temperature in the central region during the hot season of March and April rises to above 43.3° C while in the northern mountainous parts of the country, it is about 36° C and on the eastern Shan plateau between 30° C and 35°C. As a result of the great variation in rainfall, temperature, and topography, there are many different forest types in Myanmar. Tropical evergreen forests occur in many places of the highest rainfall zone especially in the southern part of the country. Hill and moist temperate forests are found in the eastern, northern and western regions where the elevation exceeds 900 m. The forest type changes to deciduous, then to dry forests along the transect towards the middle of the country as a result of a decreasing rainfall. Mangrove forests are characteristic of the coastal areas.

1.2. The state of forest management in Myanmar

Myanmar is still endowed with natural forests that cover about half of the country's territory, stretching over an area of 34.4 million ha. They are a prime source both for production of valuable wood and non-wood forest products and provide indispensable protective services. The most important forest types are: mixed deciduous forests including teak (38% of the total forest area); hill and mountain evergreen forests (26%); tropical evergreen forests (16%); dry forests (10%); deciduous dipterocarp forests (5%); and tidal swamp forests (4%). The forest land is owned by the State and is classified legally as either reserved forest (30%) or public and unclassified forest (70%). 13 million ha of the forest area (i.e., 37.8% of the total) are recognized as Permanent Forest Estate (PFE), of which 3.3 million ha are designated as conservation reserves and the remaining 9.7 million hectares as production forests. The production forests include 8.3 million of mixed deciduous and 1.4 million ha of evergreen forests (Forest Department, 2003).

Myanmar has for a long time recognized the essential role of institutional instruments for realizing a sustainable forest management. The first forest legislation applied to Myanmar was the Indian Forest Act VII of 1863, which was replaced by the Burma Forest Act XIX in 1881. The Burma Forest Act and subsequent amendments were in use until new legislation, the Myanmar Forest Law, was promulgated in 1992. The Myanmar Forest Policy (1995) was also reformulated in line with the forestry principles adopted in the Earth summit conference of 1992, and important institutional instruments were developed in order to support the implementation of policy stipulations. These include the Forest Rules (1995); the Protection of Wildlife, wild Plants and Conservation of Natural Areas Law (1994); the Community Forestry Instruction (1995); the Myanmar Agenda 21 (1995); the National Forestry Action Plan (1995); the Criteria and Indicators for sustainable forest management (1999); the Guidelines for District Forest Management Plans (1996); and the National Code of Practice for Forest Harvesting (2000).

Forest management in Myanmar could also be traced back over centuries, when Myanmar kings declared Teak trees as royal property and formulated a complex system designed to maximize revenue and control (Brandis, 1896; Gyi and Tint, 1998). The sustained yield concept was introduced as early as 1752, however, it has been officially recorded that scientific forest management started in 1856 with the introduction of the so-called Brandis management system (Dah, 2004). Since Teak was the only commercial species at that time, management was designed to favour Teak, but in later years, management of other commercially important species was also considered. Accordingly, the original Brandis Selection System was modified into the Burma Selection System in 1920, which is still in use and known as the Myanmar Selection System (MSS)(Gyi and Tint, 1998; Kyaw, 2000).

The first management plan (formerly called Working Plan) of Myanmar was prepared in 1857 (Blanford, 1956). The Working Plan Manual was first printed in 1935 and revised in 1957 (Bryant, 1993). In 1996, a new era was set up through a reformulation of the Management Plan Guidelines in line with the modern management concepts and principles. Based on the new Guideline, a separate management plan has to be devised for every District and a total of 62 Forest Management Plans need to be prepared around the country accordingly. The Annual Allowable Cut (AAC) is prescribed for a particular District Forest Management plan by using the Brandis yield regulation method of 1857 based on inventory and girdling enumeration data (Forest Department, 1998; 2003).

For the management purposes, the forests are organized into different working circles based on the nature and form of forest products and accessibility. The working circles consists of a group of reserves, which are further divided into felling series for the convenience of working according to the drainage and the geographic situations. As MSS adopts a 30-year felling cycle, a felling series is then divided into 30 blocks of approximately equal yield capacity. Each year, selection felling is carried out in one of these blocks and the whole forest under a particular felling series is therefore worked over a felling cycle. All marketable trees with a prescribed exploitable girth (that usually varies with forest types) in the planned block are selected for cutting. Marketable unhealthy trees that have not attained the prescribed size, but are unlikely to survive through the subsequent felling cycle, are also selected for cutting. Some high quality stems of different species are intentionally retained as seed trees spread over the area of felling.

It is standard practice that Teak trees selected for exploitation are girdled and left standing for 3 years before being felled and extracted. However, some mature teak trees are sometimes green-felled in certain accessible areas for the plywood industry. Improvement Felling (IF) and thinning in very dense young stands are also carried out at the time of girdling to favour especially teak. Logging activities are guided by the national code of forest harvesting practices, which gives detail guidelines for activities such as the alignment and construction of extraction roads, skid trails and stream crossings; the marking of tree positions on a map; climber cutting before felling; and the directional felling of selectively marked trees. Logging is done mainly by elephants and, to a lesser extent, water buffalo. The usage of animals in log extraction has a low impact on the environment and biodiversity, and wastages are low compared to mechanical logging. Heavy machines are used mainly for road construction, the loading and unloading of logs, and transportation.

With the understanding of the importance of resource assessment in forest management planning, linear valuation surveys through subjective strip sampling were conducted just after the organized forestry started in 1856. These survey data were basic in the Brandis's system (1857) of yield regulation. Cent percent enumeration of teak trees with specified minimum limit left during girdling was initiated in 1916-17 and the same for other hardwoods down to the class one-foot below the prescribed girth limit has also been carried out afterward. These enumeration data have been used in the estimation of AAC ever since they were initiated. The use of such enumeration data in yield regulation however posed some drawbacks: longer time requirement associated with comparatively high operational costs to cover the whole felling series; lack of information on smaller size classes in the growing stock. Subsequently, various inventories based on statistical designs were conducted in Myanmar from 1946 to 1975 to overcome this situation and estimates from these surveys were then used in calculating the annual cut. However, as they were not on a continuous basis, growth and mortality information that were essential for long-term management planning, were still lacking. To fill this important gap in forest management, the continuous system of inventory was introduced with the start of a National Forest Inventory (NFI) Project in 1980-81 funded by FAO and UNDP. A design known as "Sampling with Partial Replacement (SPR)" was applied and sample plots each covering approximately one ha were distributed in a grid of approximately 3 km x 3 km over the forest area. Alternate sample plots were defined as permanent for monitoring the conditions of the forests and its growth by successive measurements. Afterward, yields were regulated for a given area based on these data.

It has been said that Myanmar enjoys a reputation for good forest management and the quality of the Myanmar Selection System has been tested for 150 years. The system therefore is believed to be an excellent one and the only feasible way to deal with multispecies, complex natural forests of the country (Dah, 2004). However, it has become discernable that the sustainability of the forest resources is under serious threats. Extraction of only a few commercial species in successive felling cycles has led to the "creaming" of the forests and resulted in their devaluation through a pronounced decrease in valuable timber species. The reduction of the forest cover through deforestation is also evident (Gyi and Tint, 1998; Kyaw, 2000; Thwin, 2003) and occurs at an alarming rate of 0.47 percent per annum (Forest Department, 1998), resulting from economic and social causes. Various studies and reports (e.g., Thwin and Han, 1991; Keh, 1993; Keh and Aung, 1995: Keh and Kyaw, 1995; Keh, 1997; Forest Department, 1998; Oo, 2000, Lwin, 2001, Kyaw, 2003) have indicated the critical problem of poor natural regeneration of some commercial species particularly Teak in most forests of the country.

1.3. Objectives of the study

It is clear that a long standing practice of forest management in the country meets a number of challenges to retain its reputation for excellence. As an effort to resolve some tactical problems of the prevailing strategic challenges, the present study was organized by the following objectives:

1. To gain a deeper insight into the spatial structure of some forest types in support to designing proper silvicultural interventions and monitoring impacts of management practices.
2. To explore a consistent modelling strategy, based on the existing data structure, for developing individual tree growth models that can be incorporated in a general stand projection system for updating forest inventories.
3. To develop a general stand projection system for providing more precise information in estimating an allowable harvest for sustainable management of particular forest areas.
4. To modify the prevailing yield regulation system for improving productivity and ensuring sustainability of timber resources of the tropical forest watershed in order to establish a trade-off between increasing demands for timber and growing concerns for environmental conservation.

2. Review of Tropical Forest Management Systems

2.1. Tropical forests of the world

According to the statistics issued by FAO (1997), the world forest area amounts to about 3.4 billion ha. Tropical forests represent almost 50% of the forest area of the world. Most of forests found within the tropical zone are generally conditioned by the climate, but some, for instance, mangrove (i.e., forest communities on swamps) are known to be conditioned by edaphic factors. In fact, the vast variations in climatic and soil conditions within the tropics produce an extraordinary diversity of forest types differing in composition and structure and it is not possible within the context of this thesis, to give a complete survey of all forests of the tropical world. Indeed, no generally accepted tropical forest classification system has as yet been developed (Whitmore and Burnham, 1984; Lamprecht, 1989). However, the majority of the forest types included in the various classification systems can generally be fitted into the main climatic forest formations of the tropics discussed below.

2.1.1. Tropical rainforests

The tropical rainforest is one of the major vegetation types of the world (Richards, 1996; Whitmore, 1998; Turner, 2001). The term tropical rainforest was derived from the German word "Tropischer Regenwald" which was coined by Schimper in his great classic work "Plant Geography (1898, 1903)" and has been generally used ever since to describe the forests of the over-wet tropics where there is no, or only minimal, seasonal water shortage (Whitmore and Burnham, 1984). Different terms such as tropical wet evergreen, evergreen Dipterocarp forest (Champion, 1936), giant evergreen (Kermode, 1964), tropical moist evergreen forest (Lamprecht, 1989; Borota, 1991) were also used. These forests are located in close proximity to the equator in all three major forest regions of Latin America, Asia and Africa, comprising about 40% of the world's tropical forests. Within the American formation, the forests are most abundant in the Amazon drainage basin (Hendrick, 2001) and represent the largest compact formation of the evergreen tropical forest in the world. The rainforests in Africa are confined to two main regions: the Western coastal region and the equatorial region. Rainforests in Asia occur somewhere from western India, mainland southeast Asia and southern China to the Islands of the Malays archipelago and Philippines. Tropical rainforests are generally composed of huge and lofty trees of largely diverse species almost all of which are evergreen in nature. These forests, especially the Asian rainforests are therefore believed to be floristically the most affluent and complicated vegetation formation in the world. The most important tree species of the tropical rainforest belong to the family Meliaceae and Leguminosae in America, Meliaceae in Africa, and Dipterocarpaceae in Asia.

2.1.2. Tropical moist deciduous forests

The nomenclature and delimitation of tropical moist deciduous forests are possibly even more confusing and imprecise than those of tropical rainforests. These formations are frequently also referred to as monsoon forests or seasonal forest (Lamprecht, 1989). Monsoon forest is used as a convenient term for those forests of the tropical Far East where the seasonal wind known as Monsoon prevails and water is a periodically seriously limiting factor to plant growth. Outside Asia where the term Monsoon for a prevailing seasonal wind is not in use, these formations are usually described as tropical seasonal forests. Moist deciduous tropical forests occur mainly in the neighborhood of tropical rainforests, but the boundaries against rainforests are quite often sharp owing to the action of fire. Typically, the moist deciduous tropical forest extends into southern and southeastern Asia from India, Nepal, Bhutan and Bangladesh to Burma (Myanmar), Thailand, Laos, Cambodia and Vietnam to Indonesia (Borota, 1991). The teak forests of India, Myanmar, Laos and Thailand are a good example of this type. This formation is also extensive in both Africa and south America as one of the complex of formations of a seasonally dry climate (Whitmore and Burnham, 1984). The flora of the tropical moist deciduous forests is very different from that of the rainforests. In general, tropical moist deciduous forests are of lesser stature than rainforests with a lower biomass. Though the number of tree species per unit area is less compared to the tropical rainforests, these forests still contain a considerable variety of species (Borota, 1991). Even if the moist deciduous forests are floristically less diverse than rainforests, they are extremely valuable commercially. The evergreens are dominant in some occasions; the majority of the species are deciduous however. Dipterocarpaceae are much less abundant (Whitmore and Burnham, 1984), but bamboo undergrowth is often characteristic. Almost all the species are utilized either as timber or firewood (FAO, 1989b). Teak is the most important economic species of these forests (Whitmore and Burnham, 1984).

2.1.3. Tropical dry deciduous forests

Tropical dry deciduous forests are interchangeably called dry monsoon forests; woodland savanna or open dry forests in different regions. In extreme dry and hot climatic conditions, these forests turn into open deciduous thorn-bush or into succulent growth (Borota, 1991). Large areas of tropical dry deciduous forest can be found in South and Southeast Asia, Africa and Madagascar, and central and South America. In Africa, dry deciduous tropical forests occur to the north of the equator in the Sudan belt and extend to the south of the equator over wide areas of Angola, Zaire, Tanzania, Mozambique, Zambia and Zimbabwe. Dry deciduous forests are also found in India, Myanmar, Thailand, Lao, and Vietnam in Asia. In Latin America, they grow in Mexico, Costa Rica and Honduras and are also abundant in the Brazilian highland called “cerradao”, the southeastern part of Peru and the central part of Bolivia. This type of forests consists mainly of hardwoods, which shed their foliage during the dry season (Borota, 1991). They are still amazingly diverse (Mastranstonio and Francis, 1997). Most of the species to be found are also found in the moist deciduous forest but there are considerably fewer species than in the latter (Kermode, 1964). The most important tree species of these forests of south and Southeast Asia are included in the Dipterocarpaceae family. Bamboos are characteristic and may be dense. In the poorest area, bamboo is often of poor quality and grass may be common (Kermode, 1964).

2.2. Deforestation in the tropics

The lush and extensive tropical forests were previously perceived as self-perpetuating systems and renewable natural resources with abundant supply. It is now apparent that the tropical forests are in danger, which was one of the main issues identified in the report of the World Commission on Environment, the Brundtland Commission. These forests are disappearing at an alarming rate and the loss of so much forest has potentially disastrous environmental effects. FAO (2001) has defined deforestation as: the removal of the forest and its replacement by another land use class (e.g. shifting or permanent agriculture, mining or water impoundment), or the long-term reduction of the canopy cover to less than 10%

Tropical deforestation has in recent years drawn a global attention, but the exact formulation of the nature of the problem is still inadequate and it also remains a controversial issue (Angelsen, 1997). Deforestation rates in the tropics have been reported to remain high despite global concern for loss of forests and wildlands (Bawa and Dayanandan, 1998). The actual rate of deforestation varies over time and from region to region (Bawa and Dayanandan, 1989) and is difficult to determine (Urquhart et al, 2002). Based on Forest Resource Assessment 1990 (FRA1990: FAO, 1993) and

2000 (FRA2000: FAO, 2001), it could be identified that the loss of natural forest for the past 20 years in the tropical domain remained alarmingly high at approximately 14.2 million ha or 1% per annum (FAO, 2001). Such a rate of deforestation of about 1% to 2% per year, should it proceed constantly as a percentage of the original area, implies that all tropical forests would disappear in 50 to 100 years, or within a human life time (Lugo, 1995). The causes of tropical deforestation are many, varied, and complex (Urquhart et al, 2002; Mastranstonio and Francis, 1997; Bawa and Dayanandan, 1998), but follows predictable patterns (Lugo, 1995). In order to understand the causes of deforestation, it is useful to distinguish between proximate and ultimate causes. Proximate (or immediate) factors explain how deforestation occurs, whereas ultimate (or underlying) causes explain why deforestation occurs (Bawa and Dayanandan, 1998).

2.2.1. The proximate causes of deforestation

Some advocate that most logging in the humid tropics only involves selective cutting that leaves a residual forest cover, a logged-over area therefore is usually not synonymous with a deforested area as defined by the FAO. Johnson and Cabarle (1993) nonetheless pointed out that in most humid tropical forest areas, logging practices today are typically mining operations that deplete or eventually eradicate tropical forests. Commercial logging was commonly blamed for primary rainforest destruction in Southeast Asia and Africa. Worldwide, it is responsible for the destruction of 5 million ha a year (Revington, 1992), contributing 10% of tropical deforestation (Lanly, 1982). More importantly, logging quite often facilitates deforestation attributed to other causes, such as shifting cultivation and land clearing. Commercial logging activities frequently trigger the direct conversion of forests to such uses as pasture or agriculture. Roads and other infrastructures built in forest areas in conjunction with logging operations create new agricultural frontiers, greatly increasing the vulnerability of the newly opened forestland (Johnson and Cabarle, 1993). Lanly (1982) notified that deforestation rates were 8 times greater in logged-over closed tropical forests than in undisturbed closed forests. In Africa, 75% of land being cleared by peasant farmers is land that has been previously logged (Revington, 1992).

It has been recognized that shifting cultivation, a traditional cultivation practice of people living in and around the forests, is one of the main culprits of tropical deforestation. In fact, shifting cultivation with a long fallow cycle by itself has not caused depletion of forests (Bawa and Dayanandan, 1998) and it would cause relatively low damage when it takes place in secondary forests. However, a shorter cycle gradually was taken on in response to demanding more arable areas for increased food and cash crop production with limited land availability. In some cases, commercialization of cash crops, additional forest lands were felled and cleared, especially when there are primary forests available without costs. In many tropical regions, it is now not uncommon that forest dwellers mine the natural resources for a period and then abandon their plots once declining fertility and weeds begin to affect the yields (Cleuren, 2001). FAO/UNEP (1981) estimated that more than 200 million ha of land in closed forest regions are part of the shifting cultivation cycle, which is the equivalent of about one fifth of the tropical closed forest areas and accounts for nearly half of tropical deforestation (cf. Manokaran, 1990; Angelsen, 1997). At the same time, the area under shifting cultivation is increased every year by 1-2% on the global level (Amelung and Diehl, 1992) with extreme variations between regions and individual countries. Cleuren (2001) reported that shifting cultivation contributed for 70% of total deforestation in Africa, 50% in Asia, and 35% in Tropical America, respectively

Agricultural expansion fuelled by population growth and migration is also renowned as a leading factor in humid tropical forest loss (Johnson and Cabarle, 1993). Historically, increased food demands of increasing population were met by enlarging the cultivated areas. Although increasing yields has become more important since 1950, croplands continue to expand. The increase in cropland was at the expense of rangeland, wetlands, and other ecosystems, particularly forests. Deforestation has been concentrated in tropics since 1950 (Manokaran, 1990). The raising of beef cattle on pastureland of low fertility is another important activity driving the clearance of forests. Typically, the forest is cleared for agricultural purposes and when the soils are depleted and weeds take over, the land is transformed into pasture by burning and establishing grasses. Therefore, the marginal costs of establishing pasture after cropping are low for smallholders. Gradually, shrubs overwhelm the planted grasses and the pastures finally become unproductive. Ranchers then clear additional patches of forests to establish pastures. Consequently, abandoned grasslands are the natural end product of the ecological degradation of the tropical forests (Cleuren, 2001). Ranching seems to be a major cause of deforestation particularly in Central and South America because Revington (1992) reported that two third of lowland tropical forests have turned into pasture in Central America, since 1950. Mining, industrial development, hydroelectric schemes and resettlement programs are also significant causes of deforestation. These developmental activities mostly associated with forest clearing. In some cases, mineral extraction used large open casts. Almost all Amazon countries have important oil and gas operations inside forest areas, with severe environmental consequences (Cleuren, 2001). Hydroelectric schemes usually result in a direct loss of forest areas through submersion and also open up previously inaccessible forests. In Brazil, the Grand Carajas Project, a huge milling development to provide cheap raw material for the world market, occupied 900,000 km^2, causing extensive deforestation (Revington, 1992). Soebiato (1990) also reported that in Indonesia a total of about 30 million ha of forests was designated as conversion forests, aiming at fulfilling the need for forest lands for other sectoral development, such as agriculture, plantation, animal husbandry, fishery, mining, transmigration, and settlement and infrastructure.

2.2.2. The ultimate causes of deforestation

As more people require more food and income, landless and resource-poor people have to seek places to grow food and cash crops, undoubtedly exerting a heavy toll on forests. It is simplistic to assume that the population pressure is responsible for deforestation (Bawa and Dayanandan, 1998) and the population explosion of the mid-twentieth century is the main cause of rapid deforestation in the tropics. The successive assessments of FAO (FRA 1990, FRA 1995 and FRA 2000) strongly supported the assumption that population density was considered to be an important predictor of forest cover change (cf. FAO, 1993; FAO, 2001). This correlation is ever stronger if population pressure is combined with poverty. The poverty-environment thesis suggests that the immediate needs for survival override long-term considerations and the paucity of resources makes it impossible to undertake environmental investment, further escalating environmental degradation. The highest birth rates occur in the poorest strata of the population, poverty largely contributes to resource degradation, then poverty, not population, would be the basic factor underlying deforestation. In some cases, a positive correlation between population density (or growth) and deforestation rate however is ambiguous (cf. Pearce and Brown, 1994; Bilsborrows and Georges, 1994) and the relative size of the population and consumption patterns are more pronounced to explain the impact of population (see Barbier et al., 1994). Ehrlich and Ehrlich (1990) similarly proposed that the environmental impact is in fact a function of population, affluence and technology. A small population with a high consumption of forest resources can have a more severe effect on the forest resource than a relatively large population with low consumption levels (Bawa and Dayanandan, 1998). Should standards of living increase, even if the population decreases, the need for forest products can still increase (Lugo, 1995). This brief review of the debate on population and poverty has made it clear that population growth alone is not responsible for deforestation. Population growth acts in concert with various external factors.

Not surprisingly, countries stressed by population pressure, economic stagnation and/or foreign debt have become concentrated on short-term economic interests. Accordingly, in economic valuation of tropical forests, the commercial value of standing timber only is taken into account (Repetto and Gillis, 1998) and the economic value of non-timber forest products and the benefit accruing from ecosystem services of forested lands have not been considered (Bawa and Dayanandan, 1998). The sustained flow of benefits from intact natural forests therefore has been consistently undervalued and the net economic benefits from forest exploitation and conversion have been overestimated, ignoring many of their costs (Johnson and Cabarle, 1993). Finally, undervalued forests are likely to be degraded by logging and then converted to other uses for generating short-term economic benefits. Deforestation is therefore the inevitable result of the land use policies being carried out in the name of development.

Competition for forest lands intensifies when the intrinsic requirement for agricultural expansion to feed a growing population are combined with extrinsic factors to boast cash crops production for generating foreign exchange. Many national governments have promoted such an agricultural development in forest areas through incentive, subsidies, and tenurial policies. Typically, these incentives lower production costs, thus making alternative land uses more profitable and accelerating the indiscriminate conversion of forest lands for farming and ranching. In some cases, incentives are so high that forests are converted to uneconomic and ephemeral uses such as solely to realize a quick one-time gain. In peninsular Malaysia, the government has converted 12% of its forest area to rubber and oil palm plantation (Repetto and Gillis, 1998) while such incentives may account for 30% or more of the deforestation in Brazil's Amazon Basin during the 1980s (Johnson and Cabarle, 1993).

The growing scarcity of agricultural land has led to both planned and unplanned (or spontaneous) migration into forest areas. While resettlement and colonization programs can be seen as the results of expansionists' agricultural policies, they can also be viewed as manifestation of other policies. In countries with burgeoning populations, concentrated landholdings, and multitudes of landless poor, moving people into forest areas is considered the least expensive and politically disruptive means of addressing social welfare needs (Johnson and Cabarle, 1993). In many Asian countries such government programs have been initiated since the 1950s. The "Grow More Food" campaign in India during the 1950s, the "Land for Landless" program in the Philippines during the 1960s, the "Integrated Rural Development" program in Sarawak and the "Transmigrasi Program" in outer islands of Kalimantan and Irian Jaya, Indonesia during the 1970s, and the "Land Reform Program" in Malaysia during the 1970s are some examples, but not all. In Latin America, Brazil also sponsored the massive settlement program to colonize forest areas in the Amazon Basin with small farmers during the 1970s and 1980s. In contrast, migration into tropical forest areas in most African countries was not government-induced, but mostly unplanned (cf. Amelung and Diehl, 1992).

Property rights regulations and land titling legislation affect the speed of conversion in tropical forests (Amelung and Diehl, 1992). In many countries, property rights to forest lands have been centralized in central governments with a view to strengthening control of forest resources, superseding the traditional rights of peoples who have dwelled in or around the forests for centuries. Although intended to strengthen control of forest resources, these actions have more often had the opposite effect, undermining local rules governing access and use, eroding local conservation incentives, and saddling central governments with far-flung responsibilities that exceed their administrative capabilities. After wresting control of forest resources from indigenous peoples, many governments have given private parties the property rights to public forests. Often, this transfer of property rights has resulted in the clearing of forest lands under the banner of development (cf. Johnson and Cabarle, 1993). They also deprive many millions of people who live and depend directly on humid tropical forests for their livelihoods of a strong legal basis for tenure on forest lands.

Market failure occurs only when markets do not take into account of the value of ecosystem services provided by forested lands. Discounting of ecosystem service is also due to distortion called “missing market” (Pearce and Brown, 1994). Basically, it is the undervaluation of forests that is responsible of market failures and missing markets. Most of the commodities, such as timber, livestock, and tropical crops are traded internationally and price making occurs in remote consumer markets. Market failures also occur when the distant consumer does not pay for all environmental costs associated with the conversion of distant forest lands and protection of goods on these lands. For example, expansion of agricultural lands for cash crop for export markets are taking place in many developing tropical countries. Such a use of land for export crops creates a wide chasm between the consumer and the place of production. A distant consumer, or multinational cooperation representing such a consumer, is not likely to assign value or pay for ecosystem services provided by the land. For the same reason, the land is likely to be more severely degraded and subject to the ill effects of pesticides and herbicides. Unfortunately, the distant consumer is often unaware of environmental costs including the costs of land conversion, and rarely asked such costs. The consequences of land degradation and pollution are left to the victims who are least able to cope with the ill effects or bear the cost. As a result, forest conversion continues unabated (Bawa and Dayanandan, 1998).

In many countries a vicious circle has arisen: loans used to finance environmentally destructive projects can only be repaid through further destructive resource exploitation. Thus, the debt crisis has exacerbated environmental destruction in the Third World (Revington, 1992). In some countries with a vast area of humid tropical forest, for instance in Brazil, Zaire, Indonesia and Myanmar, the per capita GNP remains very low. More troubling, these countries also are heavily indebted (Johnson and Cabarle, 1993). World Bank (1998) reported that the average debt/GNP ratio for the top ten deforesting countries rose from 26% in 1975 to 60% in 1996. Countries suffering from heavy external debt must raise cash quickly to service debt or to pay loan instalments. Cash can be rapidly generated by liquidating forest stocks or converting forest lands to agriculture to raise cash crops for exports (Bawa and Dayanandan, 1998). Hence they are now under tremendous pressure to cut and clear rainforests to finance debt repayments. Nongovernmental organizations in the third World have repeatedly pointed out that there is no change to stop this impoverishment and destruction of nature without a solution to the debt crisis (Revington, 1992).

2.3. Sustainable tropical forest management

Forest management involves the organized application of any particular silvicultural procedure to regulate and control yield and to ensure restocking of harvested areas with a view to achieve pre-determined objectives. Forests can produce a variety of goods and services, singly or in combinations depending upon the type and intensity of management to which they are subject to. Historically, forest management has mostly considered biological issues with a strong focus upon silviculture for the production of wood (Armitage, 1998). Most recently, the scope of forest management has however broadened to span wider economic matters, environmental issues and social affairs and, more generally, the concept of sustainability. Sustainable forest management will ensure that the values derived from the forest meet present-day needs while at the same time ensuring their continued availability and contribution to long-term development needs (FAO, 1993).

For perpetuating and managing tropical forests productively, suitable techniques were introduced long ago and some had been proved to be both biologically sustainable and materially beneficial for at least a century (see Wyatt-Smith, 1987a; Dawkins and Philip, 1998). Unfortunately, good examples of sustainable forest management are hard to find around the tropical world. Unit very recently, it was only in exceptional cases that the treatment of tropical forests could be described as systematic management (Lamprecht, 1989). Today, only a minute fraction of the world's tropical forests are being managed sustainably for timber production (cf. Wardsworth, 1983; Wyatt-smith, 1987a; Budowski, 1988; Poore et al., 1989; Johnson and Cabarle, 1993). The idea of a forest management system as an entity in itself, rather than a loose coalition of specialists is a very old one, but its development into a practical operational form is not easy (FAO, 1989b). If tropical forests were exploited at all, it was rather along the line of mining management and there was no question of sustainability (Lamprecht, 1989). If tropical forests were considered only as physical commodities of an economic asset; then the potentials to management of tropical forests might face overwhelming negative odds (Lugo, 1995). The existing deforestation rates indicate that there is a considerable gap between the original principle of sustainable forest management and much of its current practices (cf. Wyatt-Smith, 1987b; Johnson and Cabarle, 1993; Hahn-Schilling et al., 1994).

Getting to the root of tropical deforestation will now unquestionably require initiatives well beyond the forest sector and sustainable forest management therefore needs to reflect the economic, social, technical aspects related to forests. In definition and practice, it must be more than a set of technical activities aimed at extracting commodities from forests on a continuous basis. A more useful way of viewing the sustainable forest management is as a practical application of a land ethic; i.e., mindfulness of the long-term consequences of abusing natural resources. One key to the sustainability of tropical forest management is to keep our wants on goods and services from forests within the forests' ability to produce them (Johnson and Cabarle, 1993). Hence, non-silvicultural preconditions must, before the technical activities of sustainable forest management are undertaken, be fulfilled as a point of departure in order to conserve the forests effectively (Bertault et al., 1995). Then, simple and well-known silvicultural systems must be adopted to maintain, if possible even to improve, the conditions of the forests with a view to the national interests in the short-term. Over the long run, such mechanistic changes must be linked to the social and economic needs of the local people.

2.3.1. Non-silvicultural preconditions

The problems of sustainable management of tropical forests are many. Perceptibly, most are technical issues; some are essentially social and political (Wyatt-Smith, 1987b). Therefore, the formulation of practical approaches to sustainable management of tropical forests requires the harmonization of human activities considering the biological and physical requirements of forest ecosystems (Maini, 1992). Thus, certain non-silvicultural preconditions at both the national and local level must be well set up in order to implement silvicultural activities effectively. Sound forest policy formulation is a basic precondition at the national level whereas motivating people participation at local level is essential for sustainable forest management.

The success of sustainable management of tropical forests depends upon the national forest policy and its effective implementation (Wyatt-Smith, 1987a). To put into effect many of the objectives and measures of a national forest policy, specific legal instruments are necessary. Forest legislation therefore must be enacted in line with the principles of sustainable forest management in order to support the implementation of a respective national forest policy. Then, forest administration should be reinstituted with the support of forest law and other necessary laws to provide the structure for the implementation of forest policy goals at each administrative level (nation and local). Again, the effective implementation of forest policy measures requires effective managing agencies. More importantly, forest management is in reality land management. Forest policies are basically statements of goals for the forestry sector. Therefore, goals of a national forest policy should reflect development patterns of the country concerned to avoid contradiction with those of other. Thus, a national forest policy should be an integral part of a national land use policy, assuring balanced forest use and conservation with agricultural and other land uses (Armitage, 1998). Likewise, the forest policy also needs to stipulate creation and allocation of suitable areas as Permanent Forest Estate (PFE) to enjoy potential benefits provided by forests. Designation of a PFE will also support legal enforcement and reduce the hazard of conversion of forest into other uses, resulting proper planning and effective implementation of the sustainable forest management.

On the other hand, not only national-level preconditions are essential, but also the local conditions. Many people living in or near forest depend heavily on them for subsistence needs and income. Through the history, the needs of these weaker elements of society have mostly been ignored in the formulation of national forest policies. It becomes eminent that forest policy decision, which only considers overall long-term development needs at the national level while ignoring the immediate needs of local communities, is one of the most contributing factors to the failure of forest conservation efforts in many cases of the past. The regulated forest management asks for integrating the local situations into a decision process to get consistency and transparency in the expression of the political, administrative, economic, social and cultural conditions within the different levels. The most important thing is that the local communities must be given a share in forest management as a matter of priority (Hahn-Schilling et al., 1994).

2.3.2. Silvicultural systems

Silviculture is generally considered as a set of theories and practices of controlling the establishment, composition, structure, and growth of a forest. Silviculture has its foundations in the biological and ecological sciences, yet it also responds to economic and administrative concerns. It depends on both knowledge and judgment: it includes the methods for handling forests stands in view of forest ecology, and modified by economic factors. Information and techniques from several related technical disciplines are drawn to help forecast the likely outcomes from a given set of silvicultural treatments and better identify and evaluate the options for practical management. In this way, silviculture assists in the decision process in the broader disciplines of forest management (i.e., the practical application of scientific, economic and social principles to the administration and working of a forest for specific objectives) (cf. Nyland, 2002). Obviously, the aims of silviculture are to achieve the implementation of management objectives through manipulation of the composition and structure of a forest. In most instances in a wood production forest, the aim is to enhance the growth and quality of potential crop trees (Armitage, 1998). Accordingly, silviculture has been historically used to ensure the perpetual supply, timely use, and optimum yield of whatever marketable values a forest can provide. Under the contemporary concept of ecosystem management, silviculture is now conceived as an effective tool for stand-level treatments to help support resource management decisions at a forest level and sustain critical ecosystem conditions on a landscape scale over the long term. While not contradictory to the traditional view of silviculture, the philosophy of ecosystem management (or sustainable forest management) redefines silviculture as a process for creating, maintaining, or restoring an appropriate balance of essential components, structure, and functions that ensure long-term ecosystem vitality, stability and resilience.

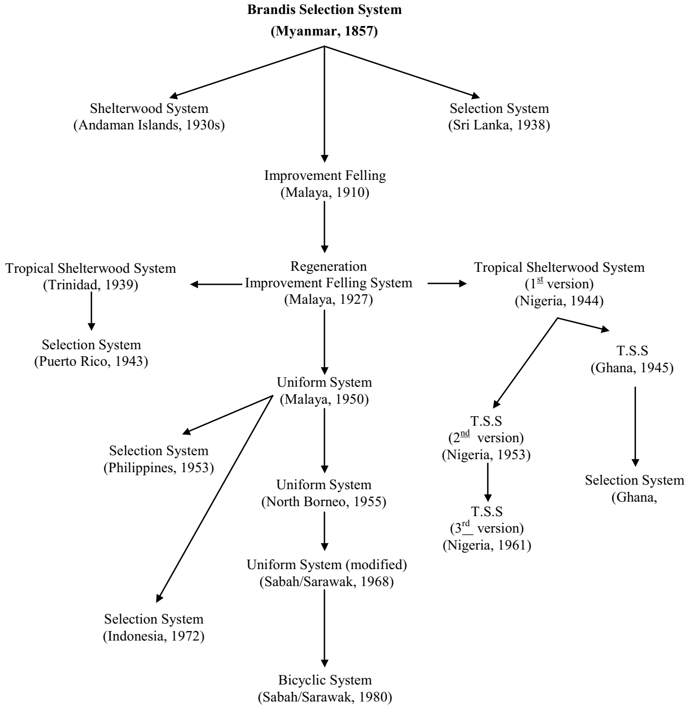
Silviculture therefore involves a set of techniques and essentially provides the biological and technical options to help attain specified forest management objectives. A combination of different silvicultural methods composed of various silvicultural techniques with a sort of intensity, frequency, and sequence that is applied to embrace the objectives of forest management is usually called a silvicultural system. In fact, a particular silvicultural system includes three basic types of treatment: regeneration, tending, and harvesting (Troup, 1928, 1952; Smith et al., 1997; Nyland, 2002): Stand regeneration then refers to creating regeneration spaces in the effective vicinity of seed trees (Seydack, 2000) while tending operations are generally carried out with a view to control inter-specific competition and to give sufficient growing space for regenerated desirable trees; Harvesting is finally used as an important mean to realize objectives of forest management. These components are in general cyclic in nature and the treatments normally move from regeneration, to tending of intermediate tree sizes, and finally to the harvest at maturity. In a multi-age, multi-species tropical forest, these components are interdependent and often take place at the same time.

Natural processes are deliberately guided, through silvicultural practice, to produce forests that are more "useful" than natural ones, and to do so in less time. It is obvious that the systematic application of an appropriate silvicultural system is a basic principle in sustainable forest management and silvicultural management of tropical forests is at the core of a forest development strategy (Armitage, 1998). The complexity, a fundamental feature of tropical forests, usually creates a major problem in practical management, but it is a foremost strength of the system as well in regard both to ecological integrity and economic diversification in a changing world. On the other hand, the structural and compositional simplification and refinement of these forest systems are also necessary for an efficient wood production, where a very few commercial timber species are sparely present. Without doubt, there certainly exist many challenges in adopting effective silvicultural techniques responsive to these two incompatible processes: ecological grounds and economic justification. A silvicultural management system for tropical forests therefore needs to be flexible enough so that it can be adapted to a specific set of circumstances. Then the choice of a silvicultural system should be based on the ecological characteristics of a forest for which sustainable management is being planned and the objectives of management.

Several conditions are necessary from the silvicultural point of view. The first condition is that harvesting should be organized as a significant silvicultural intervention and a log production operation by maintaining a level of harvest within the productive capacity of the forests. Such a relatively low impact log extraction may serve as the most formative silvicultural operation to be applied during the management cycle in any particular area of forest through its limited effects on the future structure, composition and growth of a forest (cf. Armitage, 1998). In this respect, inventory and growth modelling techniques need to be used to gain reliable estimate of productivity and enable informed management. The second necessary condition is to establish properly planned and controlled logging systems with sound consideration on economic, ecological and silvicultural requirements. Even if forest harvesting affects residual growing stock and soil condition, it can still be thought that timber harvest constitutes a silvicultural operation under a proper planning and control mechanism of logging. Here, Reduced Impact Logging (RIL) techniques become crucial in this context. The third essential condition is concerned about the enforcing the appropriate post-logging measures to stimulate desirable species and to maintain natural biodiversity and sufficient regeneration. Selective thinning of dominant secondary species is a key in this stage.

2.4. Silvicultural management systems of tropical forests

It appears that tropical forests have always been part of man's environment. Fossil evidences show that humans have evolved near the margins of tropical and sub-tropical forests. Initially, man made no serious alteration of forest environments, but gradually they began to modify them through exploitation of forest resources and clearing of the forests for agricultural purposes without any regulation. Later on, they also made efforts to secure desired products from the forests. In fact, the silvicultural management of tropical forest is a relatively new phenomenon. Neil (1981) suggested that the tropical forest management system had developed through three distinct phases dating from around 1850 to the present days: the Indo-Burma (Myanmar) phase (1850-1900), the Afro-Malaysian phase (1900-1950), and the Pan-tropical Exploitive phase (1950-today). These systems were actually developed based on the systems which originated in Europe. The first involvement of a European forester was the appointment of Dietrich Brandis, a German and the product of the European system of forest education, as an officer in charge of forests in Myanmar (formerly Burma) in 1856. Brandis introduced the "Brandis Selection System" which is based on a yield regulation system applicable to the moist deciduous forests of Myanmar (Champion, 1936, Blandford, 1956). This first effort to bring the natural tropical forests under conditions of scientific management was the basis for future management development in the tropical world. The general developmental pathways of tropical forest management is present in Figure 2.1.



Note: Uganda is not included as it generally follows its own course

Figure 2.1 General developmental pathways of the tropical forest management systems (based on Neil, 1981)

Silvicultural management systems for tropical forests have been classified by Lamprecht (1989) and Whitmore (1991a) and are presented in Table 2.1. Lamprecht (1989) proposed two groups of management systems applied to previously unmanaged forests: conversion systems and transformation systems. The conversion systems refer to replacement of the original growing stock by artificial forest stands over a fairly large area with a view to increase economic efficiency. In contrast, the transformation systems are generally understood to mean the gradual restructuring of a forest as regards its composition and/or structure with the hope to avoid the damaging repercussions of silvicultural operations on the stability of the site and stand and to reduce costs. Similarly, a different way of grouping of tropical forest management systems was also given by Whitmore (1991a). Whitmore (1991a) classified the silvicultural systems that have been applied to tropical forests as two kinds: monocyclic and polycyclic. Monocyclic systems cover all systems that remove all saleable trees at a single operation with the cycle, the length of which more or less equals the maturation age of the trees. On the other hand, a polycyclic system refers to the system which is based on the repeated removal of selected trees in a series of felling cycles, the length of which is less than the time it takes for the trees to mature (i.e., rotation period). It is clear that these two classification systems are not directly comparable, but each provides different insights into numerous silvicultural management systems of the tropical forests.

Table 2.1 Specific silvicultural management systems for tropical forests.

Lamprecht (1989)	Whitmore (1991a)
1. Conversion systems • "Taungya" systems	1. Monocyclic systems • Uniform systems • Tropical shelterwood systems
2. Transformation systems • Uniform systems • Tropical shelterwood systems • Selection cutting systems	2. Polycyclic systems • Soft selection cutting systems • Hard selection cutting systems

The comment by Poore et al. (1989) "no timber without trees" highlighted the significance of the ecological aspects of sustainability while Lawrence (2003) articulated the phrase "no forest without timber" to pinpoint the relative importance of economic gainfulness in tropical forest sustainability. It is quite obvious that modification of the tropical forests is inevitable for economic reason. However, an unsolved pressing question is to what extent a natural tropical forest ecosystem may be modified for economic rewards without seriously impairing its integrity. Almost all silvicultural management systems are associated with the structural homogenization to hold economic competence and thus also to some extent with negative ecological impacts. Accordingly, universally valid silvicultural recipes cannot be given and all systems always have to be adapted to local conditions when they are applied in practice. It would be impossible here to go into all of the systems in detail. Instead, in the following the essentials of certain systems will be outlined, using a particular method as an example in some case.

2.4.1. Uniform Systems

Uniform systems were designed to achieve abundant regeneration of valuable species by careful manipulation of the canopy (Synnott and Kemp, 1976). Removal of the over-story - either promptly or after cutting- is a characteristic of the system, depending on the capacity of the regeneration to compete with weeds and vines (Wardsworth, 1987). The selection for removal is operated against the unwanted trees over the whole regeneration area, irrespective of the local presence of valuable individuals, ensuring the survival and growth of an adequate amount of advanced regeneration to produce an even-aged crop. The success of these systems is therefore dependent on the existence of advanced regeneration of desirable species. Accordingly, the objective of management of the uniform systems is a more or less even-aged forest with a high proportion of commercially desirable species (FAO, 1989b; Lamprecht, 1989; Seydack, 2000). An example is the "Malayan Uniform System" (MUS), also known as "Malayan Regeneration System" developed for the lowland Dipterocarp forests of the Malay Peninsular. This system was generally operated on a 70-year rotation and involved a series of operations (see Table 2.2).

Table 2.2 Sequence of operations of the Malayan Uniform System (after Thang, 1987; Lamprecht, 1989; FAO, 1989b; Seydack, 2000). "E" means Exploitation (using a 70-year cutting cycle)

Year	**Operations**
E – 1½	Linear sampling (2m x 2m) of regeneration, and enumeration of merchantable trees
E to E +1	Exploitation, followed by poison-girdling of unmarketable trees
E + 3 to E + 5	Linear sampling (5m x 5m) of new crop, followed by cleaning, climber cutting and poison-girdling as required
E + 10	Linear sampling (10 m x 10m) of new crop, followed by treatment as required or passed as regenerated
E + 20, E + 40	Sampling and thinning as required

In principle, logging under the MUS is not permitted without having a sufficient regeneration of marketable species (i.e., occurrence of 40% at the time of regeneration sampling). The entire marketable growing stock with dbh over 40 cm is felled and poisoned girdling is applied to unmarketable trees with dbh above 5 cm. The practical consequence of the MUS is that areas which have been exploited in a way more or less resemble are left untreated until the aggressiveness of the pioneer flora has passed its peak. The advance seedling regeneration, present on the ground at the time of felling, should survive undamaged, develop rapidly and grow through to crop dominance without assistance (Seydack, 2000). Then the treatments that follow are intended to accelerate natural development of the valuable young growth. The number, distribution, need for tending and development of these so-called "potential crop trees" are also assessed afterward and treatments are, if necessary, also provided for intensive stand improvement. The system was successfully applied in the lowland Dipterocarp forests of Malaysia, but was not considered suitable for hill Dipterocarp forests mainly due to a lack of seedlings in virgin stands (Thang, 1987; FAO, 1989b; Seydack, 2000).

2.4.2. Tropical Shelterwood Systems (TSS)

TSS was developed in Nigeria in 1944 based on the experience of the "Malay Regeneration Improvement Felling System" (Neil, 1981; Lamprecht, 1989; FAO, 1989a; Parren, 2000). It was a variation of the MUS adapted to Nigerian conditions (FAO, 1989a). The aim of TSS is to produce a more or less even-aged forest by establishing sufficient regeneration of economic species before logging (Neil, 1981; Seydack, 2000). The natural regeneration of commercially valuable species (mainly Meliaceae) in West African tropical rainforests is often considered inadequate. As a result, TSS was initiated to induce the regeneration of such species. It entailed the gradual opening of the canopy, by felling or using arboricide treatments, to induce regeneration and promote the development of the target seedling or advanced growth (FAO, 1898a). This is pursued through the formation of a shelterwood of seed trees, which are subsequently removed when regeneration has become established (Seydack, 2000). A summery of the operations undertaken under the "Nigerian TSS" is presented in Table 2.3. It has been reported that various modified forms of TSS were also used in Ghana, the Andaman Islands, Trinidad and Uganda (see Neil, 1981; Lamprecht, 1989).

Table 2.3 Sequence of operations of the Tropical Shelterwood System practiced in Nigeria (after Seydack, 2000) "E" means Exploitation (using a 100-year cutting cycle).

Year	**Operations**
E-4	a) Demarcation of compartment b) 1st climber cutting and seedling assistance c) 1st poisoning (= 1st canopy opening)
E – 3	a) 2nd climber cutting and 1st regeneration count b) 2nd poisoning
E – 2	a) 1st and 2nd cleanings (=under-storey opening)
E – 1	a) 3rd and 4th cleanings and 2nd regeneration count
E	a) Exploitation in the case of sufficient regeneration, otherwise the whole procedure shifts accordingly
E + 1	a) 5th cleaning and 3rd regeneration count b) Repair of exploitation damage c) Removal of overwood depending on light demand of regeneration
E + 6 or up to E +10	a) 6th cleaning b) Removal of overwood c) 4th regeneration count

2.4.3. Selection cutting systems

Selection cutting systems are characterized by cutting limits (minimum harvestable diameter) and residual growing stock levels and are designed to optimize economics and sustainability of the forest, with minimum cost. The category under "Soft Selection Cutting Systems" includes any selection system that permits successful natural regeneration without any additional regeneration enhancing measures. Such a system fully integrates harvesting and natural regeneration. This requires a harvesting regime much more analogous to natural disturbances and implies that the degree of canopy opening associated with harvesting must result in that range of canopy gaps which is congruent with the regeneration space requirements of the species required to regenerate sustainably (Seydack, 2000). A good example is the "Myanmar Selection System" (MSS; see section 1.2). Other examples of the systems are the "Basal Area Normality System" and the "Senility Criteria Selection System" practised in Afromontane forests in the Knysna Region of South Africa (see Gadow and Bredenkamp, 1992; Seydack et al., 1995).

The senility criteria selection system developed by Seydack et al. (1995) for the Knysna forest in the Southern Cape costal belt of South Africa involves mortality pre-emption through the selective harvesting of over-mature trees proportional to a species-specific turnover. Harvest tree selection is accomplished by the senility criteria. The system relies on the claim by Seydack (2000) that if the mortality can be effectively pre-empted through harvesting of over-mature trees with declining vigour and short remaining life expectance, the growth potential of the site may be optimally utilized. The inherent tendency in multi-aged, multi-species forest is thus to concentrate growth on fewer and larger trees. In conjunction with the relatively high increment of trees in the larger diameter classes, such forest offers scope for maximum volume production with an appropriate harvesting strategy. Fortunately, no regeneration constraints are observed for the most canopy species in these forests, avoiding provisions for stand regeneration measures. It was also observed that these forests have a fine-grained pattern of age classes resulting from a predominance of single trees death (see Geldenhuys and Maliepaard, 1983; Midgley et al., 1990). The consequences of silvicultural release operations on the productivity of desirable species are reportedly uncertain and in most cases negligible in economic terms. Therefore this system is characterized by a yield optimization strategy through a high residual growing stock, the species-specific maturity thresholds of harvestable trees identified by maturity condition criteria, the absence of silvicultural operations to enhance the productivity of selected trees and adoption of a 10-year felling cycle to partially mimic the prevailing natural disturbance regime. The sequence of operations of the senility criteria selection system of the Knysna forest is given in table 2.4. Accordingly, this system maximizes production, guarantees sustainability, ensures regeneration, facilitates biodiversity conservation, precludes creaming effect, and reduces operational costs. Some drawbacks are also recognized (see Seydack et al., 1995).

Table 2.4 Sequence of operations of the Senility Criteria Selection System of Knysna forest of South Africa (after Seydack et al., 1995) "E" means Exploitation (using a 10-year cutting cycle).

Year	**Operations**
E –1	a) Selection marking of harvestable trees b) Crown lopping for harvestable trees with large crown
E	a) Felling of marked tree
E + 1	a) Monitoring of stand dynamic in harvested stands

These systems in their drastic form often prescribe low cutting limits and relatively short felling cycles, resulting in intense harvesting impact and requiring specific stipulations to retain residual seed trees. Accordingly, they are in most cases associated with special measures such as the enhancement of regeneration of commercially desirable species (enrichment planting). Examples of hard selection cutting systems are the "Selection Management System" (SMS) of Peninsular Malaysia, the "Queensland Selection System" and the selection system practiced in Ghana (cf. Seydack, 2000). The SMS of Malaysia prescribed cutting regimes that would yield an economically viable volume of timber while retaining adequate advanced regeneration to ensure future economic harvesting within the shortest time (Tang, 1987). Under the SMS, all commercial species above 45 cm dbh for non-Dipterocarps and 50 cm bdh for Dipterocarps are felled every 25-30 years. A certain minimum number of trees per ha are left behind as residual stocking (Thang, 1987; FAO, 1989b; Seydack, 2000). The sequence of operations in the SMS is shown in Table 2.5. The SMS assumes that advanced growth, which represents the nucleus of the new timber stand, will form the basis of a second economic crop within a reduced cutting cycle of 25-30 years (Tang, 1987). Therefore, the success of the system will undoubtedly depend upon the efficacy of the control of logging (Dawkins and Philip, 1998).

Table 2.5. Sequence of operations in the Selection Management System of Malaysia (after Thang, 1987; FAO, 1989b; Dawkins and Philip, 1998; Seydack, 2000). "E" means Exploitation (using a 25/30-year cutting cycle)

Year	**Operations**
E2 to E1	Pre-felling forest inventory using systematic-line-plots and determination of cutting regimes
E1 to E	Climber cutting to reduce damage during logging. Tree marking incorporating directional felling. No marking of residual trees for retention.
E	Felling of all trees as prescribed
E+2 to E+5	Post felling inventory using systematic-line-plots to determine residual stocking and appropriate silvicultural treatments

3. Analysis of Stand Structure and Diversity

3.1. Aspects and scales in quantifying the structure of forest stands

Forest conditions have been conventionally interpreted by their composition, structure and functions. In this respect, various efforts considerably contributed to the knowledge on forest structure, its dynamics, and its significance in ecosystems (e.g., Franklin et al., 1981; Harmon et al., 1986; Spies et al., 1990; Ruggiero et al., 1991; Spies, 1997). It has become apparent that the existing bio-physical structure of three-dimensional forest systems is the result of ecological processes and human influence. The composition and structure will in turn influence ecosystem functions. Forest structure can therefore be thought of as both a product and driver of ecosystem processes and biodiversity. Consequently, understanding forest structure can help unlock an understanding of the history, function, and future of a forest ecosystem (Spies, 1998) and such knowledge of variation in forest structure over time and space can serve as the basis for forest management strategies that seek to sustain a broad array of forest goods and services (Spies et al., 1991; McComb et al., 1993).

There has been a long history of traditional practices in forestry that variations in forest structure is typically manipulated and restricted to maximize timber output (see Franklin et al., 1981; Hansen et al., 1991). Therefore, the three-dimensional geometry of stands has both ecological and economic implications (Kint et al., 2003). However, the term "forest structure" encompasses many things and can be described in numerous ways. It needs to be described for simplifying the process of measuring, understanding, and manipulating forests and hence making objective decisions in management planning. In fact, the measurement of structural heterogeneity, complexity and diversity, however, is not relatively simple. More importantly, forest management planning would appreciate variables, which can be easily measured and taken into account in practical forestry (Jaehne and Dohrenbusch, 1997).

By definition, stand structure is related to the spatial and temporal arrangement of individual trees in the forest stand. The spatial structure defines the organization of the trees in space while temporal structure refers to successional patterns over time. Different studies revealed that spatial pattern of the tree locations strongly affect (1) competition among neighbouring trees, (2) size variability and distribution, (3) regeneration, growth and mortality, and (4) crown structure (e.g., Kuuluvainen and Pukkala, 1987; Kenkel, 1988; Kenkel et al., 1989; Moeur, 1993; Rouvinen and Kuuluvainen, 1997; Newton and Jolliffe, 1998; Pretzsch, 1995; Emborg, 1998; Dovciak et at., 2001). The number and distribution pattern of different tree species control a variety of biotic and abiotic processes through setting diverse light regimes (Canham et al., 1994) and litter composition (Ferrari, 1999). Likewise, vertical and horizontal size differentiation determines the spatial variation in microclimatic conditions, availability of resources, varied niches, thus directly and indirectly affecting the biological diversity (see Spies 1998; Brokaw and Lent 1999).

Therefore, the structure of a forest stand may be defined by three major aspects: the spatial distribution of the tree position (i.e., spatial distribution), the particular mingling patterns of the different tree species (i.e., mixture), and the spatial arrange of the tree dimensions (i.e., size differentiation) (see Albert and Gadow, 1998; Gadow and Hui, 2002; Pommerening, 2002; Aguirre et al., 2003). In fact, the spatial structure of a particular forest is scale-dependent. It implies that the pattern of a particular stand in a given scale may change at other scales. In order to reflect the scale effects in quantifying spatial forest structure, various measures were introduced to evaluate the three critical aspects of the forest structure at different scales. In terms of spatial scale, the pattern of a stand can broadly be categorized as whole stand pattern (i.e., macroscale structure), neighbourhood pattern (i.e., microscale structure) and point pattern. A classification of measures characterizing critical aspects of spatial forest structure at different scale is presented to get a deeper insight into the different concepts (see Figure 3.1)

3.2. Whole stand pattern analysis

In the 1950s and 1960s numerical variables were developed to describe important aspects of spatial variability at forest stand level by a single average value. Well-known indices are the aggregation index (Clark and Evans, 1954), the Shannon index (Shannon, 1949), the segregation index (Pielou, 1977). The Clark and Evans index has been used to describe the spatial distribution of the individual trees while the Shannon index was used as a measure of species diversity. Similarly, the Pielou's segregation index was defined to account for species mingling at the stand-level.

The spatial index proposed by Clark and Evans (1954) can provide a first general impression of the structure of a particular forest stand, but they cannot be used to describe the great variety of spatial arrangements (Zenner and Hibbs, 2000). This deficit is especially serious in very irregular stands where small-scale structural characteristics are highly variable (Albert, 1999). The Shannon index is in fact a distance-independent measure and has been used to quantify the species diversity and variation in tree sizes as elements of biodiversity based simply on the proportion of attributes without any spatial information. The Shannon index therefore quantifies species richness or size class richness of the entire stand, hence representing species and size diversity at a stand-level, but disregarding small-scale differences. When assessing the biodiversity by sampling, the sampling method and intensity have a significant effect on the index-values (Pelz and Luebbers, 1998). Distance-dependent variables such as Pielou's segregation index have the major disadvantage of a possibly large sampling error due to edge effects when used on small plots. More importantly, the description of stands using such average or summary measures are no longer adequate for present day forest management processes that need to account for the trade off between contrasting benefits. Figure 3.1 gives an overview of the critical aspects of stand structure based on different measures.

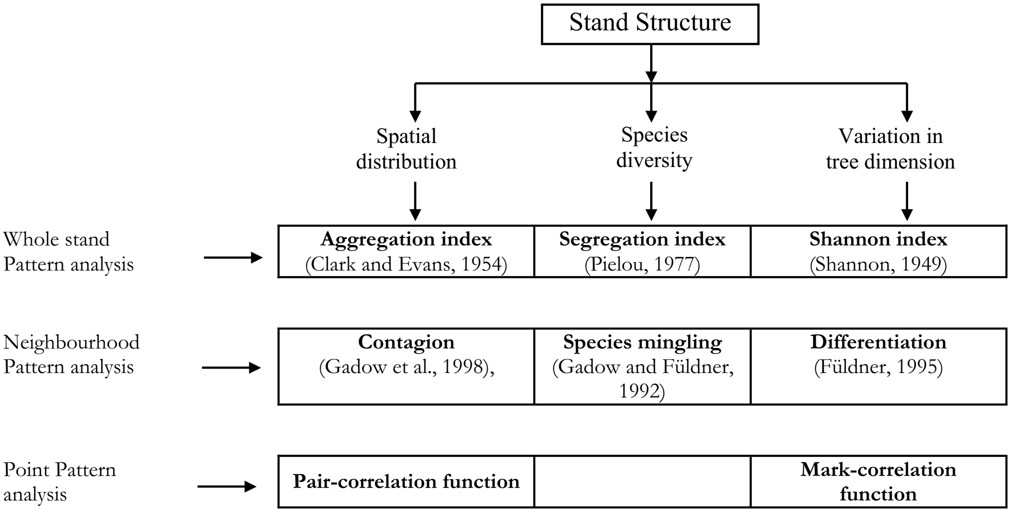


Figure 3.1 Overview of the critical aspects of stand structure and groups of measures by which forest structure is assessed (modified based on Albert, 1999; Pommerening, 2002)

3.3. Neighbourhood pattern analysis

Nowadays, an exact description of small-scale structural attributes is considered to be increasingly important as a basis for silvicultural decision-making in regions where selective harvesting and continuous cover forest management is practiced (Spellmann, 1995; Albert, 1999). In this study, a special attention therefore was drawn to three neighbourhood-based variables defined as contagion (Gadow et al., 1998), mingling (Gadow and Füldner, 1992), and differentiation (Füldner, 1995) to define the small-scale spatial structural of a stand by the spatial distribution of the tree positions, by the spatial mingling of the different tree species, and by the spatial arrangement of the tree dimension. These parameters can be used to provide a comprehensive description of the spatial structure of a stand (Gadow and Hui, 2002; Augirre et al., 2003).

By using these neighbourhood-based variables, assessment and description of the spatial forest structure could be defined either as tree-based or point-based. In the tree-based approach, a sample tree closet to a sample point is chosen as reference tree and the attributes of its immediate neighbours (e.g., size, species) and the regularity of their positions are related to the reference tree. In the point-based approach, the structural attributes of a neighbourhood group of trees (variation of tree species and sizes; regularity of tree positions) are assessed at each sample point (Staupendahl, 2001). In this study, the tree-based approach was adopted and four neighbours were related to every reference tree based on practical considerations in connection with field assessment methods as suggested by Albert (1999) and Hui and Hu (2001).

3.3.1. Contagion

The contagion index was first proposed by Gadow et al. (1998) as *Winkelmass* (a German word meaning *uniform angle index*) and then interchangablely used as aggregation or regularity index (Gadow and Hui, 2002). The contagion describes the degree of regularity of the spatial distribution of the trees nearest to a reference tree. This variable is based on the classification of the angles between the immediate neighbours in terms of the reference tree. An immediate neighbour is the next tree following a given clockwise (or anticlockwise) direction. A special case is a constellation in which the angle between two trees exceeds 180 degrees. Between such two trees, the angle measurement is taken in the opposite direction, thus the used angle between any two trees is always less than 180 degrees. An appropriate reference quantity is the standard angle, which would be the angle if the distribution would be perfectly regular. In the case of a four-tree sample, the standard angle could, for instance, assume a value of 360/4 = 90 degrees. However, Hui and Gadow (2002) found, based on a simulation study, the optimum standard angle producing a random distribution to be 72 degrees. The binary random variable is then determined by comparing each angle with the standard angle. The contagion can further be defined as the proportion of angles between the four neighbouring trees, which are smaller than the standard angle (see equation 3.1).

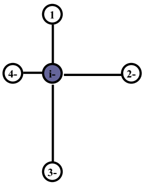
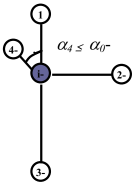
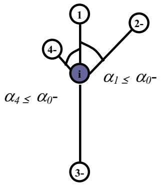
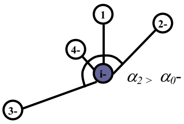
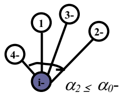
$$W_i = \frac{1}{4}\sum_{j=1}^{4} v_j \tag{3.1}$$

$$v_j = \begin{cases} 1, & \alpha_j < \alpha_0 \\ 0, & \textit{otherwise} \end{cases} \quad \textit{and} \quad 0 \le W \le 1$$

where,

W_i = the contagion for the reference tree i
v_j = the binary variable
α_j = the angle between neighbouring trees
α_0 = the standard angle (i.e., 72 degrees)

With four neighbours, there are five possible values that W_i can assume. $W_i = 0$ indicates that the trees in the vicinity of the reference tree are positioned in a regular manner, whereas $W_i = 1$ points to an irregular or clumped distribution (see Figure 3.2).

very regular	**regular**	**random**	**irregular**	**very irregular**
				
$W_i = 0.00$	$W_i = 0.25$	$W_i = 0.50$	$W_i = 0.75$	$W_i = 1.00$
none of the α_j is smaller than α_0	one of the α_j is smaller than α_0	two of the α_j is smaller than α_0	three of the α_j is smaller than α_0	all four of the α_j is smaller than α_0

● the reference tree ① ② ③ ④ neighbouring trees

Figure 3.2 Possible values of the contagion at a particular reference tree.

The estimator for the contagion of a given forest is the arithmetic mean of all W_i-values. Gadow and Hui (2002) demonstrated through a simulation that W_i mean values fallowed the normal distribution in which 99.7% of all values are found within the interval $\mu \pm 3\sigma$ with lower and upper bounds of 0.475 and 0.517 and concluded that using a standard angle of 72°, $\overline{W}$ -values of less than 0.475 were most likely from a regular distribution and those greater than 0.517 were most likely from a clumped distribution. However, they also pointed out that there were no exact thresholds and the two zones of transition between random and regular and between random and clumped were rather narrow. Although the contagion mean value $\overline{W}$ is quite informative for characterizing a point distribution, it is often advisable to study the distribution of the W_i values which reveals the structural variability in a given forest stand.

3.3.2. Species mingling

Mingling describes the species variety in the vicinity of a given reference tree and has been defined in this case as the proportion of the four nearest neighbours that do not belong to the same species (Gadow and Füldner, 1992) (see equation 3.2).

$$M_i = \frac{1}{4}\sum_{j=1}^{4} v_j \qquad (3.2)$$

$$v_j = \begin{cases} 1, \textit{neighbour } j \textit{ belongs to the same species as reference tree } i \\ 0, \textit{otherwise} \end{cases} \qquad \textbf{and} \quad 0 \leq M_i \leq 1$$

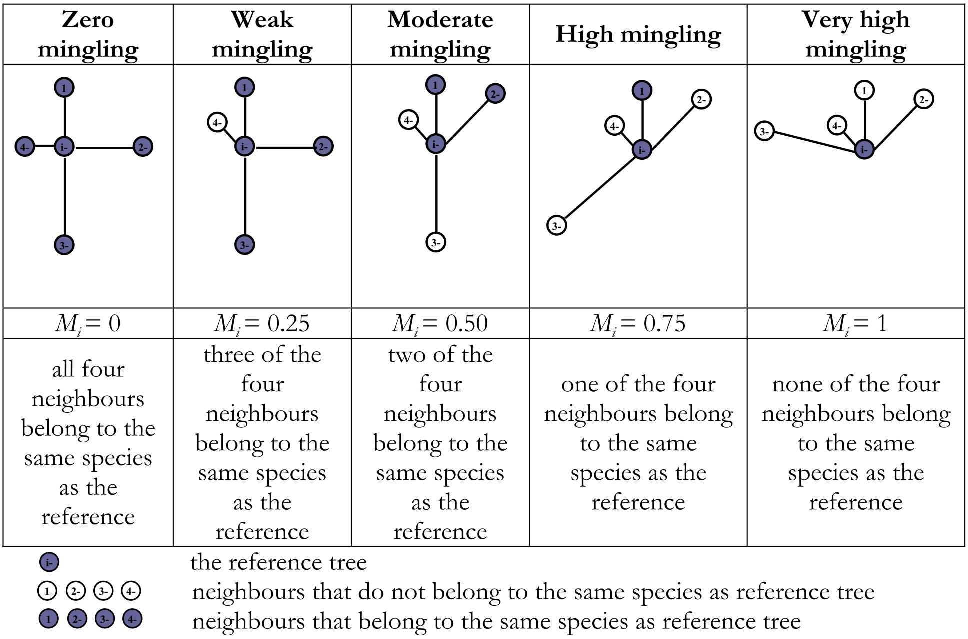
Where,
M_i = the mingling for the reference tree i
v_j = the binary variable

With four neighbours, there are five possible values that M_i can assume. $M_i = 0$ indicates that the trees in the vicinity of the reference tree are the same species with the reference tree, whereas $M_i = 1$ points to all neighbours considered are different species as the reference tree (see Figure 3.3). Mingling can be used to describe spatial diversity as a function of a specific tree attribute. Of particular interest is species-specific mingling. Then the relation between the average mingling value of a given species and the proportion of the number of trees that the species contributes to the stand as a whole (P_{sp}) can be expressed by the following ratio:

$$M_{ratio} = \frac{1 - P_{sp}}{\overline{M}_{sp}} \qquad (3.3)$$

where,
P_{sp} = the proportion of the number of trees of a particular species in the stand
$\overline{M}_{sp}$ = the average mingling value of that species

Graz (2002) found that the low value of M_{ratio} indicates a high degree of clumping of a particular species within the forest, while a value close to 1 indicates a more even distribution.



Zero mingling	**Weak mingling**	**Moderate mingling**	**High mingling**	**Very high mingling**
$M_i = 0$	$M_i = 0.25$	$M_i = 0.50$	$M_i = 0.75$	$M_i = 1$
all four neighbours belong to the same species as the reference	three of the four neighbours belong to the same species as the reference	two of the four neighbours belong to the same species as the reference	one of the four neighbours belong to the same species as the reference	none of the four neighbours belong to the same species as the reference

● the reference tree
○ ○ ○ ○ neighbours that do not belong to the same species as reference tree
● ● ● ● neighbours that belong to the same species as reference tree

Figure 3.3 Possible values of the species mingling at a particular reference tree.

3.3.3. Size differentiation

The tree attribute dominance (Hui et al., 1998) relates the relative dominance of a given tree to its species to the immediate neighbours. It is defined here as the proportion the four nearest neighbours of a given reference tree which are smaller than the reference tree (see equation 3.4).

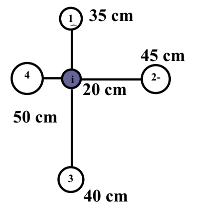
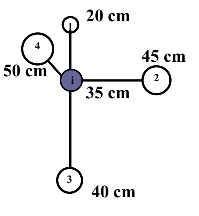
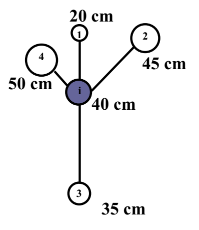
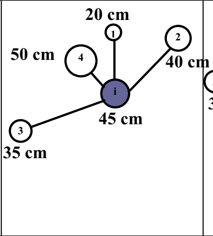
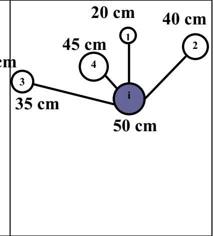
$$U_i = \frac{1}{4}\sum_{j=1}^{4} v_j \tag{3.4}$$

$$v_j = \begin{cases} 1, & neighbour\ j\ is\ smller\ than\ reference tree\ i \\ 0, & otherwise \end{cases}$$ ***and*** $0 \leq U_i \leq 1$

Where,
U_i =the dominance criterion of the reference tree *i*
v_j = the binary variable

With four neighbours, U_i can assume five values. $U_i = 0$ indicates that the reference is very suppressed while U_i=1 indicates that the reference tree is very dominant (see

Figure 3.4). The dominance criterion can also be used as the species–specific dominance.

Very suppressed	Moderately suppressed	Co-dominant	dominant	Strongly dominant
				
$U_i = 0$	$U_i = 0.25$	$U_i = 0.50$	$U_i = 0.75$	$U_i = 1$
all four neighbours are larger than the reference tree i	three of the four neighbours are larger than the reference tree i	two of the four neighbours are larger than the reference tree i	one of the four neighbours are larger than the reference tree i	none of the four neighbours are larger than the reference tree i

● the reference tree ①②③④ neighbouring trees (Note the size difference)

Figure 3.4 Possible values of the dominance at a particular reference tree.

3.4. Point pattern analysis

A forest stand can be reduced to a finite set of points - a point pattern- to represent the horizontal locations of trees in the stand. Then, the spatial pattern of trees can be described by using spatial point process (Tomppo, 1986). If, in addition to the locations of the trees, various qualitative or quantitative tree characteristics such as tree species, sizes and so on are taken simultaneously into account in the analysis, the forest stand can be represented as a marked point pattern. The theory of marked point process then offers various characteristics for the quantitative description of the interaction of trees in a forest (Penttinen et al., 1992). Indeed, the study of spatial point patterns has a long history in ecology and forestry (e.g., Goodall, 1952; Pielou, 1977).

The aim of the analysis of spatial patterns is to measure, by using quantitative characteristics, how individuals are located with respect to each other and to describe with mathematical models the laws regulating the locations (Tomppo, 1986). The general concern is answering questions about the distribution of those locations, specifically whether they are clustered, randomly or regularly distributed. Therefore, methods for spatial point patterns often involve a comparison between empirical summary descriptions of the pattern and the corresponding theoretical summary descriptions of a point process model. Unlike classical statistical applications, the observed point pattern is only an available realization (or measurement). This important limitation imposes in practice a common assumption on "stationary" and "isotropy" to overcome technical difficulties. In this respect, stationary means that all properties of the process are invariant under translation (i.e., its properties do not vary from one point in space to another), isotropy that they are invariant under rotation (i.e., its properties do not vary with space orientation)(Diggle, 2003). This implies that there are no systematic fluctuations of point density and no preferred directions in the point pattern.

3.4.1. Pair correlation function and Ripley's *K*-function

Under the assumptions of stationary and isotropy, the main characteristics of a univariate point process (i.e., the pattern has only a single point type) can be summarized by density (first-order property) and product density function (second-order property). In this respect, the first-order property of the intensity measure plays a similar role in the theory of point processes as the mean does for a random variable while second-order characteristics have some similarity to correlation functions of a stochastic process. In point process theory, a normalized quantity of the product density function referred to as the "pair-correlation function" (Cressie, 1993; Stoyan and Stoyan, 1994) is usually used to summarize a univariate point process. Indeed, it is not a distribution function in the accepted statistical sense (Diggle, 1983; 2003), but is a second-order function of nature similar to that of a density function (Stoyan and Penttinen, 2000). Generally, the pair-correlation function can take all values between zero and infinity, but for large distance, it approaches to one. For a completely random point process, the function equals one. Values of the function larger than 1 indicate that particular inter-point distances are relatively more frequent compared to those in a complete random point process, which is typical of a cluster process. Conversely, values smaller than 1 indicate that the corresponding distances are rare and this is typical of an inhibition process.

Ripley (1977) proposed a reduced second moment measure as an alternative function characterizing the second-order properties of a stationary isotropic process. It is therefore well known as Ripley's K function. One definition of which is

$$K(r) = \frac{E[N_0(r)]}{\lambda} \tag{3.5}$$

where,

$K(r)$ = Ripley's *K*-function
$E[N_0(r)]$ = expected number of further points within distance r of an arbitrary point
λ = density, i.e., number of points per unit area

With assumptions of an orderly process (meaning that multiple coincident points cannot occur), it is possible to establish the relationship between a pair correlation function and Ripley's K-function by the equation (3.6) mentioned below (for detail formulations see Diggle, 1983; 2003).

$$g(r) = \frac{1}{2\pi r} * K'(r) \tag{3.6}$$

Where,
$g(r)$ = pair-correlation function
λ = intensity
$K'(r)$ = first derivative of the Ripley's K-function
r = distance

Note that the pair correlation function and the K-function respond to slightly different biological questions. The K-function can detect aggregation or dispersion *up to* a given distance r, whereas the pair correlation function can detect aggregation or dispersion *at* a given distance r. Therefore the K-function has a similar relation to the cumulative distribution function while the pair correlation function is related to the probability density function for random variables. The pair correlation function with the interpretation of a neighbourhood density thus has the additional advantage that it is easier to interpret (Stoyan and Stoyan, 1994) and more intuitive than a cumulative measure (Stoyan and Pettinen 2000). Wiegand and Moloney (2004) therefore argued that second-order spatial analysis should include not only the cumulative K-function, but also the complementary pair correlation function. Accordingly, the pair-correlation function is more suitable for exploratory statistics whereas the K-function is better when used in the final stage of confirmatory analysis, particular for goodness-of-fit tests (Stoyan and Stoyan, 1994). Besag (1977) proposed the L(r) function given in equation (3.7), a normalized counterpart of the K-function, to stabilize variances and to improve interpretation.

$$L(r) = \sqrt{\frac{K(r)}{\pi}} - r \tag{3.7}$$

In a Poission process, $L(r)$ therefore equals zero at every distance. If $L(r)$ is negative (i.e., it is smaller than expected under the Poisson process assumption), the points are relatively far from each other, suggesting regularity, inhibition or repulsion. In contrast, the positive values of $L(r)$ (i.e., $L(r)$ is larger than expected) indicates that points are clustered or attracted. The $L(r)$ function can thus be used more effectively for examining the type of point pattern as a function of scale (Moeur, 1993).

The definition of the *K*-function based on the expression of an observable quantity has a practical importance when estimating the function from data. Ripley (1976; 1981) therefore proposed a common analytical estimator for the *K*-function (equation 3.8) by relating the theoretical definitions and observed numbers of ordered pairs and the density of points:

$$\hat{K}(r) = A * \frac{1}{n^2} * \sum_{i=1}^{n} \sum_{j \neq i} \delta_{ij}(r), \qquad for \quad i \neq j \tag{3.8}$$

where,

$K^{\wedge}(r)$ = estimator of the K-function
n = number of points
A = area of the study region
δ_{ij} = counter variable [$\delta_{ij}(r) = 1$ if $r_{ij} \leq r$, and $\delta_{ij}(r) = 0$ otherwise]

It is noticeable that the summation in the above equation (3.8) necessarily excludes pairs of points for which the second point is outside the study region and therefore unobservable. It simply implies that points located close to the domain border are problematic because a part of the circle inside which points are supposed to be counted is outside the domain. Ignoring this edge effect results in underestimating the *K*-function (Marcon and Puech, 2003). Several methods have been proposed to correct this source of bias (see Ripley, 1984; 1988; Diggle, 1983; 2003). However, the edge-correction scheme proposed by Ripley (1977) has been widely applied in the literature (Marcon and Puech, 2003). Based on the estimated *K*-function and the relationship expressed in equation (3.6), a pair correlation function can further be estimated using smoothing splines to approximate the derivative.

The classical exploratory approach for univariate point patterns is to compare a given point pattern to the null model of a homogeneous Poisson process which generates patterns consistent with complete spatial randomness (CSR) (Wiegand and Moloney, 2004). The essence of CSR is that points are located independently of each other (implying that there are no interactions amongst the points). When the occurrence of a point at a particular location makes it more likely that other points will be located nearby, the resulting patterns display a kind of pattern, which might loosely be described as "aggregated". In contrast, when each point is likely to be surrounded by an empty space, the overall pattern will be of a more "regular" spatial distribution of points (Diggle, 2003). Accordingly, CSR acts as a dividing hypothesis to distinguish between patterns, which are broadly classified as "regular" or "aggregated" (Diggle, 1983; 2003).

For examining the type of pattern as a function of scale, estimated values of $L(r)$ are compared to a benchmark given by a homogenous Poisson process where $L(r) = 0$ at every distance r. The most common approach however is to develop a confidence envelope from multiple realizations generated from a Poisson process using Monte Carlo techniques (e.g., Diggle, 1983; Ripley, 1988; Moeur, 1993; Stoyan and Stoyan, 1994; Diggle, 2003). Besag and Diggle (1977) proposed a simple procedure for generating a confidence envelope through Monte Carlo simulation. A hypothesis test is used to compare the observed distribution with values obtained from multiple realizations generated from a Poisson model. If $\hat{L}(r)$ falls outside the confidence region around the Monte Carlo distribution of the multiple random realizations, the observed distribution is judged to be non-random. Furthermore, the scale (i.e., values of r) and direction (above the upper or below the lower envelope boundaries) of the departures from randomness provide additional insight into the pattern (Moeur, 1993).

An important generalization arises if there are points of several distinguishable classes or types, the process is then called multivariate (see for more detail Cox and Isham, 1980). In fact, a multivariate process is composed of a set of possibly interdependent univariate processes realized on the same space. Since various types of points coexist in the study region, it might be profitable to analyse the pattern of interdependence amongst the different components patterns. Accordingly, the various summery descriptions introduced for univariate pattern can be extended to cover the multivariate case (Diggle, 1983). However, primarily because of its exceeding complexity, its applications to multiple point patterns have been limited to pairwise interactions among two or three types of points (see Diggle, 1983; Penttinen et al., 1992; Szwagrzyk and Czerwczak, 1993; Moeur, 1993; Peterson and Squiers, 1995; Mateu et al., 1998), which are based on the same ideas as univariate (single point type) models.

A natural working hypothesis in a bivariate point process is that the process consists of two independent components. Independence is analogous to complete spatial randomness for a univariate pattern in that it provides a convenient reference point for the characterization of more interesting bivariate structures (Diggle, 1983). For a preliminary analysis of a bivariate pattern of events, the hypothesis of independent components might be used as a dividing hypothesis in order to classify the components as positively or negatively dependent. Given a complete map, formulating a class of bivariate models and testing for independence within this class might be considered, but for a preliminary analysis, it still seems preferable to avoid such parametric assumptions (Diggle, 1983). The plot of the empirical K-function for a bivariate process, accompanied by simulation envelopes to assess sampling fluctuations, is often quite informative. For a square or rectangular region, Lotwick and Silverman (1982) proposed a procedure for conditional Monte Carlo tests through random toroidal shift for developing a confidence envelope.

3.4.2. Marked correlation function

A second general framework for bivariate processes arises if assumptions were made such that locations are determined by a univariate spatial point process, and types then determined by a second random mechanism (Diggle, 1983). In other words, while recognizing their locations, each event in the process is assigned some qualitative or quantitative features called marks. The resulting process can be referred to as a "marked point process". In the theory of point processes, a mark is a value which is assigned to an event (Pommerening, 2002). It is also possible to consider simultaneously a collection of marks for each event. A good example of a marked point process model is that the points are tree positions and the marks are qualitative or quantitative tree characteristics, for instance, tree species, or tree sizes. For marked points pattern, there are further second-order characteristics describing the correlation between the marks (Stoyan and Stoyan, 1994). Particularly important is the mark correlation function.

3.5. Empirical data

Three stands of quite different types were selected in the Paunglaung watershed in order to pinpoint the diverse nature of forests only within a watershed area. The first stand is located near Sinthwat village that can be classified as a mixed deciduous forest according to the departmental instructions of the Forest Department of Myanmar. The second one is sited near Nansake village on the east bank of the Paunglaung river whereas the third stand is situated near Thapyaygone village on the west bank of Paunglaung river. Both stands of Nansake and Thapyaygone can be identified as evergreen forests, but they can further be subcategorized as typical and hill evergreen forests respectively. In each stand, a 1-ha square plot of 100 * 100 m was established and all trees with diameter at breast height (dbh) larger than 20 cm were identified and measured with diameter types. Heights and crown classes of all trees with ≥ 20 cm dbh were also measured and assessed, and their locations were recorded. The establishment of the plots, measuring and assessing procedures followed the field instructions of National Forest Survey and Inventory (see detail in Forest Department, 1985). The spatial distributions of trees ≥ 20 cm dbh in each research plot and respective stand parameters are presented in Figure 3.5.

The Thapyaygone plot seems to be the most diverse stand because it contains a total of 42 tree species while Sinthwat and Nansake have only 34 and 24 species. However, not only more commercial trees species but also a greater number of commercial trees are found in the Sinthwat plot compared to the other two. In Sinthwat, there are 59 commercial trees, comprising 53% of a total number of trees found in the plot and 9 commercial tree species, representing 27% of all trees species identified. The largest number of trees are found in Thapyaygone plot (i.e., 140), but Nansake plot has the largest basal area (i.e., 45.78 m²) contributed from large dipterocarp trees.

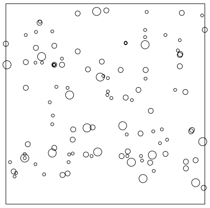
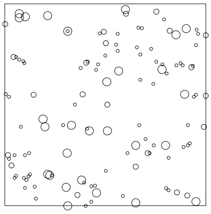
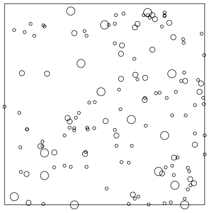
			
Plot	Sinthwat	Nansake	Thapyaygone
Forest type	Mixed deciduous	Typical evergreen	Hill evergreen
Number of trees (≥ 20 cm dbh)	111	123	140
Number of species	34	24	42
Number of commercial trees	59 (53%)	35 (29%)	35 (25%)
Number of commercial species	9 (27%)	4 (17%)	6 (14%)
Stand basal area	18.16 m²	45.78 m²	20.70 m²

Figure 3.5 The spatial distribution of trees ≥ 20 cm dbh in three different research plots covering 1 ha each, and the respective stand parameters.

3.6. Developing algorithms for calculating variables and functions

The calculations for all neighbourhood-based variables of contagion, species mingling and size differentiation were carried out using the SAS system (Statistical Analysis System) version 8. Separate algorithms were developed for each variable within the SAS system to improve internal consistency in the calculation process. The buffer method was adopted to eliminate the edge effects and improve the accuracy of the estimates. The buffer was defined based on the maximum distance between two nearest trees in a given stand, which was found to be 10 m in all study plots. It is in fact the simplest method for boundary correction in the point pattern analysis, but it substantially reduced the information collected. Thus the calculation only covered 84 out of 123 trees in the Sinthwat plot, 67 out of 135 trees in the Nansake plot and 84 out of 140 trees in the Thapyaygone plot.

Likewise, different algorithms for calculating second moment measures of point patterns were also developed in R version 2.0.0 (Programming Environment for Data Analysis and Graphic) developed by the R Development Core Team. Various default functions of the library SPATSTAT version 1.5.4 developed by Baddeley and Turner (2005) were widely used in calculating. In all situations, the border correction scheme proposed by Ripley (1977) was used to reduce edge effect and improve accuracy of estimates. Short simulation programs for generating the particular confidence envelope for the test of complete spatial randomness and of independence were also developed. Stepwise verification and validations were carried out to obtain internal consistency and external validity.

3.7. Results

3.7.1. Spatial arrangement of tree locations

Contagion values were estimated for each research plot for assessing quantitatively the spatial locations of the trees on a finer scale. Then contagion distributions were developed for the different plots. The estimated $\overline{W}$ values for the 3 study stands of Sinthwat, Nansake and Thapyaygone are 0.530, 0.530 and 0.491 respectively. It can be inferred based on the work of Hui and Gadow (2002) that the stands of Sinthwat and Nansake have spatial distributions characterized as clumped while the stand of Thapyaygone has a random distribution in the spatial arrangement of the tree locations. The contagion distribution in the three research plots differ with regard to their means and variances (see Figure 3.6).

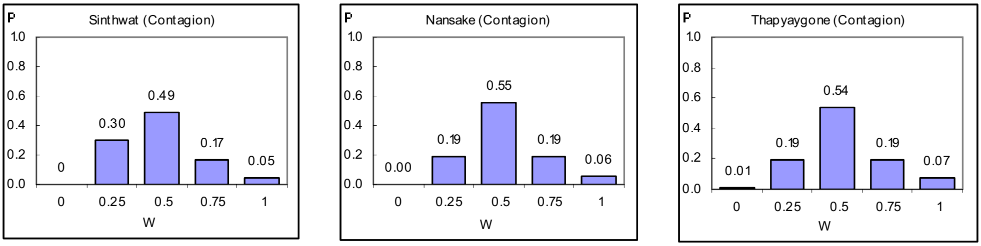


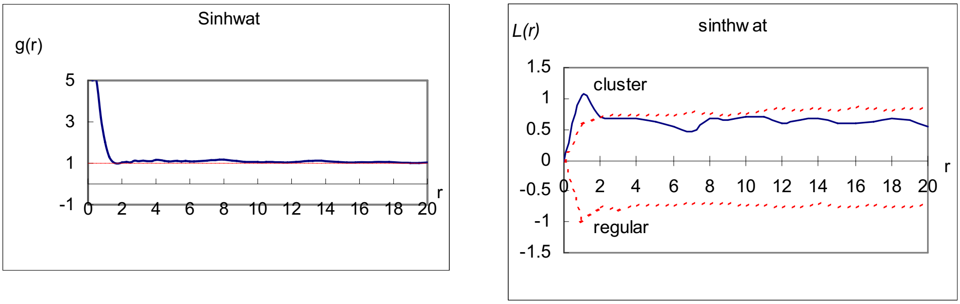
Figure 3.6 Contagion distributions in the three research plots.

The pair correlation functions were also estimated to provide more information on the overall pattern of tree locations. *L(r)* functions were also calculated for testing the existing spatial point patterns were significantly different from the complete spatial randomness. A confidence envelope was developed from multiple realizations of a

Poisson process through Monte Carlo simulation. In this study, 1000 random realizations were drawn in each simulation for values of distances from 0 to 20 m in 1 m increments, $L\hat{}_{24}(r)$ and $L\hat{}_{976}(r)$ defining the lower and upper boundaries of a two-sided pointwise 95% confidence envelope.

The estimated second moment measures of the pair-correlation function and *L*-function for the Sinthwat plot are shown in Figure (3.7). These data summaries indicate that the cluster process between trees exists. It has the typical from of the pair correlation function for a cluster process (see Figure 3.7 (a)). The pair-correlation function of Sinthwat plot almost allways takes on a value greater than 1, which means that at these distances there are more trees observed than would be expected under random conditions. However, the curve for *g(r)* reaches 1 at distance of 2 m and then shows indistinct fluctuations around 1 for further distances, one can conclude that inter-tree interaction does not go further than 2 m. The range of correlation in that stand is only about 2 m.

This situation can be confirmed from the observation of the *L(r)* function (see Figure 3.7 (b)). It is also revealed that the estimated *L(r)* values for all inter-tree distances of Sinthwat are positive, implying clustering. However, a cluster process is significant only up the inter-tree distance of 2 m. Since the estimated *L(r)* curve lies almost inside the confidence envelope except for these distances mentioned above, it is not possible to reject the null hypothesis of the complete spatial randomness with 95 % confidence, suggesting that trees other than those inter-tree distances of 2 m, are distributed randomly. Trees with an inter-tree distance less than 2 m seem to be relatively more frequent, so that there must be a cluster process perhaps resulting from overdue tending operations, e.g., improvement felling.

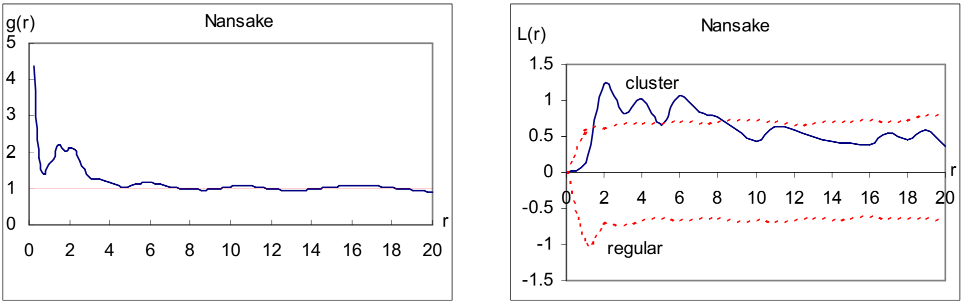


(a) the estimated pair-correlation function for the locations of trees

(b) the estimated L-function (solid line) and a 95% acceptance region (dashed line) for the Poisson process hypothesis

Figure 3.7 The estimated second-moment measures for the stand of Sinthwat

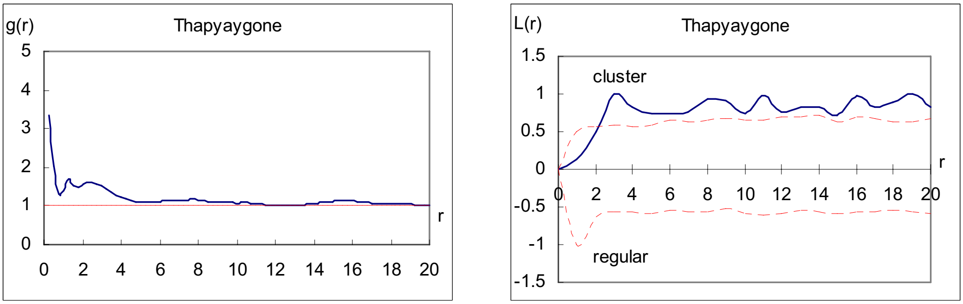
In Nansake (see Figure 3.8 (a)) the curve for a pair-correlation function *g(r)* approaches 1 at r = 8 m. It can be concluded that the interaction does not go further than 8 m and the fluctuation for larger values of *r* is only due to a random rise and fall around the value one. Figure 3.8 (b) also confirms that the cluster process between the distances 2 to 8 m is significant. The spatial location of trees inside the stand of the Thapyaygone shows also a typical cluster process (see Figure 3.9). The *g (r)* curve almost bares the value larger than one for all distances. It implies that at every inter-tree distance, there are relatively more trees compared to those in a complete random point process. The clustered process is significant at all distances larger than 2 m since the curve of *L(r)* explicitly lies outside the acceptance region.



(a) the estimate of pair-correlation function for the locations of trees

(b) the estimate of L-function (solid line) and a 95% acceptance region (dashed line) for the Poisson process hypothesis

Figure 3.8 The estimated second-moment measures for the stand of Nansake



(a) the estimate of pair-correlation function for the locations of trees.

(b) the estimate of L-function (solid line) and a 95% acceptance region (dashed line) for the Poisson process hypothesis

Figure 3.9 The estimated second-moment measures for the stand of Thapyaygone

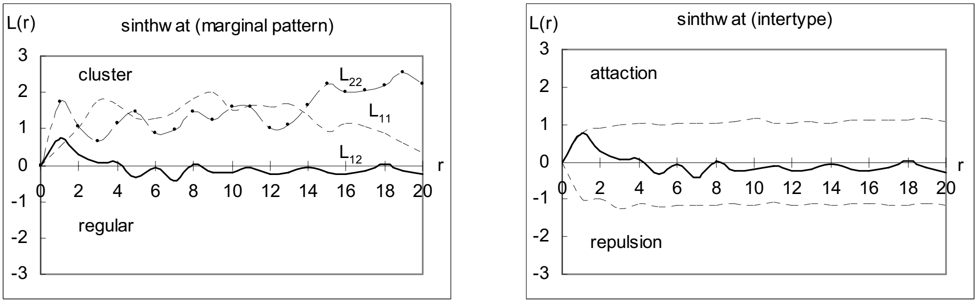
3.7.2. Marginal patterns and interrelation between commercial and non-commercial species

In a bivariate process, there are essentially four elements that may be considered: 1) the pattern of type *i* points viewed on its own; 2) the pattern of type *j* points viewed on its own; 3) the combined pattern of the intermingled type *i* and type *j* points; and 4) the interaction between the type *i* and the type *j* pattern. The first two elements can be perceived as marginal patterns of the individual component types and the third element as a composite pattern. Since the first three elements of a bivariate pattern (i.e., two marginal patterns and one composite pattern) refers to a single point pattern, the methods of analysis that are concerned for a univariate point process can be used to draw conclusions about each pattern. The appearance of combined pattern that welds the marginal patterns and the composite pattern reflects the fourth element of the bivariate process, namely the interrelation between the two point types.

A natural extension of the *L*-function for a bivariate point process can be used to conceive the underlying interrelation between component types (i.e., attraction, independence or repulsion). A suitable diagnostic step would be to superimpose the graphs of three *L*-functions of two separate marginal processes and the interrelation process between component types and then examine the extent of their correspondence. For the goodness-of-fit test for the hypothesis of the dependence of two point types, a confidence envelope is generally developed through conditional Monte Carlo realizations.

In order to investigate the marginal patterns of commercial and non-commercial species, the *L*-functions were estimated for commercial species and non-commercial species separately. Commercial species were specified according to the grouping system of the Forest Department of Myanmar. These essentially included Teak, all (8) species of the commercial group I and, all (26) species of the group II. In addition, Taung-thayet (*Swintonia floribunda*), which belongs to group III, but with a locally preferable wood quality, is considered as a commercial species in this study. Thus a total of 36 species were categorized as commercial and other remaining species as non-commercial. Then a bivariate *L*-function was also estimated for testing the hypothesis of independence between the two categories. The confidence envelope was formed from the actual n_1 commercial trees and multiple Monte Carlo realizations of a n_2 Poisson population of non-commercial trees. *L*-functions were estimated for every distance of 1 m up to 20 m and then $\hat{L}_{24}(r)$ and $\hat{L}_{976}(r)$ from the ordered 1000 realizations were defined as the lower and upper boundaries of the 90% confidence envelope for two-sided tests.

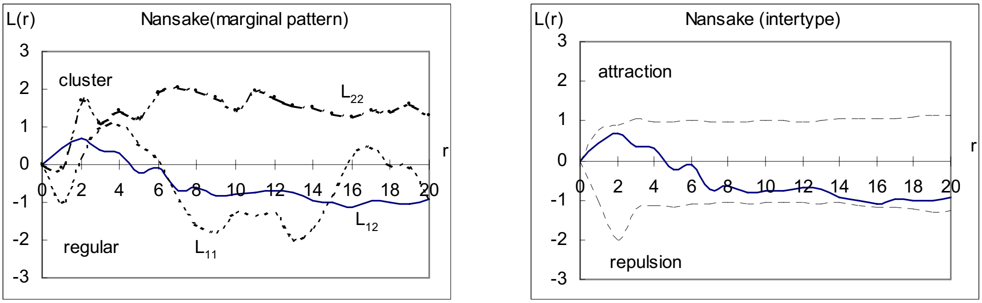
Figure 3.10 shows the marginal patterns and the interrelation between commercial and non-commercial species in the stand of Sinthwat. In Figure 3.10 (a), the L_{11} (marginal pattern of commercial species) and L_{22} (marginal pattern of non-commercial species) have positive values at all inter-tree distances. This simply implies that the marginal patterns of both commercial and non-commercial species have cluster processes. But the curve for L_{12} (interaction) in Figure 3.10 (a) fluctuates around the value of zero at all inter-tree distances, indicating that commercial and non-commercial species in the Sinthwat stand are located independently of each other. Since the L_{12} curve in Figure 3.10 (b) runs for all distances noticeably inside the acceptance region, it is not possible to reject the null hypothesis of independence at the risk of 10%. It supports the conclusion that there is no spatial correlation between commercial and non-commercial species in the stand.



(a) (b)

Figure 3.10 Marginal patterns and the interrelation pattern of commercial and non-commercial species at Sinthwat: (a) Comparison of marginal patterns of commercial species (L_{11}), non-commercial species (L_{22}) and the interrelation pattern between them (L_{12}) (b) the interrelation pattern L_{12} (solid line) and the confidence envelope formed from conditional Monte Carlo simulation (dashed line)

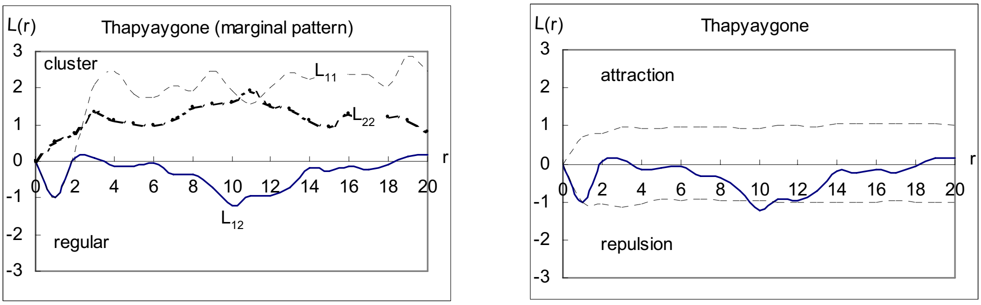
In Nansake (see Figure 3.11 (a)), L_{11} has negative values at some particular distances and positive values in others while L_{22} merely retains values larger than one for all inter-tree distances. It can firstly be inferred that most trees of the commercial species are distributed as clusters at some distances, but few trees are located regularly in other distances. Conversely, non-commercial species are clustered at all distances. Similarly, function L_{12} holds the positive value up to the inter-tree distance of 5 m, afterwards it preserves the negatives, representing an attraction process up to 5 m, and inhibition afterwards. However, these processes are not significant, because a rise and fall of the values of L_{12} is only within the acceptance regions (see Figure 3.11 (b)). The fluctuation is perhaps due to a random variation so that the null hypothesis of independence cannot be rejected. Thus, the commercial species and non-commercial species of the Nansake plot are spatially distributed without correlation.



(a) (b)

Figure 3.11 Marginal patterns and the interrelation pattern of commercial and non-commercial species at Nansake: (a) Comparison of marginal patterns of commercial species (L_{11}), non-commercial species (L_{22}) and the interrelation pattern between them (L_{12}) (b) the interrelation pattern L_{12} (solid line) and the confidence envelop formed from conditional Monte Carlo simulation (dashed line)

Like in Sinthwat, most trees of both commercial and non-commercial species within the stand of Thapyaygone are located as clusters around all inter-tree distances (see Figure 3.12 (a)). Although, in Figure 3.12 (b), the curve L_{12} shows a variation around the value zero, but it is not significant to reject the null hypothesis of independence. It can be deduced with some confidence that there is no spatial correlation between commercial and non-commercial tree species within the stand of Thapyaygone.

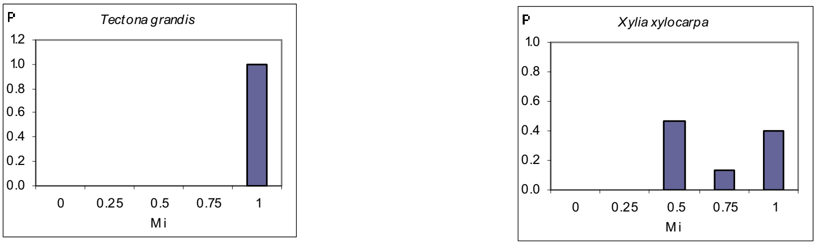


(a) (b)

Figure 3.12 Marginal patterns and the interrelation pattern of commercial and non-commercial species of Thapyaygone: (a) Comparison of marginal patterns of commercial species (L_{11}), non-commercial species (L_{22}) and the interrelation pattern between them (L_{12}) (b) the interrelation pattern L_{12} (solid line) and the confidence envelop formed from conditional Monte Carlo simulation (dashed line)

3.7.3. Species diversity

All study stands have the average mingling values very near to one, indicating that almost all reference trees are surrounded by trees of different species. It simply implies that all research plots show very high mingling. Figure 3.13 presents the distribution graphs for two most commercially important species Teak (*T. grandis*) and Pyinkado (*X. xylocarpa*) in the Sinthwat stand. The mingling distribution of *T. grandis* shows that the species is surrounded by neighbours that belong to a different species. Likewise, *X. xylocarpa* does not form pure or almost pure groups, but occurs most frequently as a single tree among other species. In addition, both species have M_{ratio} values around one, suggesting that both species are distributed evenly within the stand.



Tectona grandis

$P_{sp}=0.07$ $\overline{M}_{sp}=1$ $M_{ratio}=0.93$

Xylia xylocarpa

$P_{sp}=0.18$ $\overline{M}_{sp}=0.73$ $M_{ratio}=1.12$

Figure 3.13 Species–specific mingling distribution for two most commercially important species Teak (*T. grandis)* and Pyinkado (*X. xylocarpa)* in Sinthwat plot. P_{sp} is the proportion of the number of trees that the species contributes to the stand as a whole, $\overline{M}_{sp}$ the average mingling value of a given species, $M_{ratio}=1-P_{sp}/\overline{M}_{sp}$

In the Nansake plot, Kanyin (*Dipterocarpus spp.*) dominates the stand and constitutes 22 % of the total stand. However, the mingling distribution of *Dipterocarpus spp.* suggests that there exists no sign of pure or almost pure groups of that species, but they occur together with other species. The M_{ratio} value near to one also advocates that they are distributed evenly within the stand (see Figure 3.14).

Dipterocarpus spp

$P_{sp} = 0.22$ $\overline{M}_{sp} = 0.82$ $M_{ratio} = 0.95$

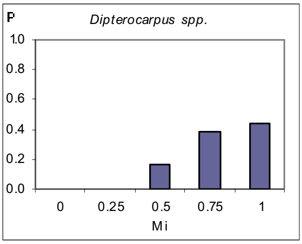
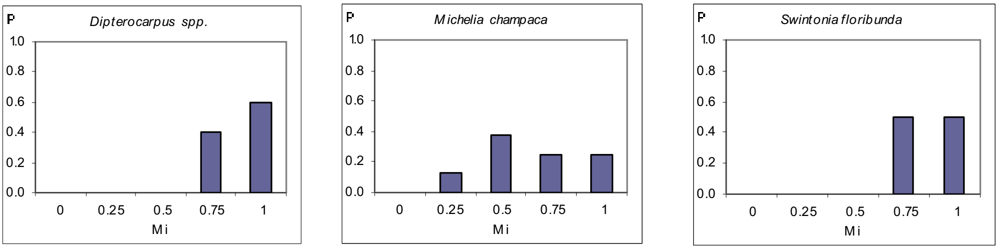


Figure 3.14 Species–specific mingling distribution for Kanyin (*Dipterocarpus spp.*) in Nansake. P_{sp} is the proportion of the number of trees that the species contributes to the stand as a whole, $\overline{M}_{sp}$ the average mingling value of a given species, $M_{ratio}=1-P_{sp}/\overline{M}_{sp}$

There are 5 stems of *Dipterocarpus spp.*, 8 stems of Sagawa (*Michelia champaca*) and 6 stems of Thaungthayet (*S. floribunda*) within the Thapyaygone study plot. Since there exist a total of 84 stems within the stand, they represent 6%, 10% and 7% respectively of the entire stand. The mingling distribution for these species are expressed in Figure 3.15. *Dipterocarpus spp.* and *S. floribuna* in this stand is surrounded by three or even four neighbours that belong to a different species. In contrast, *M. champaca* occurs in a variety of mingling constellations: either in almost pure group (12.5%), in groups where half the trees are *M. champaca* (37.5%), or in groups where none of the neighbours is *M. champaca* (25%). The M_{ratio} values of these species reveal that all commercial species described above are distributed evenly within the stand.



Dipterocarpus spp.
$P_{sp} = 0.06$ $\overline{M}_{sp} = 0.90$
$M_{ratio} = 1.04$

Michelia champaca
$P_{sp} = 0.1$ $\overline{M}_{sp} = 0.66$
$M_{ratio} = 1.36$

Swintonia floribunda
$P_{sp} = 0.07$ $\overline{M}_{sp} = 0.88$
$M_{ratio} = 1.06$

Figure 3.15 Species–specific mingling distribution for three commercially important species Kanyin (*Dipterocarpus spp.*), Sagawa (*M. champaca*) and Thaungthayet (*S. floribunda*) in Thapyaygone P_{sp} is

the proportion of the number of trees that the species contributes to the stand as a whole, $\overline{M}_{sp}$ the average mingling value of a given species, $M_{ratio}=1-P_{sp}/\overline{M}_{sp}$

3.7.4. Size differentiation

Species specific size differentiation indices were calculated form some commercial species in each sample plot to assess species-specific dominance. Figure 3.16 presents the dominance distribution for two most commercially important species Teak (*T. grandis*) and Pyinkado (*X. xylocarpa*) in the Sinthwat stand. The dominance distribution of *T.grandis* is left-skewed, showing that most reference trees are dominant in their immediate vicinity. Conversely, *X. xylocarpa* was found in all social classes in the stand: dominant, co-dominant, and suppressed trees. In the Nansake plot (Figure 3.17), Kanyin (*Dipterocarpus spp.*) occurs in almost all dominance classes. However, more than half of the trees are strongly dominant, Kanyin (*Dipterocarpus spp.*) and Sagawa (*M. champaca*) occurs in almost all dominance classes in the Thapyaygone research plot, but Taungthayet (*S. floribunda*) appears to be more dominant (see Figure 3.18).

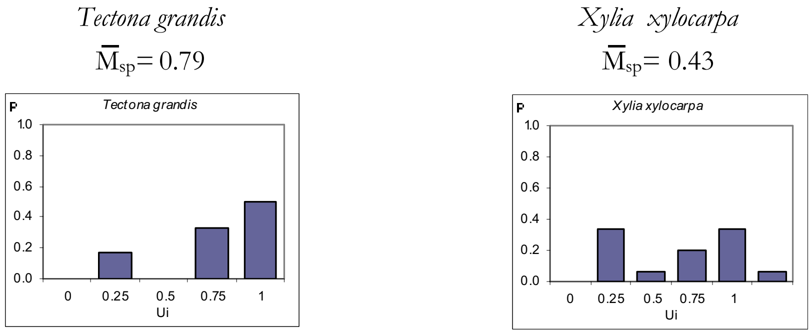
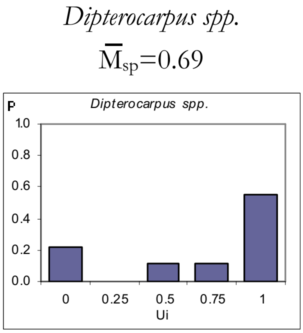

Tectona grandis $\overline{M}_{sp}= 0.79$ *Xylia xylocarpa* $\overline{M}_{sp}= 0.43$

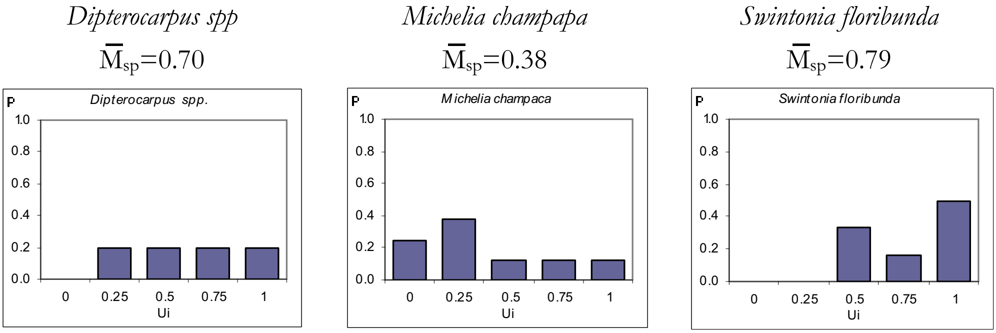
Figure 3.16 Species–specific dominance distribution for two most commercially important species Teak (*T. grandis)* and Pyinkado (*X. xylocarpa)* in Sinthwat plot. $\overline{M}_{sp}$: the average dominance value of a given species.



Dipterocarpus spp.

$\overline{M}_{sp}=0.69$

Figure 3.17 Species–specific dominance distribution for Kanyin (*Dipterocarpus spp.*) in Nansake. $\overline{M}_{sp}$ = the average dominance.



Dipterocarpus spp — $\overline{M}_{sp}=0.70$

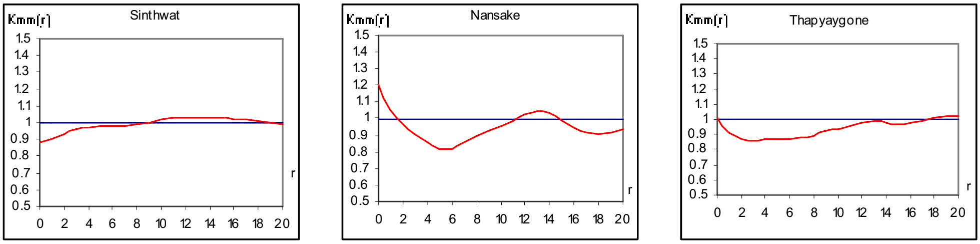
Michelia champapa — $\overline{M}_{sp}=0.38$

Swintonia floribunda — $\overline{M}_{sp}=0.79$

Figure 3.18 Species–specific dominance distribution for Kanyin (*Dipterocarpus spp.*), Sagawa (*M. champaca*), and Taungthayet (*S. floribunda*) in Thapyaygone. $\overline{M}_{sp}$ = the average dominance of a given species.

To investigate the spatial correlation of the tree sizes within different study stands, marked correlation functions for diameters were estimated for each stand. Figure 3.19 presents the estimates of the marked correlation functions for diameter in each study stand. Applying the marked correlation function $K_{mm}(r)$ as another measure to characterize the spatial arrangement of tree dimensions, it was found that there were correlations between the diameters of trees at different inter-tree distances in different plots. Figure 3.19 (a) of Sinthwat reveals that the diameters of trees located more closely to each other tend to be negatively correlated, because at distance of up to 8 m between trees the values of $K_{mm}(r)$ are below 1. This indicates a trend that at small inter-tree distances, both trees of a pair have a smaller diameter, which is the price that they have to pay for being close together. At distances greater than 8 m, there are only random fluctuations around 1, indicating that there is no longer any correlation between diameters.

The value of $K_{mm}(r)$ has an interesting peak at an inter-tree distance around 1 m in the stand of Nansake (see Figure 3.19 (b)). This could be a sign of a special occasion, where two or more dominant trees are located closely to each other, and they still appear to be growing satisfactorily, perhaps as a result of local management and/or good site conditions. Then there exists negative correlations between the diameters of trees within the distances of 2 m and 12 m and afterwards $K_{mm}(r)$ values rise and fall around the value 1, suggesting that diameters of the trees are not spatially correlated at inter-tree distances greater than 12m. The tree interaction radii appear to be greater in the Thapyaygone plot than the Sinthwat plot because the value of 1 is reached much later, at an inter-tree distance of around 14 m (see Figure 3.19 (c)). The speed with which the function approaches the value 1 denotes the extent of interaction between trees based on their dimensions.



(a) Sinthwat (b) Nansake (c) Thapyaygone

Figure 3.19 The estimates for the marked correlation functions for diameter in different research plots

4. Modelling Individual Tree Diameter Growth of Naturally Grown Teak[1]

Teak is one of the most valuable timber tree species in the world and indigenous only to four countries of continental Asia - India, Myanmar, Thailand and Laos (Kaosa-ard, 1981; Gyi and Tint, 1998). However, dense natural forests with large and premium quality teak have degraded and shrunk so rapidly that at present they are confined to Myanmar and to some parts of India. Natural teak has now almost become an endangered species (Gyi and Tint, 1998). In Myanmar, Teak is found in a number of different forest types with an altitudinal limit of about 1000 m and a latitudinal range between 10°00' and 25°30' N. The remnant natural Teak forests of Myanmar cover approximately 16.5 million ha (Gyi and Tint, 1998; Forest Department, 2000), which are capable of producing 603.485 m^3 of Teak annually. Myanmar's good Teak forests with the highest density where Teak may contribute between 10 and 20% of the total growing stock are found in the Bago Yoma (i.e., Bago mountain ranges) (Kermode, 1964; Gyi, 1972). Accordingly, the Bago mountain ranges were once reputed to be a true home of teak.

4.1. Review of growth modelling of natural Teak in Myanmar

The study of growth and yield of naturally grown Teak seemed to be initiated by Brandis in 1857 through linear valuation survey and stem analysis. However, systematic studies on growth and yield of natural forest of Myanmar may be said to start with the commencement of the working plan operation in 1883. Using working plans data, Troup analyzed the growth and yield of teak forests and published the results in 1911. The growth rate of teak trees was estimated by counting stump annual rings, and the rotation age of the respective reserved forest was derived from this estimates. The ages corresponding to trees with a diameter of 68 cm (i.e., yield tree) was also deduced from the stump analysis (see for detail Gyi and Tint, 1998). The

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[1] Teak (*Tectona grandis* Linn)

growth studies was restrained to Teak possibly because Teak was the only in one commercial species at that time and the accurate estimation of age from ring counting was possible for it.

Tint and Schneider (1980) developed regression models based on the stem analysis for teak trees collected from the reserves of the Bago mountain ranges and diameter, height and volume growth of individual Teak trees were predicted using tree age as a predictor variable. A stand level model was also developed by Tint and Schneider (1980) to simulate the growth and yields of the teak bearing forests of Myanmar. The model was able to predict growth, mortality and ingrowth, and generate future stand tables from an initial stand table or tree list provided by a forest inventory. A number of control functions were used to restrict predictions within reasonable limits (for details see Tint and Schneider, 1980). The model was an important tool for ensuring the sustainable management of teak bearing forests in Myanmar confirming a statement by Vanclay (1995) that stand table projection may be the most popular way to forecast yields from tropical forests.

Another contribution was the Spread-sheet Stand-table Projection Model (SSPM) developed by Vanclay (1992a) for an immediate use of the ForMIS (Forest Management Information System) that the Forest Resources Division of the Forest Department of Myanmar was constructing at that time. It was implemented in the LOTUS 1-2-3 system (release 2.2). The model predicts growth (diameter increment) and recruitments and assumes parameters for harvesting (removal, defect and damage), but assumptions need to be made for an annual mortality rate. It was restricted to project only two species groups – teak and other species combined. The enhanced SSPM version 2.2 (Vanclay 1992b) was implemented on LOTUS 1-2-3 (release 3.1) and used density dependent mortality. It could moreover be employed for three species groups – Teak, Pyinkado[2] (i.e., the second commercially most important species of Myanmar), and all other species. The SSPM is simple and easy to use, but it poses a wide scope for further improvement for applications in the management of teak bearing forests to embrace contemporary objectives. Very recently, Kyaw (2003) also studied the climate-growth relationship of teak through tree ring analyses and developed age-dependent volume growth models for three different forest types (upper moist deciduous forest of Taungoo, lower moist deciduous forest of Mabein, and dry deciduous forest of Kanbalu) of Myanmar.

Teak bearing forests, like other tropical forests, are characterized by multiple species, indeterminate tree ages, and a wide range of growth habits and stem sizes. Although Teak shows annual growth rings, this cannot be used in a growth model because it would be impractical to establish an age for each tree in the field. Furthermore, most of the other species have no distinct annual rings. Thus modelling

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[2] Pyinkado [*Xylia xylocarpa*]

concepts based on age and site index are not applicable in these forests. The use of age as an independent variable in a growth model for Teak will not be consistent with the requirements of other species. It will therefore not be possible to use an age-based model in a stand projection system supporting the size-limit-based forest management practice and inventory data structure of Myanmar. In this context, an age-independent individual tree model is considered to be the only suitable option for modelling growth under the specific conditions in Myanmar, featuring a large variation in species composition and stand structure.

4.2. Empirical data

The present growth study uses the re-measurement data of permanent sample plots (PSPs) installed on the Bago mountain ranges. The Bago mountain ranges, renowned once as a home of good teak forests, are situated in the central region of the country, running from north to south and rising up to about 300 m in elevation, are accessible from all directions. Most of these forests have been declared as reserved forests and protected public forests since early 1900s and some areas are still categorized as unclassified forests. At present, they are managed under eight different Forest Management Plans. Annual yields of these forests are prescribed as 55,449 m^3 for Teak and 379,945 m^3 for other hardwoods under a thirty-year felling cycle (Forest Department, 2004). They also serve as watersheds supplying a total of seventy-three dams and reservoirs for irrigation and domestic water supply. Accordingly, these forests play a critical role not only for national economic development but also for conservation of watershed and natural heritage. Its reputation is a true home of teak and the origin of tropical forest management. The sustainable management of these forests is crucial for the country.

A national forest inventory was initiated in 1980-81 with the assistance of FAO and UNDP. The basic sampling design involved sampling with partial replacement (SPR). Sampling units consist of L-shaped strips laid out systematically in a grid of 3,300 x 3,300 yards (approx. 3 x 3 km) over the forest areas. Each sampling unit measures 30 m by 175 m in both west-easterly and north-southerly directions. Twenty five percent of the units were permanently marked (PSPs), the remaining seventy five percent were temporary units (TSPs). Each sampling unit was divided into seven record units (RU), each comprising 0.15 ha (30 m x 50 m except for the RU 4 which was L shaped). The total area of a sampling unit was 1.05 ha (Figure 4.1). Trees with a breast height diameter (dbh) of at least 20 cm were enumerated on the whole plot, i.e., on the strip of 15 m horizontal distance to either side of the center line. In the PSPs, trees were labeled with aluminium tags, and the position of each tree was marked. These marked trees have to be measured every five years (see more details in Forest Department, 1985). In the Bago Yoma area, inventory plots were established for the first time in 1982. Permanent plots were marked so that they could be relocated for remeasurement, but kept inconspicuous in order to eliminate research plot bias and ensure that forest inventory was representative of growing conditions and forest management throughout the country. They were remeasured in 1987 and 1992. To improve the reliability of inventory data, field crews had no access to previous records in the field of the second measurement, some plots could unfortunately not be recognized properly. Therefore, these plots were reinstalled.

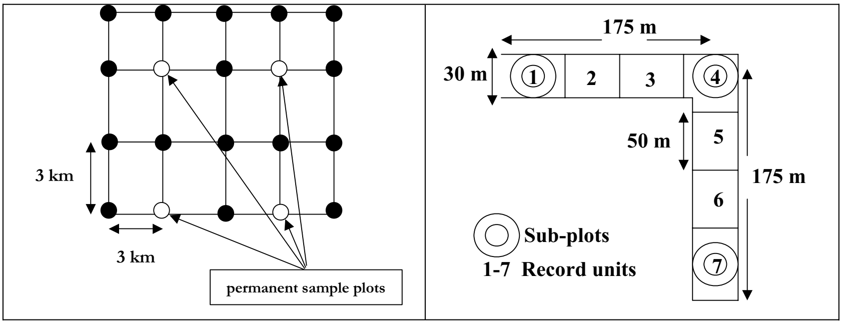


Figure 4.1 (a) Schematic representation of systematic grid of units (b) layout of an individual L-shaped sampling unit comprising different record units.

The present study covers 46 PSPs from the Bago mountain ranges, some of which have two measurement records and some have three. Then pairs of remeasurements were selected from the database to obtain growth interval data of 5 years. Exploratory data analysis established that some diameter increments had negative values and some showed comparatively high positive values. The measurement data with negative increments have not been used in calculating increment, but only in calculating stand basal areas. Comparatively high positive values of increment could be considered as outliers. Outliers are not necessarily incorrect data but can have a substantial effect on curve fitting process. Therefore, outliers on increment data were detected by using a modified form of a boxplot suggested by NIST/SEMATECH (2004). The increment values outside the upper outer bound which was defined by the upper quartile plus 3 times the interquartile range were labelled as extreme outliers and these data were omitted in further analysis. A data file was then created and used as input to the statistical package STATISTICA for further analysis and contained 297 observations of diameter increment derived from 272 individual trees. The data file also holds records of dbh and stand variables such as stand basal area, the BAL index (Basal-Areas -of-Larger trees; Wykoff et al., 1982) and the GD competition index (Gadow, 2003).

4.3. Analysis of individual tree growth of Teak

Stand growth is the combined growth of all individual trees (Oliver and Larson, 1990). Individual trees accumulate growth over time in different ways and at different rates in response to recent site conditions. Generally, the growth of a tree is a function of different factors, such as age, tree size, competition, site and so on. More importantly, tree size reflects the effects of the past competition or vigour on tree growth (Monserud and Sterba, 1996). Tree size, therefore, accounts for most of the species' effect on tree growth. In other words, big trees often grow faster- regardless of the species and much of the variation in tree growth can be explained with the initial tree size (Hilt, 1983). Consequently, the evaluation of increment as a function of tree size is the logical starting point in any modelling effort (Wykoff, 1990) and it would provide a first step toward the development of a stand projection system based on the current forest structure (Gadow, 1984).

The growth of individual trees may be expressed as diameter increment or the corresponding basal area increment. Bella (1971) and Johnson (1973) urged that the use of basal area increment had some theoretical advantages. However, West (1980) concluded that no a priori reason exists for expressing growth as diameter or basal area increment. The use of diameter increment or basal area increment as a response variable, therefore, is largely a matter of personal convenience (Vanclay, 1994) or personal preference (Alder, 1995). In this analysis, annual diameter increment was selected as a response variable for individual tree growth.

Generally, trees are not remeasured every year but after some time interval. If one wishes to obtain an accurate assessment of growth patterns over time, the trees should be measured at short intervals (Perresol, 1995). Here, the interval of re-measurement for all PSPs under the study is 5 years. Then the averaging method (Equation 4.1) that assumes a constant growth for the entire period is used to calculate the annual diameter increment of individual trees.

$$\Delta d_i = \frac{d_{i2} - d_{i1}}{t_2 - t_1} \tag{4.1}$$

where,

Δd_i = annual diameter increment during the period t_2 .. t_1 of tree i.

d_{i1} = diameter of tree i at the period t_1

d_{i2} = diameter of tree i the period t_2

The scatter plot is used as an exploratory data analysis technique to maximize the insight into the underlying structure of the data set, hereby a particular model can be fitted to the data set and the parameters of those models can also be estimated precisely. Specifically, the scatter plots can provide the degree, pattern and direction of a relation between the variables. The scatter plot of the annual diameter increment against the initial diameter for Teak is shown in Figure 4.2. The scatter plot reveals that there are no imaginable relationships between the dhh and the annual diameter increment. Outliers of high-leverage points were observed in the data set while most show heteroscedastic variability. The existence of outliers suggests that the distribution of the data is non-random and the heteroscedastic pattern puts forward unequal variability in the data set. Therefore, the existence of outliers and heterosceasticity is very important as they deviate from the basic assumptions in regression analysis, leading to parameter estimates with inflated variances. Accordingly, transformation of data and appropriate regression procedure were required to obtain a suitable model that best fits the specific data set.

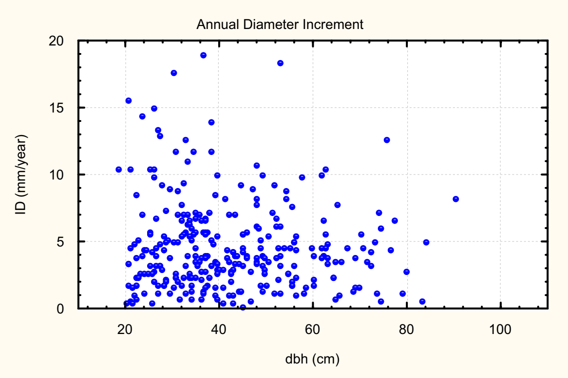


Figure 4.2 The relationship between annual diameter increment (ID) and dbh at the beginning of the growth interval.

4.4. Model development

There are two conceptual approaches to model development for tree growth: the potential-modifier approach and the average-adjusted (or composite) approach (see Holdaway, 2000: Wykoff, 1990). However, Martin and Ek (1984) described these respective choices as "semi-empirical" and "empirical". In practical terms, the differences in the approaches are mostly semantic (Wykoff, 1990). If relationships within a model are based on generally accepted principles of tree growth (Assmann, 1970), either approach can produce acceptable behaviour (Wykoff and Monserud, 1988). The potential-modifier approach nonetheless seems to be more appropriate for modelling tree growth. Because this formulation is a succinct expression of such biological principle that the growth of a tree is the result of the interaction of two opposing forces: multiplicative biotic potential and restrictive environmental forces.

The models based on this approach have a potential component and a modifier component. Then the actual increment is estimated from the potential growth by the use of a modifier function such that:

$$\textit{Expected growth} = (\textit{potential growth}) * (\textit{modifier function}) \tag{4.2}$$

The potential-modifier approach generally proceeds in two stages. Firstly, the potential growth of tree growing free of competition is modelled, and secondly an adjustment is made to reduce the potential growth to that actually observed. The potential growth represents an upper bound for the growth rate that may be attained by a tree of a given species based on inherent characteristics. Therefore, the potential growth function represents the maximum growth attainable for a tree. The modifier component limits the maximum growth of trees by taking into account various environmental resistances (e.g., inter-tree competition, limited resources etc.). As a result, the modifier function represents deviations from the potential due to limiting factors. The modifier thus gives greater accuracy and precision to the growth model by allowing the predicted values to increase or decrease from those given by the potential model.

4.4.1. Potential growth function

The concept of a growth potential has been used in mathematical modelling of biological processes for many years (Hahn and Leary, 1979). The use of such a concept in forest growth modelling was introduced by Botkin et al. (1972), Arney (1974), Hegyi (1974) and Ek and Monserud (1974) and extended by some others (see Monserud, 1975; Alder, 1979; Hahn and Leary, 1979; Leary and Holdaway, 1979, Shifley and Brand, 1984, Holdaway, 1984; Shifley, 1987; Belcher et al., 1982; Teck and Hilt, 1991; Gourlet-Fleury and Houllier, 2000; Cummings et al., 2001; Bragg, 2001, 2003).

Biological growth is the outcome of numerous and complex processes but appears remarkably simple, particularly for trees. If more and more similar trees were combined, the increase in their size would follow an ever-smoother sigmoid curve. In the beginning, the curve is concave, while in later life it becomes convex. Although growth responds to environmental trends and fluctuations, this long-term pattern remains surprisingly stable (Zeide, 1993). A basic approach to develop the potential growth component therefore is to use a theoretical growth equation with the form of sigmoid curve. Theoretically based equations may be more reliable for predictions, which involve extrapolations beyond the range of the data. Nonetheless, there are some particular theoretical equations relating specifically to the growth of trees (Vanclay, 1994). Most theoretical equations have been borrowed from other disciplines. A family of asymptotic, nonlinear growth equations, for example, Gompertz (1825), Logistic (Verhulst, 1838) and Bertalanffy (1957), have been frequently used in modelling the diameter growth of a tree. Despite the elegant theoretical development of these growth equations, when applied to diameter increment data of forest trees, these equations have limitations that may be attributed to their original purpose and uses (see Vanclay, 1994). They are ecologically appealing, but rarely empirically based (Bragg, 2003). Consequently, various modified equations were applied for modelling maximum diameter growth of trees by different researchers (e.g., Botkin et al., 1972; Hahn and Leary, 1979; Leary, 1979; Martin and Ek, 1984; Botkin, 1993). Therefore, the theoretical equations currently available remain rather empirical in application (Vanclay, 1994).

An alternative approach is to develop empirically based potential growth equations by using the data of maximum dimensions obtained for trees of different ages or size-classes from temporary and permanent measurement plots records. This approach assumes that maximum dimensions observed in measured plots represent the maximum potential growth for different stand or tree conditions (Reed et al, 2001). The problem with this approach is the difficulty in defining a subsample of trees for fitting the potential growth equation. In this respect, a data set of the fastest growing 5% (Shifley ,1987) and 10% (Teck and Hilt, 1991) of trees can be used to estimate the potential growth rate. Vanclay (1994), however, pointed out that such data could represent measurement errors rather than real growth and proposed alternatives to base the potential growth equation on the average growth rate between the first and the last measurement or on the trees assessed as open-grown or free of competition. Again, Hahn and Leary (1979) judged the open-grown trees as not suitable for potential diameter growth studies because of the significant difference in the distribution of increment among bole, branches, and limbs. They intended to approximate diameter growth of forest trees not subject to significant competition from neighbouring trees by taking the 95th percentile of diameter growth from 25 cm diameter classes of dominant and co-dominant trees. Likewise, Cummings et al. (2001) introduced the frontier function analysis to estimate the maximum relative growth rate, which utilizes all available data in estimating functional coefficients and eliminates the need to apply arbitrary partitioning in the data, removing subjectivity and arbitrator data selection decision from the estimation process. However, this analysis is mathematically tricky and comparatively time consuming.

The model to be developed in this study is an age-independent one and intended for application of the National Forest Inventory data. The choice of the modelling strategy therefore is restricted to the data availability. Subsequently, the present study adopts the Potential Relative Increment (PRI) approach suggested by Bragg (2001, 2003). The PRI approach balances the use of empirical data to predict growth with an ecologically robust assumption. The calculation procedure is relatively simple and independent of age. This system can then be combined with the appropriate environmental modifiers into a comprehensive diameter growth model capable of predicting increment changes under a variety of scenarios (Bragg, 2001). For all individuals the Actual Relative Increment (ARI) was calculated using the equation (4.3) which is a form of a simple interest formula that has been earlier applied to calculate tree growth and represents the proportional change in diameter (Bragg, 2001).

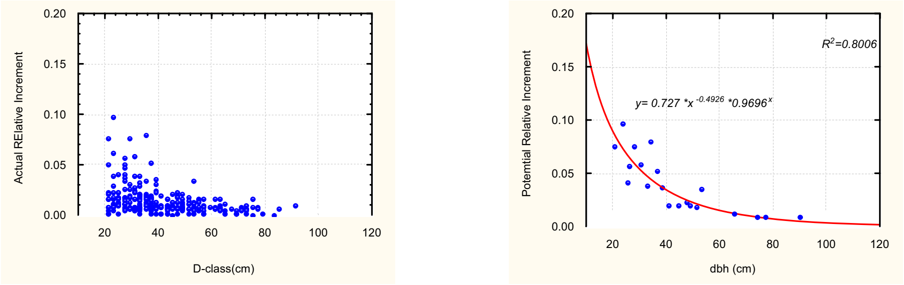
$$ARI = \frac{dbh_2 - dbh_1}{dbh_1} * p \tag{4.3}$$

where,
ARI = Actual Relative Increment (dimensionless)
dbh_1, dbh_2 = the diameter at breast height at previous and current inventory (cm)
p = the measurement interval standardization factor

The ARI values were then classified by 2 cm dbh_1-classes and the highest value for every class was selected. It was assumed that the highest ARI values represented trees growing at near-optimal conditions. While developing a best subset is a partially subjective process, since the goal was to fit an idealized response curve to a biologically intuitive relationship between tree size and growth potential, some bias was unavoidable (Bragg, 2001, 2003). The power function (equation 4.4) was then fitted to the maximum ARI data within the STATISTICA software using a non-linear ordinary least square estimation procedure to provide an equation for PRI, which represents the maximum possible growth rate for species at a given dbh (see Figure 4.3). The estimated parameters and the coefficient of determination (R^2) are given in Table 4.1.

$$PRI = b_1 * (dbh_{\max})^{b_2} * b_3^{(dbh_{\max})} \tag{4.4}$$

where,
PRI = the Potential Relative Increment (dimensionless)
dbh_{max} = the dbh for the trees with maximum ARI within each 2 cm dbh class (cm)
b_1, b_2, b_3 = species-specific regression coefficients



(a) (b)

Figure 4.3 **(a) The Annual Actual Relative Increment and (b) the fitted curve for the Potential Relative Increment of teak**

Table 4.1 Parameter estimates for PRI equation of Teak

Scientific Name	**b_1**	**b_2**	**b_3**	**R^2**
Tectona grandis	0.7270	-0.4926	0.9696	0.8006

The potential relative increment responses follow a declining monotonic curve, reaching a maximum PRI at the smallest diameters. The rapid decline in the PRI value with diameter of teak indicates that the relative growth rate drops appreciably with increasing tree size. This reflects the fact that large trees experience disproportionately lower rates of diameter change than small trees. It should also be noticed that the most important features of the PRI method is the fact that while PRI approaches zero, it never actually reaches this asymptote. Once the model parameters have been obtained, the predicted maximum increment (ID_{max}) was calculated by equation (4.5).

$$ID_{max} = dbh * PRI \tag{4.5}$$

where,

ID_{max} = the predicted maximum diameter increment (mm/year)
dbh = the diameter at breast height(cm)
PRI = the potential relative increment (dimensionless)

The maximum growth response at different dbh's of teak is presented in Figure 4.4. As seen in Figure 4.4, teak grows with small increment at larger diameters. However, it is advisable that projecting their increments over the range of the data is strictly an artefact.

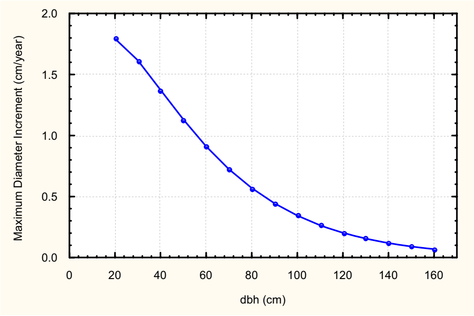


Figure 4.4 Estimated maximum Diameter Increment in relation to the initial dbh

4.4.2. Modifier Function

A forest stand is a highly complex ecosystem. Trees inside a stand affect each other directly in local neighbourhoods. However, trees have the ability to respond and adjust to a wide range of changes in their environment. This ability is manifested in changing patterns of growth. Many details of the regulation processes of a tree's growth in response to changing environmental conditions are not yet known. However, it is generally accepted that a primary factor influencing tree growth is spatial interaction (Gadow and Hui, 1999). The interaction involves both positive aspects (e.g., co-existence) and antagonistic aspects (e.g., competition). Trees within a stand can therefore seldom reach their maximum growth potential because of the antagonistic aspect of interactions (such as competition, resources availability and so on) that result in growth reduction. Modifier functions are generally developed to represent the proportional impact of one or more limiting, or suboptimal, environmental factors. The actual growth can range from nil to the maximum, depending on restrictive environmental factors. These modifier functions are therefore scaled from zero to one, where a value of one indicates no impact on the potential growth due to the environmental factor in question, and a value of zero the extreme level of impact, where the factor is so limiting that no growth can occur at all (Reed et al., 2001).

It is clear that in reality there are many different environmental factors that can impact a tree's growth. Nevertheless, a finite number of factors with the relative importance in impacting actual tree growth are considered in a modelling exercise. An appealing idea is the use of competition as an essential modifier function for adjusting the potential growth of a tree inside a particular stand. Thus, competition is a vital ingredient in an individual tree growth model (Holdaway, 1984). Competition is a term often used to describe the interaction among plants in a community (Woodall et al., 2003). More specifically, Weiner (1990) divided the plant-to-plant competition into two parts: competitive effect (i.e., the influence of plant competitors on resource availability) and competitive response (i.e., the response of plant to the available resource in an environment modified by the competitor plants). This implies that a neighbour larger than the subject tree, a dominant neighbour, places the subject tree at a competitive disadvantage, whereas a smaller neighbor, a suppressed competitor, places it in a competitive advantage (Tome and Burkhart, 1989). However, the term competition most often refers to a direct influence (e.g., physical abrasion) or to exploitative competition (e.g., competition for light, nutrients or water; Bravo et al., 2001).

The level of light competition imposed by larger trees is considered one-sided whereas competition for below ground resources, such as nutrients and moisture is referred to as two-sided (see Vanclay, 1994). Both one-sided and two-sided competition effects have asymmetric influences on tree development. One-sided competition amplifies the variation in relative growth rate (i.e., competition for light exaggerates relative difference in plant size). Two-sided competition acts to slow the growth of all plants (i.e., competition for nutrient and water dampen the divergence in plant size; Weiner, 1990; Bravo et al., 2001).

Inter-tree competition is usually quantified using competition indices. A competition index is a mathematical formulation derived to represent or describe competition from adjacent trees that could be affecting the growth of any considered tree (Daniels, 1976; Schreuder and Williams, 1995: Woodall et al., 2003). There are two major classes of competition index: those which utilize the individual tree location are termed distance-dependent, and those not using locations which are termed distance-independent (Munro, 1974). Distance-dependent indices attempt to quantify an individual tree's zone of influence, while distance-independent competition indices use stand-level estimates of density and thus may not actually gauge competition surrounding individual trees (Biging and Dobertin, 1995). Distance-independent indices are easy to calculate and less demanding in data and computer time, which make them preferable to distance-dependent indices in some application (Tome´ and Burkhart, 1989). Conceptually, some improvement in precision would be expected when going from distance-independent to distance-dependent indices. However, distance-dependent indices, at best, only marginally improve estimates of individual growth over distance-independent indices (see e.g., Daniels et al., 1986; Martin and Ek, 1984; Tomé and Burkhart, 1989; Biging and Dobbertin, 1995). Additional research is needed to gain a broad understanding of the relationships that underlie competition in an uneven-aged stand (Woodall et al., 2003).

In this context, it should be noted that a biologically interpretable distance-independent competition index should distinguish between stand density (i.e., a measure of how completely a stand is occupied by trees) and specific competition (i.e., a tree's social ranking). Therefore, a plausible distance-independent index should account simultaneously for the population attribute- stand density- and for the individual tree attribute- relative position (Schröder and Gadow, 2000). In the present study, two distance-independent competition indices: basal-area-of the-larger-trees (BAL) index (Wykoff et al., 1982) and the GD index (a short form of the German words Grundflächen-Durchmesser-Index; meaning basal area-diameter index) proposed by Gadow (2003) were applied in comparison to constrain the potential growth of naturally grown Teak from restrictive environmental forces.

The BAL index introduced by Wykoff et al. (1982) is a commonly used competition measure in individual tree growth models and has been used in several studies (e.g., Wykoff, 1990; Teck and Hilt, 1991; Quicke et al., 1994; Monserud and Sterba, 1996; Murphy and Shelton, 1996). BAL combines an individual tree's basal area percentile with the density measure stand basal area (Wykoff, 1990; Quicke et al., 1994). This stand level index is based on the assumption that smaller trees do not influence the growth of bigger trees (Jogiste, 2000). BAL describes a tree's competition status more accurately (Wykoff, 1990). Another important advantage of the two resolution levels - competition index- BAL- is the possibility to avoid high collinearlity between explanatory variables, which may occur when several variables measure the same effect in overall growth modelling (Schröder and Gadow, 2000). The BAL index can be obtained as a linear function of the stand basal area expressed in equation (4.6). Thus, it is a simple count of the stand's basal area from trees with a diameter larger than the subject tree's diameter. BAL for the largest tree is 0.0, and for all smallest trees equal the stand basal area minus that tree's basal area.

$$BAL_{ij} = BA_i\,(1-p_j) \tag{4.6}$$

where,

BAL_{ij} = the sum of the basal areas of all trees larger than the subject tree
BA_i = the basal area of the stand i
p_j = the basal area percentile of the subject tree j

Another competition index applied as a modifier function is the GD index. This index simultaneously takes into account two most important social characteristics of a particular stand - stand density and stand structure - that should be reflected in a modifier function. It expresses the stand density as a relative stand basal area and relates the stand structure as a relative tree size. The index has the form as mentioned in equation (4.7). The basic term of the index can assume values between zero and one (i.e., $0 < G_i/G_{max} \leq 1$) while the power term of relative tree size can bear certain values (i.e., $d_j/\bar{d}_i > 0$). If a tree has the relative size of 1, the GD index represents only competition due to stand relative density. If $d_j/\bar{d}_i > 1$, the GD index become small, meaning a relatively large tree in a given stand will have a small GD index. In turn, if $d_j/\bar{d}_i < 1$ (i.e., a relative small tree), the GD index will get larger value.

$$GD_j = \left(\frac{G_i}{G_{\max}}\right)^{\left(d_j / \bar{d}_i\right)} \tag{4.7}$$

where,

GD_j = GD index for tree j (dimensionless)
G_i = the basal area of the stand i (m^2/ha)
G_{max} = the observed maximum stand basal area (m^2/ha)
d_j = the diameter of the reference tree j (cm)
$\bar{d}_i$ = the average diameter of the stand i (cm)

The modifier function is a multiplicative term that reduces potential growth in response to competition. The modifier term describes the relationship:

$$Modifier = (actual\ growth) \ / \ (estimated\ potential\ growth) \tag{4.8}$$

Preliminary analyses showed that there exists a negative exponential relationship between the modifier values and these two modifier functions- BAL and DG index. Finally, the following two different modifier functions were developed which assume values between one and zero in order to proportionally reduce the potential growth to expected growth depending on the intensity of the competition.

$$Modifier = exp\ (-b * BAL) \tag{4.9}$$

$$Modifier = exp\ (-b * GD) \tag{4.10}$$

where,

BAL= the BAL index (m^2/ha)
GD = the GD index (dimensionless)
b = the parameter to be estimated

Modifier values and associated BAL and GD values were classified into classes of 2 cm dbh. Then the mean modifier values for each class were used as the dependent variable for both equations while the mean values of BAL and GD were used as independent variables in the respective equation. Afterwards, the respective parameters were estimated through ordinary least square using the Levenberg-Marqurdt algorithm in STATISTICA. For each model, the mean residual (MRES) and the coefficient of determination (R^2) were calculated to examine the prediction differences in term of bias and precision. The mean residual, a measure of average model bias, describes the directional magnitude; i.e., the size of expected under and overestimates (Gadow and Hui, 1999). The mean residual was calculated by the formula (equation 4.11) expressed below.

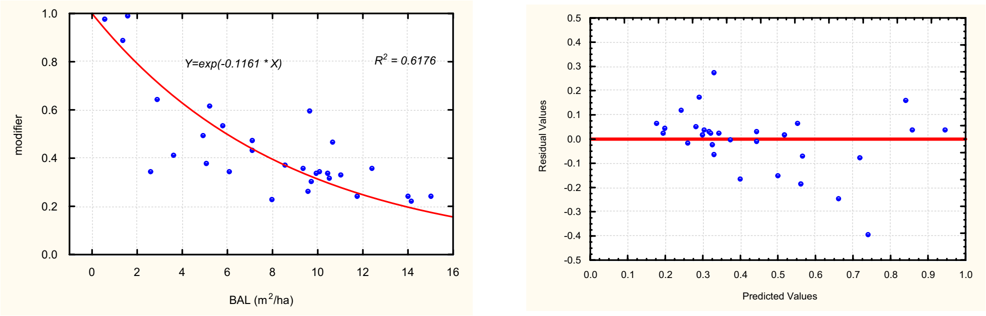
$$MRES = \frac{\sum (y_i - \hat{y}_i)}{n} \tag{4.11}$$

where,
$MRES$ = the mean residual
y_i = observed value
$\hat{y}_i$ = predicted values
n = number of observation

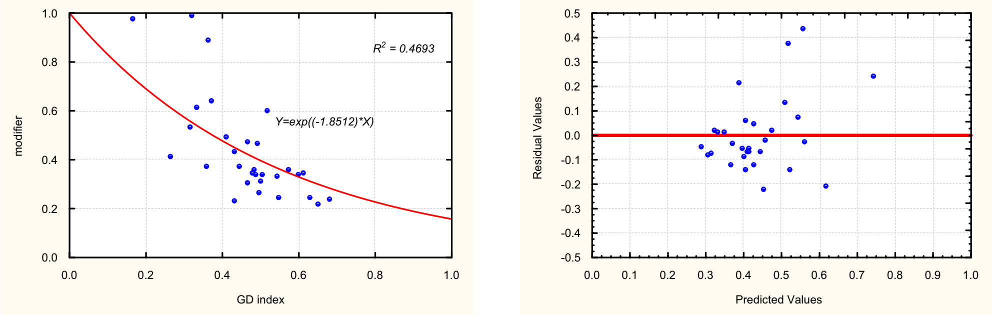
The parameter estimates and associated statistics are given in Table 4.2 and Figure 4.5 provides an illustration for a visual comparison between the performance of the BAL and GD index equations. As revealed in Table 4.2 and Figure 4.5, the BAL index model with the mean residual value of –0.0024 will generally overestimate and the GD index model with the mean residuals value of 0.0106 underestimates the modifier values. However, the magnitude of bias in the BAL index is small. Likewise, the BAL index function can explain more effectively than the GD index function the variation from potential growth due to competition.

Table 4.2 Parameter estimates and associated statistics for different modifier functions

Function	b	Asymptotic standard deviation	Mean residuals	R^2
BAL index	-0.1163	0.0083	-0.0024	0.6280
GD index	-1.8512	0.1460	0.0106	0.4693



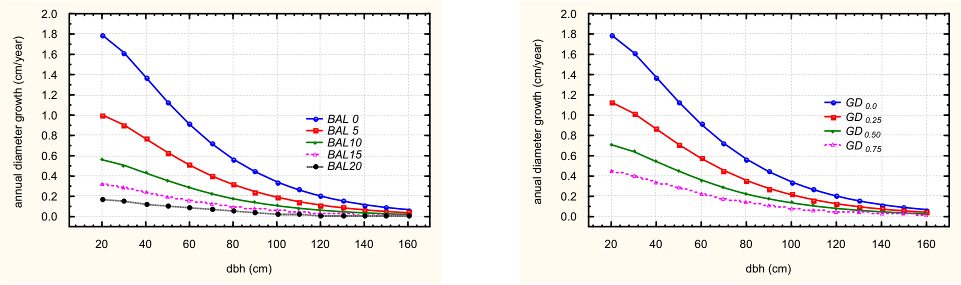
(a) *BAL* index equation



(b) *GD* index equation

Figure 4.5 Modifier functions for (a) BAL index and (b) GD index (left) and residuals (right)

Finally, actual growth of the individual teak tree can be expressed as a product of potential function and modifier function. Annual growth responses to different intensities of competition are demonstrated in Figure 4.6.



BAL index *GD* index

Figure 4.6 Annual diameter growth response to different competition intensities at different diameters

5. Modelling Stand Development for All Species

Forest management is implemented at the stand level (Monsured, 2003). A forest stand, a contiguous area that contains a number of trees that are relatively homogenous or have a common set of characteristics, will be managed as a single unit (Brack and Wood, 1996). Forecasting the growth and yield of individual stands is a prerequisite for planning the management of a forest at any level. For this reason, the knowledge on stand development is one of the most important requirements for intelligent forest management. Several components need to be considered in assessing the stand growth. These include: regeneration, ingrowth, accretion, mortality and drain. In this connection, ingrowth represents the quantity of trees entering the measurable stand since the previous assessment while accretion stands for the sum of individual increases in the size of trees of measurable size present at the commencement of the growth period. Mortality is the quantity of trees lost through death while drain characterizes the quantity of trees harvested during the growth period.

Quality information is a fundamental precondition in a decision procession. Inventories of forest stands and information about how these stands are growing are crucial elements of making wise forest management decision (Lessard, 2000). Forest inventories with different objectives have therefore been organized to accumulate the current information pertaining to forest resources at a specific point in time and various modelling approaches have been used to predict the future states of the forests based on the inventory data. Forest inventory data are generally summarized and reported as stand tables. In fact, a stand table is a tabular summary showing the number of trees in each of several size classes (Vanclay, 1994) and therefore a basic tool in forestry (Alder, 1995). They provide information to compute product volume and are thus a desirable feature in growth and yield modelling (Cao and Baldwin, 1999).

5.1. Stand table projection approach for updating forest inventories

Sustainable management of natural tropical forests for timber production requires an effective system for predicting future forest growth and yields (Alder and Silva, 2000). Inventories have to be updated for scheduling stand management practices and making economic evaluations of future stands. For most purposes, a future stand table is required to characterize the forest condition so size-specific production definition can be applied (Nepal and Somers, 1992). Future stand tables can be commonly derived from current ones through stand projection. Such a growth projection could be accomplished by separately projecting each diameter class of the stand tables using an approach called stand table projection. In this sense, stand table projection represents the oldest class of mathematical model developed for growth projection in tropical forests, with their application beginning with Brandis in Burma (now Myanmar) in 1856 (Brasnett, 1953). It was originally devised as a simple and efficient method (Vanclay, 1994) and has been widely applied to the problems of selection forest management (Alder, 1995). Silva (1989) evaluated the stand table projection approach as an accurate one for short periods, but requiring modification for long-term projection.

The approach predicts the future stand table from the present stand table by adjusting each entry in the table with the estimated diameter increment (and mortality; Vanclay, 1994). The basic concept of the stand table projection is that the forest is represented as a stand table of tree numbers classified by size classes (especially diameter classes). The change in the stand table is calculated over a particular interval using periodic increment data. The revised table is then used as the starting point to repeat calculations. In this way, such components of stand development as increment, mortality, and ingrowth can be incorporated to estimate growth over a full felling cycle. Therefore, this approach begins and ends with a stand table showing the number of trees by species (or species group) and diameter classes. The stand table projection approach assumes that provided drastic changes in growth condition have not occurred, the stand projection can be based on past increment in two ways: future growth will equal past growth and future growth will follows the trend established by past growth. In general, these projections are excellent for short-term estimate because the best indicator of how tree will grow in the near future is how they grew in the recent past (Shifley and Fischer, 1992).

Accordingly, the traditional stand table projection procedure deals with the following steps: (1) developing local stand table based on current forest inventory, (2) estimating periodic growth by species (or species group) and/or diameter classes, (3) estimating periodic survival rates by species (or species group) and (4) estimating periodic ingrowth. These estimates are then used to move the initial stand table to a future condition, species by species (or species group by species group) and diameter class by diameter class. The estimates for diameter growth, survival rate and ingrowth may be obtained from continuous forest inventory plots or increment core taken at the time the initial stand table is developed (Shifley and Fischer, 1992). However, an educated guess remains as a standby where data are deficient (Vanclay, 1994).

Mathematically, the process of stand table projection can be define as:

$$N_{K,t+1} = N_{k,t} + I_k - O_k - M_k - H_k \tag{5.1}$$

where,

$N_{k,t+1}$ = the number of tree in the k^{th} class at period $t+1$
$N_{k,t}$ = the number of trees in the k^{th} class at period t
I_k = the ingrowth into the k^{th} class during the period
O_k = the outgrowth from the k^{th} class during the period
M_k = the mortality from the k^{th} class during the period
H_k = the trees harvested from the k^{th} class during the period

It will be apparent that the ingrowth into class *k* will be numerically equal to the outgrowth from class *k-1*. Ingrowth is therefore restricted to imply external ingrowth only (i.e., recruitment to the lowest class). Consequently, the equation (5.1) can be rewritten as

$$N_{k,t+1} = N_{k,t} + R_k + O_{k-1} - O_k - M_k - H_k \tag{5.2}$$

where,

$N_{k,t+1}$ = the number of trees in the k^{th} class at period $t+1$
$N_{k,t}$ = the number of trees in the k^{th} class at period t
R_k = the number of trees appearing in the k^{th} class as a result of external ingrowth
O_{k-1} = the outgrowth from the $k\text{-}1^{th}$ class during the period
O_k = the outgrowth from the k^{th} class during the period
M_k = the mortality from the k^{th} class during the period
H_k = the trees harvested from the k^{th} class during the period

If ingrowth, outgrowth, mortality and harvest may be defined in terms of the percentage of the current tree numbers, equation (5.2) can be modified as:

$$N_{k,t+1} = R_k + (N_{k-1,t} * o_{k-1}) + N_{k,t} (1 - o_k - m_k - h_k) \tag{5.3}$$

where,

$N_{k,t+1}$ = the number of trees in the k^{th} class at period $t+1$

$N_{k,t}$ = the number of trees in the k^{th} class at period t

$N_{k-1,t}$ = the number of trees in the $k\text{-}1^{th}$ class at period t

R_k = the number of trees appearing in the k^{th} class as a result of external ingrowth

o_{k-1} = the outgrowth from the $k\text{-}1^{th}$ class during period (in percentage)

o_k = the outgrowth from the k^{th} class during the period (in percentage)

m_k = the mortality from the k^{th} class during the period (in percentage)

h_k = the trees harvested from the k^{th} class during the period (in percentage)

5.2. Aggregating species for stand table projection

It is apparent that tropical watersheds are generally clad with forests characterized by a large number of tree species with diverse growth habits. In most cases, one hectare of forest may contain a few hundred identified species of trees with a diameter at breast height (dbh) greater than 10 cm (c.f. Newmann et al., 1996). An important corollary to this high diversity is that most of the tree species are locally rare (Lieberman and Lieberman, 1994), implying that some are widely distributed whilst most occur infrequently. These peculiar problems of tropical forests are generally compounded by the limited availability of regional growth information for empirical growth modelling. In addition, the growth response function of trees was found to be significantly different for trees of different species. This necessitates the modelling of growth separately for these species. However, the large number of species in these forests and the extremely low occurrence frequency of many species meant that separate modelling for each individual species was impossible (Phillips and Van Gardingen, 1999). Consequently, earliest efforts were emphasized on average data quantities over all species in stand table projection, resulting in a loss of information on individual species. However, some information on certain species (e.g., commercially significant species) was essential in growth projections and subsequent development of a management plan for natural tropical forests. It revealed the fact necessary to compromise between exceedingly detailed modelling efforts for individual tree species and highly generalized modelling efforts for all species combined in order to obtain plausible and interpretable results. Such compromises led to introduce some system of species grouping for developing a stand projection system in a more realistic way.

Accordingly, the formation of species group is a key process in the development of a model for natural tropical forests (Alder and Silva, 2000). Various researchers from the tropical world have proposed different approaches to collapse the great number of topical tree species into a much smaller set of “tree types” or “functional groups”. A typical approach is a taxonomic one at the level of the family or genus to obtain an appropriate and meaningful grouping in biodiversity applications. Another useful means is to use some statistical approach to form meaningful groups in terms of the similarity in growth response. Different statistical techniques, for example, the "pairwise F-test" (e.g. Vanclay, 1991) and more commonly "cluster analysis" (e.g., Alder, 1995; Eba'aAtyi, 1997; Atta-Boaten and Moser, 1998: Finegan et al., 1999; Alder and Silva, 2000; Eba'aAtyi, 2000) were effectively used. Later the ecological approach has, in response to avoid some inherent problems associated with statistical approach, been initiated in some studies (e.g., Bossel et al., 1994; Vanclay et al., 1997; Gourlet-Fleury and Houllier, 2000) to form functional groups based on ecological characteristics. Grouping based on commercial or trade categories may be adequately used in practical forest management (e.g., Vanclay, 1991, Vanclay, 1994; Finegan et al., 1999). A combined approach on these alternatives explained earlier is now commonly used (e.g., Silva, 1989; Phillips and Van Gardengen, 1999) as a means of summarizing the state of the forests, and describing some phylogenetic and ecological characteristics.

Interspecific variations in tree growth rate play a pivotal role in the determination of the structure, composition and timber yields of forests (Whitmore, 1984; Alder, 1995; Finegan et al., 1999). However, considerable understanding of forest stand dynamics and productivity have been gained from the major research initiatives without complete botanical identification (e.g., Schmitt and Bariterau, 1990) and without information on growth rates of individual species (e.g., Silva et al., 1995). Likewise, pure statistical techniques are often less than ideal. There are subjective choices that must be made about the spatial scaling and weighting of points and the possible clustering algorithm that influences the result. The many rarer species represented by one or two observations reduce the effectiveness and functional clarity of the grouping (Alder et al., 2003). In addition, the grouping produced is clearly dependent on the choice of equation and dependent variables used to model growth. In this connection, Phillips and Van Gardingen (1999) pointed out that Vanclay (1991) and Rombouts (1998) used the same method, but arrived at different species groups. Clark and Clark (1999) also highlighted that the conclusions of the studies of Lieberman et al. (1985), Vanclay (1991), Condit et al., (1996) were subject to the following important constraints: very limited total sample size per species and/or lack of growth data from all sizes classes; uncertainty in the increment data due to imprecise measurement in large inventories; and usually a lack of temporal replications. Similarly, some particular studies (e.g., Leech et al., 1991; Swaine and Whitmore, 1988; Vanclay, 1991) have insufficient generality, which might limit their scope of application (Atta-Boatang and Moser, 1998). It is clearly not yet possible to estimate the nature and number of functional types that predominate in these complex tree communities, or even to know if they are comprised of a coherent group of species in terms of key functional traits (Clark and Clark, 1999).

5.3. Mortality function

Many growth models for plantations avoid the problems of predicting mortality by assuming that no mortality occurs in well managed stands. This assumption may be untenable for natural forests (see Vanclay, 1994). Mortality is a significant process and an important component of natural forest stand development. Unfortunately, mortality is extremely variable and difficult to predict (Lee, 1971; Tint and Schneider, 1980; Dobbertin and Biging, 1998). Since mortality is an important, but sensitive parameter (Gertner, 1989; Alder, 1995), accurate prediction of mortality is an essential feature of any stand projection system (Monserud, 1976; Yao et al., 2001). Mortality remains one of the least understood components of natural processes (Hamilton, 1986; Alvarez et al., 2004). The causes of mortality are numerous. Tree age may be a contributing factor in the death of a tree. Many deaths may be attributed to competition, pests and diseases. Weather events such as drought, lighting, hail and wind storm may also kill trees. Damages arising from harvesting activities may also contribute to mortality in forest stands. Likewise, patterns of mortality may differ in scale, frequency and severity. Tree age is not a direct cause of the death of trees, but associated with susceptivity to death from other causes. Mortality caused by competition is most likely to affect small trees. Fungal infection may be typically associated with old trees, but it may occur at any age as a result of insect infestation or physical damage. Logging damage affects all sizes but tends to cause abrupt mortality in smaller trees, and have more lingering consequences among the larger ones.

Accordingly, two broad categories of fatal agents of forests have long time been recognized: natural phenomena and anthropogenic activities. Vanclay (1994) broadly further categorized natural mortality as regular and catastrophic. Regular mortality refers principally to aging, suppression and competition, but also to mortality arising from chance, and from normal incidence of pests, diseases, and weather phenomena (e.g., drought, storms, etc.; events which typically occur less frequently than once every ten years). Catastrophic mortality includes wildfire effects, occasional but severe losses from abnormal weather conditions, and major pest and disease outbreaks (Vanclay, 1994). The two classes of natural mortality may not always be independent of each other (Dobbertin and Biging, 1998) and there is no precise differentiation between regular and catastrophic mortality (Alder, 1995). Many techniques that predict forest growth incorporate a method for estimating natural mortality (or survival), but regular mortality was considered in most cases. The earliest mortality models focused on stand-level estimations, predicting the number of trees per unit area at several stages (e.g., Lee, 1971; Ek, 1974; Moser, 1972; Tint and Schneider, 1980; Somers et al., 1980; Clutter et al., 1983; Harms, 1983; Arney, 1985). With the advent in computing techniques in recent years, individual tree mortality functions have been developed using individual trees as basic prediction units (e.g., Monserud, 1976; Hamilton and Edwards, 1976; Buchman et al, 1983; Hamilton, 1986; Wan-Razali, 1988; Hamilton, 1990; Vanclay, 1991; Monserud and Sterba, 1999; Fridman and Stahl, 2001; Yao et al., 2001; Alvarez et al., 2004).

Vanclay (1991; 1994) pointed out many practical limitations of elegant theoretical concepts of even-aged, pure stands such as the relative spacing (Wilson, 1951), stand density index (Reineke, 1933), and self-thinning rule (Yoda et al., 1963) when applied in uneven-aged, mixed species forests. Since mortality is a rare event in the process of stand development, large data sets are required to get adequate representative samples for developing a mortality model. In the absence of appropriate data, mortality (or survival) appears to have been handled by assumption or subjective judgement (e.g., Newnham, 1964: Lin, 1970; Hegyi, 1974; Arney, 1972). In general, such approaches have provided adequate results because individuals making the assumptions or subjective judgement had a good understanding of the overall system they were modelling (Hamliton, 1986).

Later, various models for predicting mortality have been developed based on empirical analyses of large data sets. Regression analyses were the most common methodology for modelling individual tree mortality. Many applications have accomplished various cumulative distribution functions, the most popular is the logistic function (e.g., Monserud , 1976: Hamilton and Edwards, 1976; Buchman et al, 1983; Teck and Hilt, 1990; Vanclay, 1991; Monserud and Sterba, 1999; Fridman and Stahl, 2001; Yao et al, 2001; Alvarez et al., 2004). Variations in mortality have been frequently explained by (1) a measure of tree size, (2) stand density, (3) individual tree competition, (4) growth rate (vigour), and (5) site quality in these models. In addition to statistical analysis, two other procedures –recursive partitioning (Dobbertin and Biging, 1998) and neural network (Guan and Gertner, 1991)- have been also used to model individual tree mortality. However, neither has led to significant improvement in the ability to predict mortality using classical statistical methods (Monserud and Sterba, 1999).

Unfortunately, few studies have been designed especially to increase the understanding of the mortality process of tropical forests (e.g., Vanclay, 1994; Alder, 1995). Tint and Schneider (1980), Wan-Razali and Rustagi (1988), Vanclay (1991) developed empirical mortality models for particular tropical forests. In many situations, where tropical forests are being managed, the growth and yield information available is limited, or even non-existent; inventories of baseline data are also often partial and incomplete (Alder, 2002). In response to these situations, Alder et al. (2002) and Alder et al. (2003) introduced an equation as an effective alternative for estimating mortality, based on some theoretical assumptions.

5.4. Forest inventory data of Paunglaung Watershed

Paunglaung watershed is located in the central part of Myanmar. It is a headwater area of the Sittung River, one of three main river systems of the country and also provides water resources for the Paunglaung multipurpose dam, which is under construction and would be the largest one in Myanmar with a view to generate hydropower and irrigate more than 15000 ha of cultivated lands for double and triple cropping (Irrigation Department, 2003). Paunglaung watershed forms part of the Hindu-Kush Himalayas and covers an area of more than 4,000 km^2, falling in three administrative boundaries of Mandalay Division, Shan and Kayah State. It has an undulating topography of mountains and valleys, with the elevation ranging from 170 m to 1,000 m above sea level. Forests cover most parts of the watershed and according to the Departmental Instructions of the Forest Department of Myanmar, they can be broadly classified as mixed deciduous forests and evergreen forests. Mixed deciduous forests, which are by far the most important ones in the country, are found mostly in parts at lower elevations (generally inside Mandalay Division) whereas areas at high elevations (most parts of Shan State) are covered with an evergreen type of forests. Most forests have been organized as reserves, but some are still under the category of unclassified forests where accessibility is difficult. The recently formed Paunglaung reserve (declared in 1995) with a total area of about 1,600 km^2, a main reserve forest within the watershed, stretches over areas mainly along both sides of Paunglaung Chaung and lies entirely on the administrative areas of Shan State. Some parts of the Yezin and Nancho reserves, run by the Mandalay Division Forest Department, are also formed as Paunglaung watershed as well. Therefore the watershed area is an important source for local timber supply, but for commercial timber production as well. The Myanmar Timber Enterprise (MTE) of the Ministry of Forestry is carrying out harvesting operations under the Myanmar Selection System. The watershed is home also to wild elephants, and various wildlife species. Therefore, the Paunglaung watershed has diverse intrinsic values not only for the local and national economy, but also for biological diversity conservation.

Since 1981, the Forest Department of Myanmar has conducted a national forest inventory with a systematic sampling design. The adopted sample unit was L-shape, covering approximately 1 ha. distributed with a grid of approximately (3*3 km) over the forest areas (see detail for design in the section 4.4.3). The Myanmar Forest Act of 1992 also mandates to organize a forest inventory every 10 years at any particular forest. Accordingly, a forest inventory was organized on parts of the Mandalay Division in 1994 and on parts of Shan State in 1997. Under these inventories, a total of 185 sample plots were laid out over the forest areas within the watershed area (63 plots in Mandalay Division and 122 in Shan State). But the inventory for Shan and Kayah State could not cover all forest areas of the watershed due to security reasons. All plots laid out were temporary and all trees with +20 cm dbh were measured according to the prescriptions of the Forest Department (1985). In parts of Mandalay Division, the inventory was carried out again in December 2004 and early 2005. However, the compilation of data was not completed by the Forest Department and the official data for the new inventory were not available for the study. The present study could use the data from the 1994 inventory for parts of Mandalay Division and from the 1997 inventory for parts of Shan State.

5.5. Developing a spreadsheet model

A harvest model is to be developed for supporting the sustainable management of the natural resource of any given watershed. For this reason, the spatial boundary of the model is defined as the boundary of the watershed under study whereas the temporal boundary of the model will coincide with the felling cycle currently practiced in Myanmar (i.e., 30 year). A spreadsheet based stand table projection model was developed with a view to update post-harvest inventories and to estimate the allowable cuts for the next cutting cycle for a watershed area. The model was coded in the spreadsheet package MS Excel. The basic input for the model are current stand tables of six species groups (i.e., Teak and 5 hardwood species groups adopted by the Forest Department of Myanmar) organized in 5 cm dbh classes. Mortality rates for each dbh class were also an important input for the system. The movement ratio method was adopted for outgrowth calculations to update a fraction of trees moving from one class to another over time.

5.5.1. Developing a local stand table

Even though stand tables are usually presented in terms of tree number, it is clear that, for management purposes, tables of volumes or basal area by size classes may be required, the tree number table is the most useful for growth projection purpose (Alder, 1995). Numbers are presented per km^2, rather than per ha, in order to give a meaningful picture at the low levels of stocking. A characteristic feature of the stand tables of multi-species, uneven-aged tropical forest is the progressive decrease in stem numbers from the smaller to the larger diameter classes. This is invariably seen when large areas and groups of species are considered. However, with typically hundreds of species being observed in these forests, diameter distributions for particular species frequently occur which show a deficit of smaller trees or a preponderance of large ones (Alder, 1995). A problem with stand table projection is the proliferation of classes with fractional numbers of stems (Vanclay, 1994) that need to be controlled through the adjustment of width of size-class and interval of projection. In addition to stand characteristics, other factors such as the purpose of enumeration, the value of the stand, and conventional practices also influence the specification of the diameter class width. In this respect, Alder (1995) suggested 5 cm as a suitable class width for most tropical forests. Consequently, 5 cm-classes were defined up to 70 cm dbh. 70 cm dbh and above was considered only a single class, resulting in 11 diameter classes in the stand table.

The objective of this study is to construct a management-oriented parameter parsimonious model for stand table projection to gain objective insights with certain degree of accuracy into setting an allowable cut and future management prescription on the watershed level. It is necessary at first to simplify the complex stands by aggregating species in a manageable number of groups, that could be handled as a single species. Given the constraints of different approaches of species grouping discussed above, the available data structure of the present inventory system in the country, and the objective of the model, the grouping system of hardwood currently used in Myanmar for timber management planning was adopted for constructing the stand tables as a base of a forest information system in the decision process of watershed management planning. Consequently, six different stand tables were developed, including Teak and five other hardwood species groups.

5.5.2. Estimating outgrowth

Because specific growth functions for particular commercial species groups have not been developed yet, the mean increment will be used for estimating outgrowth. Again, there is no continuous forest inventory system in the study area. Thus, the mean diameter increment for a given species group will be taken from increment data of the permanent sample plots of Bago mountain ranges. The mean increment of a particular species group was estimated from pooled data of species. Before estimating the mean values, outliers were discarded from the respective increment data sets. The estimated mean diameter increment of a particular species group as compiled from the forests of Bago mountain ranges are presented in table 5.1.

Table 5.1 The estimated mean diameter increment for Teak and other hardwood groups

Species Group	Timber value	Mean diameter increment (cm/year)	Number of species
Teak	premium wood	0.64	1
Group I	construction	0.55	8
Group II	decoration	0.32	27
Group III	local use	0.29	24
Group IV	box-wood	0.44	17
Group V	lesser-used	0.36	> 400

Then the proportion of trees moving to the next class as outgrowth may be calculated from the following equation (5.4), based on two assumptions (1) trees are uniformly distributed within the classes and (2) all trees in the class grow at the mean rate.

$$O = \frac{i}{w} * t \tag{5.4}$$

where,

O = the proportion of trees moving to the next class (outgrowth)
i = mean increment (cm/year)
w = the width of the diameter class (cm)
t = the projection period (year)

5.5.3. Estimating periodic mortality

Mortality is an important component in a stand projection system. A mortality model therefore is incorporated in the stand projection system in order to get more realistic future stand conditions. The stand tables were developed for six species groups: Teak and five other hardwood species groups. Even though a survival function was readily available for naturally grown Teak, no mortality or survival model has been developed for other hardwood species. For Teak, Tint and Schneider (1980) developed an empirical function for estimating the annual survival ratio by using girth at breast height (gbh), a common measure for expression of tree size in Myanmar, as an explanatory variable. Later, Vanclay (1992b) modified this function using dbh as an explanatory variable. The original function and modified function are mentioned below.

$$ASR = 0.987 + 0.012\left(1 - e^{\left[(-0.0744959 * gbh) * (1 + 0.0744959 * gbh)\left(0.0027748 * gbh^2\right)\right]}\right) \tag{5.5}$$

$$ASR = 0.987 + 0.012\left(1 - e^{\left[(-0.0921 * dbh) * (1 + 0.0921 * dbh)\left(0.00424 * dbh^2\right)\right]}\right) \tag{5.6}$$

where,

ASR = the annual survival ratio
gbh = the girth at breast height (inches)
dbh = the diameter at breast height (cm)

The modified function was used for estimating annual survival ratios for Teak in the stand projection system and estimates of annual survival ratios for different diameter classes of Teak are given in Table 5.2. Then periodic mortality ratios were calculated using equation 5.7 to commensurate the time step used in the stand projection system (i.e. here 5 years).

Table 5.2 Annual survival ratios for different diameter classes of Teak

Diameter classes (cm)	Annual survival ratio
20-25	0.9911
25-30	0.9926
30-35	0.9939
35-40	0.9950
40-45	0.9960
45-50	0.9967
50-55	0.9973
55-60	0.9978
60-65	0.9981
65-70	0.9984
> 70	0.9985

$$PMR = 1 - ASR^{t} \tag{5.7}$$

where,

PMR = the periodic mortality ratio
ASR = the annual survival ratio
t = the time interval (year)

With the lack of the appropriate data to develop empirical models for predicting mortality of other hardwood species groups, a theoretical approach has to be adopted as an alternative. Alder et al. (2002) and Alder et al. (2003) proposed an equation for estimating the annual mortality rate (AMR) based on two assumptions: (1) diameter increment is constant over the life of the tree, and (2) mortality rate is constant over the life of the tree. Although neither of these is likely to be true in practice for a particular tree, variability of both increment and mortality is so high that the average behaviour of increment and mortality for many species does not appear to deviate greatly from these assumptions (Alder, 2002). If mortality rate and increment are assumed to be approximately constant for a species between 20 cm dbh and the typical diameter that is specified by the 95% point on the cumulative diameter distribution and the diameter itself can also be assumed to represent an equilibrium distribution, then the annual mortality rate can be estimated from mean increment and typical diameter (D_{95}). By definition, the typical size limit represents the point at which a cohort of trees has been reduced in numbers by 95% from its value at 20 cm dbh. This is because, given the assumptions of constant increment and mortality rate, one is dealing with an idealized exponential distribution (Meyer, 1952). Under the first assumption of constant diameter increment, the time taken by the tree to grow from 20 cm dbh to the typical diameter (D_{95}) can be estimated by the equation (5.8).

$$T_{95} = \frac{D_{95}}{ID_{avg}} \tag{5.8}$$

where,
T_{95} = the time required to reach the typical diameter D_{59} (year)
D_{95} = the typical diameter (cm)
ID_{avg} = the mean diameter increment (cm/year)

Given that the general formula for AMR and survival (S) after a period *t* can be expressed as equation 5.9.

$$S = (1 - AMR)^t \tag{5.9}$$

where,
S = the survival percent after a period t
AMR = the annual mortality rate
t = the time interval (years)

Only 5% of the initial population would survive at $D_{95.}$ By substituting equation (5.8) and the survival value as 0.05 into equation (5.9), the equation for estimating the annual mortality rate (AMR) can be formulated as follow:

$$AMR = 1 - 0.05^{\left(\frac{ID_{avg}}{D_{95}}\right)} \tag{5.10}$$

where,
AMR = the annual mortality rate
D_{95} = the typical diameter (cm)
ID_{avg} = the mean diameter increment (cm/year)

Based on results of validation tests using data sets of three different tropical regions of Brazil, Costa Rica, and Papua New Guinea, Alder et al. (2002) and Alder et al. (2003) concluded that the estimates of *AMR* provided by the method tends to be a little high, but were generally approximately correct. The equation (5.10) was, therefore, used to estimate the mortality for other hardwood species groups, based on the data from PSPs of Bago mountain ranges. Mean diameter increment, typical diameter (D_{95}), and annual mortality rates for different species groups are presented in table 5.3.

Table 5.3 Mean diameter increment, typical diameter (*D_{95}*), and mortality rates for different species groups

Species Groups	Mean diameter increment (cm/year)	D_{95} (cm)	Annual mortality rate
Group I	0.55	101.2	0.0161
Group II	0.32	72.2	0.0132
Group IIII	0.29	85.6	0.0101
Group IV	0.44	71.0	0.0184
Group V	0.36	67.0	0.0160

Periodic mortality rates were then calculated using the formula (5.11) to use in stand projecting system.

$$PMR = \left[1-(1-AMR)^t\right] \tag{5.11}$$

where,

AMR = the annual mortality rate
PMR = the periodic mortality rate
t = the time interval (year)

5.5.4. Ingrowth

Ingrowth estimation is also a crucial component in long-term projection. The projection system however is intended to update the post harvest inventory for forecasting future stand conditions and for estimating a realistic allowable cut for the next felling cycle at the watershed level. Moreover, the data for estimating ingrowth could not be available adequately. Therefore, ingrowth was not considered in the present system. Current stand tables for different species groups were projected adjusting only with outgrowth and mortality estimates.

5.6. Updating the forest Inventories on Paunglaung watershed

Inventory data from Paunglaung watershed were used to develop local stand tables. The estimates of outgrowth and mortality rates for different species groups were filled up in the concerning cells in the EXCEL spreadsheet program. Then current stand tables for different species groups were updated for a period of 30 years. The resulting stand tables are presented below.

Table 5.4 Stand table for Teak

Projection year	Size classes (cm)										
	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60	60-65	65-70	+ 70
	Number of trees per km^2										
0	23	8	6	6	6	8	4	0	4	0	0
5	7	17	7	6	6	7	7	3	1	3	0
10	2	10	13	7	6	6	6	5	2	2	2
15	1	5	11	11	6	6	6	6	4	2	3
20	0	2	7	11	9	6	6	6	5	3	4
25	0	1	3	8	10	8	6	6	6	4	6
30	0	0	2	5	8	9	7	6	6	5	9

Table 5.5 Stand table for species group I

Projection year	Size classes (cm)										
	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60	60-65	65-70	+ 70
	Number of trees per km^2										
0	57	22	32	20	16	10	9	9	2	2	11
5	21	40	24	25	17	13	9	8	6	2	11
10	8	26	31	23	20	14	10	8	7	4	11
15	3	14	26	25	20	16	11	9	7	5	13
20	1	7	17	24	21	17	13	9	7	6	14
25	0	3	10	18	21	18	14	11	8	6	16
30	0	1	6	12	18	18	15	12	9	7	18

Table 5.6 Stand table for species group II

Projection year	Size classes (cm)										
	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60	60-65	65-70	+ 70
	Number of trees per km^2										
0	117	137	119	93	89	60	38	30	18	12	30
5	72	122	117	95	85	65	43	31	21	13	32
10	44	98	111	96	83	67	47	32	23	15	34
15	27	75	100	95	82	68	51	35	24	16	37
20	17	55	85	90	81	68	53	38	26	18	39
25	10	39	70	83	79	68	54	40	28	19	43
30	6	27	56	73	75	67	55	42	30	21	46

Table 5.7 Stand table for species group III

Projection year	Size classes (cm)										
	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60	60-65	65-70	+ 70
	Number of trees per km^2										
0	133	130	97	71	68	32	23	15	8	2	7
5	88	124	102	75	66	41	24	17	10	4	7
10	58	108	103	79	65	46	28	18	11	5	8
15	38	88	99	82	66	49	32	20	13	7	9
20	25	69	91	83	67	52	35	22	14	8	11
25	17	53	80	81	69	54	38	25	16	9	12
30	11	40	68	77	69	55	41	28	18	11	14

Table 5.8 Stand table for species group IV

Projection year	Size classes (cm)										
	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60	60-65	65-70	+ 70
	Number of trees per km^2										
0	53	65	63	51	56	33	13	13	12	9	29
5	25	54	58	52	49	40	21	12	11	10	30
10	12	36	51	50	46	40	27	15	11	9	32
15	6	22	40	46	44	39	31	19	11	9	33
20	3	13	29	39	41	38	32	22	14	9	34
25	1	7	19	31	37	36	32	25	16	10	35
30	1	4	12	23	31	33	31	25	19	12	37

Table 5.9 Stand table for species group V

Projection year	Size classes (cm)										
	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60	60-65	65-70	+ 70
	Number of trees per km^2										
0	684	480	416	294	229	146	102	64	39	25	46
5	385	516	407	315	235	165	110	73	45	28	51
10	216	429	415	324	245	177	121	80	51	32	58
15	122	319	388	331	255	188	132	89	58	37	65
20	68	223	333	326	263	197	142	97	65	41	73
25	39	150	268	303	265	206	151	106	71	47	82
30	22	98	205	267	258	211	159	114	78	52	92

6. A Yield Regulation System for Sustainable Watershed Management

Tropical forest watersheds generally provide a range of goods and services to society. Traditionally, their land use is dominated by a direct use of forests such as timber extraction and the conversion of forest to agricultural or livestock uses to generate local and national benefits. Moreover, ecological services both on-site (e.g., habitat and soil conservation) and off-site (e.g., water flow and sediment yield regulation) and social services (e.g., off-farm season income for local communities) provided by tropical forest watersheds have also been important. With the recognition of both tangible and intangible products and services with temporal and spatial effects of the tropical forest watersheds, recent conservation efforts have focused on one of two approaches: outright protection of high priority areas and sustainable forest management (SFM). Although protection is widely accepted as a most desirable conservation strategy, expanding protected areas is often too costly and politically unfeasible in many cases. Accordingly, sustainable forest management has become a standard approach to conservation of tropical forest watersheds. Since SFM is usually subject to three main criteria: economic gain, ecological integrity and emotional acceptance, commercial timber production is indispensable for economically viable use of tropical forests in order to prevent the conversion of these forests into other land uses. Therefore sustained production of timber yield is still a major objective of SMF and numerous discussions have been conducted at the national and international level on the subject of SFM, biological diversity, ecosystem management, wood certification, and criteria and indicators for assuring the sustainable production of timber from the natural tropical forests. At the same time, various concerted attempts have been made to interpret the implications of these initiatives into practical operations in the field. The concerns have been focusing on three major problem areas: yield regulation, silvicultural system, and harvesting system.

The concept of yield regulation may be described as the process by which the objective of sustainable yield is translated into operational forestry practices via planning and monitoring (cf. Alder, 2000). It involves making decisions that lead to a clear specification of terms and conditions under which timber harvests may take place using technical information about the forest. Yield regulation, irrespective of the silvicultural system being applied, provides a basis for deriving a log harvest which is in balance with forest increment and for controlling output to ensure that the cut is neither exceed nor undercut (Armitage, 1998). In general, the aims of a proper yield regulation system are 1) to optimize the sustained yield, 2) to minimize the ecological impacts to the forests and, 3) to reduce the managerial input such as manpower, funds etc. It is thus a central concept in SFM and a means to achieving sustained yield (Alder, 2000).

Yield regulation in its wider meaning includes the analysis of silvicultural and logging methods (cf. Seydack, 1995). The successful implementation of a given sustained yield regulation is therefore most often determined within the broader socio-economic/political context. Numerous socio-economic factors such as demographic pressure, poverty, short-term expediency and the ineffectiveness of controlling institutions often jeopardize the successful implementation of sustained yield regulation system (cf. Weidelt, 1989; Schmidt, 1991). Although this state of affairs is mostly attributable to socio-economic and political constraints, some basic methodological issues are still evident in developing a more rational yield regulation system. The methodological issues include a conceptual dilemma that need to be refined for specifying sustainable harvest without semantic confusion and operational problems crucial for characterizing an appropriate yield regulation system in practice.

6.1. Conceptual dilemma

Although the term sustainability was popularized by the Brundtland report (WCED, 1987), the concept has been evident for centuries in forestry practices especially in Europe. Conventionally, the sustainability concept has been equated with the principle of sustained yield. Under the sustained yield principle, "yield" was only referred to amount of timber that can be harvested at any point in time whereas "sustained yield" implied timber that can be harvested from a forest perpetually at a given management intensity (i.e., a non-declining even-flow of timber from forests). However, sustained yield concepts have been criticized for failing to take thorough account of natural ecological processes, leading to ecologically inappropriate management (Mladenoff and Pastor, 1993). A more strict interpretation of the concept became widespread in countries outside Europe during 1980s (e.g., Gadow, 1980; Parry et al., 1983), pointing out that a non-declining even-flow is neither necessary nor sufficient for sustainability. Non-declining yields in the medium term do not necessary ensure sustainability in the long term, since focus on timber yields may divert attentions from other issues such as habitat, soil and watershed conservation (cf. Vanclay, 1996). SFM must be assumed a systematic approach to sustaining each component of the forest ecosystems and their interactions. In forests available for wood supply, this means combining wood production with other management objectives, above all, the conservation of plants and animal biological diversity and soil and water conservation. Similar intentions were not as clear in the classical management concept of sustained yield but it is now agreed that forest management must systematically address a fuller range of environmental, social and economic issues (Lanly, 1995). In order to maintain the supply of wood to the forest industry and to safeguard the important environmental and social functions of the forests, it is of fundamental importance to change from pure extraction of the forest under the sustained yield management to multiple use forest management. Therefore, the scope of SFM became wider than the production-oriented sustained yield principles and adopted a more conservation-oriented approach.

A prerequisite of SFM is that removal of forest products does not exceed levels of regrowth (Higman et al., 1999) and the fundamental basis therefore is to set a harvest at a sustainable level. Ultimately, the same timber production level should be obtained in each cutting cycle (Jonker and Foahom, 2004). It is however difficult to assess the sustainability of a harvest at any point in time (Vanclay, 1996) and determining the sustainable harvest levels from natural tropical forests is in fact a complex matter for the reasons that not only the actual and future production potential of the forest (i.e., ecological factors), but also marketability of different species (i.e., economic consideration) and quite often the utilization pattern of local communities (i.e., social aspect) are required to be considered. In the natural forests, the first harvest consists of accumulated timber capital which has built up over a long periods. After harvesting, there is a major change to the species composition and size class mixes that noticeably affect the productive potential of the forests.

Here, it is necessary to distinguish between “sustained yield” and “sustainable yield”. Sustained yield is an objective of SFM- a measurable activity, or output specified to achieve during a given period of time. It generally implies that the volume of wood harvested is equal to the amount of new wood being grown within the forest as a whole. Wood harvested in one stand is balanced by wood growth in the forest remaining stands. Conversely, sustainable yield is a goal of SFM or the end point of a strategy to achieve forest resource development to meet current needs without prejudice to their future productivity, ecological diversity and regenerative capacity. It is a long-term aim for maintaining and enhancing the health of the forest ecosystem while providing environmental, economic and social opportunity for present and future generation. Ultimately, sustainable yield can be proved only by demonstrating repeated commercial harvesting over a long period, coupled with detailed monitoring and inventory (e.g., Vanclay, 1990). Clearly that sustained yield can only be obtained realistically from a forest in a steady-state or normal condition, when increment and the yield are equal. It is highly unlikely that any forest is in that condition, although such a forest structure may be an ideal goal. If the strategic goal of forest management is to get the forest into a truly sustainable condition (from a timber production perspective), the aim of day-to-ay forest management is to harvest that amount of timber at such a rate that some "ideal condition" is achieved as soon as possible. This is a transition phase as opposed to a steady-state phase of management. This necessarily means that over time this quantity will vary as it is not possible to predict with certainty how the forest will react to structural manipulation. Normally, this will be achieved by frequent revision of management prescription: adaptive management at the strategic level is called for (Turner, 2003).

The quantity to be removed in the transition phase is usually described as the "allowable cut" (or prescribed cut, prescribed harvest, prescribed yield, permissible yield). It is a practical measure or a dearly expressed management specification of the average quantity of wood that may be harvested from a forest annually or periodically over a specified period. When the allowable cut is expressed on an annual basis, it is called Annual Allowable cut (AAC). AAC is usually expressed as quantity per unit area and quoted as an aggregate figure for all commercial species, but can be broken down by species and localities for more detailed planning. The setting of an AAC is to impose a ceiling on the harvest, to monitor forest production and to set limits for the timber industry. Classical empirical procedures have been used to determine the allowable cut where there is little or limited information on forest increment and where forest management is being introduced for the first time. Many formulae for determining the allowable cut generally contain almost all of four basic elements: forest area; felling cycle (the biological rotation period); growth (the forest volume increment); and existing growing stock of the forest. Each of these methods therefore provides only a general guideline for deriving an allowable cut (Armitage, 1998). In contrast, sustainable yield must be analyzed through some form of growth projection and modeling with the use of stand table information derived from pre- and post-harvest inventories and permanent sample plots. The projection system should use not only reliable data on stand growth components such as recruitment, growth and mortality, but also that of logging damage to achieve more realistic predictions on the future forest composition and structure.

Sustainability has to ensure the availability for a specific "critical mass" (both in quantity and quality) over time and space. In order to use sustainability as a functional guiding principle in the development of a yield regulation system, sustainable yield (or sustainable timber harvest) must, however, be defined more explicitly in terms of prerequisites and constraints. Sustainable harvest should imply that similar amounts and types of products (dimensions, quality, species) continue to be harvestable at periodic intervals indefinitely (Seydeck, 1995). Harvesting must be organized within the regenerative and renewability capacity of the forest system. In regard of environmental services (e.g., soil and water protection) and maintenance of biodiversity, harvest levels must remain within the spatial and temporal extent of the natural disturbance regime. The definition of a sustainable harvest should not only be based on the productive forest ecosystem as a whole but also respect the contrasting biological characteristics of individual species within the system that determine the ability of a particular species to tolerate or to recover from harvesting.

6.2. Operational problems

6.2.1. Operational economics

Timber harvesting (logging) for yield realization and silvicultural operations aimed at the improvement of regeneration and productivity are subject to constraints of economics with important consequences in the development of yield regulation systems (Seydack, 2000). Due to a limited share of marketable timber species and spatially disperse individuals within a wide area of the forests, the minimum profitable volume per unit area is often much lower than believed (cf. Palmer, 1975). Therefore, in the tropics large tracts of forests are required to extract a given volume of timber and this demands delicate operations in felling trees and hauling logs, involving higher costs of harvesting. The requirement of a large tract of forests under each harvest event poses a huge constraint on economic viability of modern timber removal operations that involve high capital investments in mechanization and high quality road construction. This often leads to the deployment of an undesirably high harvesting intensity and spatially concentrated logging to gain economic efficiency, resulting in serious negative ecological impacts to the forests. In addition, selection felling needs special care not to damage the trees that are left, especially young saplings that will constitute the future crops. These operations, which cannot be accomplished by mechanization, but only by employment of skilled manpower, are labor-intensive processes, which involve higher operational costs. On the other hand, given a diverse species composition and stand structure of the tropical forests, a large-scale silvicultural operation is often not viable and specific operations are required for particular stands. Such diverse operations necessarily require massive technical input, vast logistical support and hence high economic costs. In consequence, careful and innovative conflict reconciliation is essential to tackle two issues of operational economics: 1) cost effectiveness of silvicultural operations through integration with timber harvesting; 2) cost effectiveness of logging through yield optimization.

6.2.2. Inducing regeneration

A second operational problem in developing a yield regulation system is to induce natural regeneration in different forest types. In fact, tropical forests possess considerable capacity to regenerate through substantial seedling-banks (reservoirs of suppressed seedlings on the ground) or seed-banks (reservoirs of viable dormant seeds in the soil). Accordingly, most tropical forest silvicultural systems depend on natural regeneration to produce new crops based on the assumption that the nature of regeneration will be highly contingent on the disturbance caused by the logging operations. The first consideration under a particular natural regeneration system of management is thus to ensure the presence of adequate regeneration of the commercial species. Nonetheless, it is most unlikely that a silvicultural system can mimic precisely the natural disturbance regime of a forest and various reports (e.g., Fox, 1976; Synott and Kemp, 1976; Schmidt, 1987; Wadsworth, 1987; Wyatt-Smith, 1987a, 1987b; Burgess, 1989; Rietbergen, 1989; Whitmore, 1991b) indicated however that the failure to ensure adequate regeneration of commercial species within the context of a practiced silvicultural system was a widespread problem

In natural forests, disturbances create gaps of different sizes in the canopy and these gaps are subsequently filled with either existing seedlings and saplings or germinating seedlings. Gap formation in the canopy is believed to modify the microclimatic conditions to initiate height growth of existing seedlings or stimulate germination of viable seeds in the soil. Therefore, an important basis of silviculture is to manipulate the forest canopy to create gaps of a size that favours regeneration of chosen species (Whitmore, 1978). Successful regeneration is simplistically taken as being a matter of canopy manipulation from the standpoint of disturbance paradigm in response to light resource. The value of canopy opening to induce regeneration has however not lived up to expectation and accumulated autecological knowledge on tree species of tropical forests revealed that it was too simplistic to recognize the uni-dimensional disturbance paradigm with light resource as a limiting factor (Seydack, 2000).

Regeneration of the forests involves recruitment, survival and growth of a very large number of species that may differ in their modes of life and the roles they play in regeneration. The interaction of resource levels, colonization pattern, and each species' ecological properties will influence changes in the spatial and temporal pattern of vegetation in a given location (Bazzaz, 1991). In addition to gap characteristics (size, timing and frequency), numerous factors such as seed characteristics (availability, size, dormancy, dispersal mechanism and susceptibility to predation), seedlings characteristics (mode of germination, initial size, tolerance and susceptibility to predation), and substrate conditions (woody debris or mineral soil) are important to successful regeneration of trees in a gap. Seydack (2000) proposed a multidimensional metabolic trade-off paradigm for forming ecological "gilds" for designing effective silvicultural interventions to induce regeneration of commercially important species in tropical forests. It is advocated that forestry operations should respect the natural regenerative capacity (i.e., seed availability, seed size, proximity of seed source, seed dispersal mechanism, ect.) to support successful colonization of gaps created by harvesting. Accordingly, a yield regulation system should ensure sufficient natural regeneration without special silvicultural input through a guiding principle that spatial and temporal impact of disturbances resulted from logging operations must be analogous to that of a natural disturbance regime. If the system of logging does not comply with these requirements, good natural regenerations should not be taken for granted and much silvicultural input is required to ensure adequate regeneration (cf. Appanah and Weinland, 1992).

6.2.3. Enhancing productivity

Silvicultural treatments are provided with a view not only to encourage the regeneration but also to enhance the productivity of the forest. Once the regeneration has assured juvenile desirable crops, silvicultural intervention is concerned with promoting the best conditions for as many individuals as the site can support. This obviously requires the reconciliation of two opposing considerations, those for the individuals and those for the total crop. Conditions for the individuals must be those under which they can grow fastest with good forms under the least possible competition to obtain an extended commercial bole height. On the other hand, the conditions for the crop must be those in which the greatest possible volume of timber per unit of time and area is produced. The treatments that usually apply to create the necessary conditions for enhancing productivity of natural tropical forests are made up of various silvicultural operations. These may be applied jointly or independently, but in all cases a relatively small number of distinct operations are found to be involved (Baur, 1964). The operations could be classified by priority and motive into two main categories: liberation (the removal of impeders to free desirables from inferior competitors) and refining (the general removal of weeds, defectives and proscripts, whether they are impeding desirables or not, in the interests of complete utilization of the site by the desirable crops). Liberation is directed towards the desirables while refining to the undesirables (Dawkins, 1958).

The potential for, and limitations of, productivity enhancement through silvicultural operations is another central operational issue in a yield regulation system. Dawkins (1959) thoroughly discussed about the limitations on efforts to improve the volume increment of the natural tropical high forests of Uganda. The upper limits to productivity are fixed by the relatively wide crown expansion of the tropical high forests species, resulting in a low stocking of crop trees per unit area. Below these limits the prospects for substantially increased growth of potential crop trees as a result of silvicultural treatments are not high (Palmer, 1975). Again, it is discernable that although some tropical trees grow faster than any trees found in other vegetation types, the great majority of stems in natural stands have a disappointingly slow diameter increment, probably due to intense competition for soil water with dense ground vegetation, narrow gaps for optimum crown enlargement, and senility especially in larger sizes. It simply implies that a time of passage to reach the harvestable size for many commercial species is very long (Dawkins, 1959).

The most advanced form of liberation is of course thinning. In all cases, thinning is generally taken to have an increment-promoting effect with the underlying reason that over-crowding affects tree growth either directly or indirectly. In effect, thinning redistributes total fiber growth of the stand to a few larger stems, and hence increases the growth of the remaining trees and the stand value, but not the total stand growth (Assmann, 1970; Emmingham and Elwood, 1983). It is obvious that the growth potential of a site can be concentrated on desirable species through the removal of competing and overtopping non-commercial species (e.g., Boxman et al., 1985; Schmidt, 1987; Hutchinson, 1988; Schmidt, 1991; Bruenig, 1996). Liberating thinning increases growth of small to medium-sized trees (e.g., Synnott, 1980; De Graaf, 1986; Maitre, 1987; Korsgaard, 1992; Bertault et al., 1993), while larger-sized canopy occupants remain unaffected by release operations (e.g., Dawkins, 1959; Palmer, 1975; Bertault et al., 1993). Moreover, growth acceleration responses may however later be cancelled by setbacks (Assmann, 1970). The surge of a growth response only can last as long as newly available crown and root zone space is being extended into and is thus relatively short (e.g., Wan Razali, 1993; Silva et al., 1995). Diminishing magnitudes of reaction are expected with repeated release operations or these become impossible to carry out due to a lack of remaining and competing trees. If the growth acceleration cannot be sustained over the felling cycle, untreated stands may be equally productive (Seydack, 1995).

A high absolute productivity of mixed stands is usually associated with high growing stock levels (e.g., Assmann, 1970; Seydack, 2000). When growth is concentrated on larger, fewer individuals in uneven-aged mixed stands (Hasse and Ek, 1981), it may seldom be possible to appreciably increase volume production per unit area with thinning operation (Seydack, 1995, 2000). There are some conflicting conclusions regarding the effectiveness of silvicultural release operations from different studies (e.g., Lee, 1981 op. cit. Tang, 1987; Primack et al., 1987). If release operations are to be applied as productivity enhancement, some explicit stipulations regarding on type of subject tree and the type and degree of release need to be made in order to address two specific issues –sustainability of growth response and life history related consequences of growth acceleration.

Different types of tree (light-demanding, shade-tolerant, or gap opportunist) show dissimilar response to different types and degrees of release. Thus, the knowledge of the commercially desirable species falling into each of these ecological groups is important in deciding the type (thinning by felling or thinning by girdling) and the intensity (heavy or light) of thinning (e.g., Bauer, 1964). Thinning by felling opens the canopy abruptly, creating large patches of high illumination, damaging and reducing growing stock, and thereby favouring the growth of light-demanding pioneer species. Thinning by girdling opens the canopy gradually and to a limited extend. This procedure causes less physical damage than does thinning by felling, thus favouring the growth of gap-opportunists species and acting to limit the proliferation of woody climbers and light-demanding pioneer species (Hutchinson, 1987). Therefore, intervention in the form of limited crown release of pole-size individuals only may provide sustainable growth increase to gap opportunists without any possible concomitant disadvantages.

Based on the metabolic trade-offs, species are inter-specifically and intra-specifically differentiated. Natural uneven-aged mixed species forests can at least be viewed as a two-layered system: canopy-occupants and sub-canopy trees. These gilds were appropriately termed as forest matrix invaders and forest matrix species by Seydack (2000). Forest matrix invaders are emergents of persistent species that appear to have greater intra-specific metabolic plasticity, which enables them to establishment within the forest matrix under shade (Ashton, 1988), recruit into the canopy through relatively small overhead gaps (Clark and Clark, 1987; Tuomela et al., 1996) and sustain growth even when relatively large in order to reach the stature required for a "supra-canopy" position (Seydack, 2002). Many commercially desirable species of the tropical forests belong to this group. On the other hand, sub-canopy trees are mainly ephemeral species and some suppressed stems of persistent species waiting to invade the forest canopy matrix.

The removal of the sub-canopy matrix may diversify the light climate and the growing space (Bruenig, 1996). The removal of almost all canopy and co-dominant trees may stimulate immature individuals to grow through a lower forest matrix than would be the case in a natural forest which may results in lower commercial bole height and thus reduced total volume of wood production (Assmann, 1970; Cheah, 1991). This response appears to be more troublesome in trees that can use available resources efficiently to sustain growth through stress tolerance (e.g., Seydack, 2002). Under canopy opening early in the development of forest matrix invaders, it is expected to result in early growth peak, more susceptible to decay (Leibundgut, 1960), insect attack and root rod (FAO, 1989a), early onset of mortality (Seydack, 2002), reduced final dimension (Assmann, 1970; Seydack, 1995) and possibly also lower strength (Appanah and Weinland, 1993) and poor wood quality (Willan, 1965; Wyatt-Smith, 1987a). High value production, both in terms of timber quality and dimension, requires that growth is concentrated onto the larger individuals. If this is to be achieved without compromising timber quality, life history strategy trade-offs should be taken noted in terms of the effects that excessive canopy opening or the absence of a nurse stand could have on the second rotation tree crop (Seydack, 1995; 2000).

6.3. Tactical elements of the yield regulation system

6.3.1. Harvest interval

The harvest interval is the length of time allowed to pass between harvest events on a given area and hence mimics the temporal resolution of a given yield regulation system. It is commonly known as "felling cycle" in uneven-aged (or Continuous Cover Forest) and as "rotation" in even-aged (or Rotation Forest) management systems. Theoretically, once a harvest interval has been established, the forest is spatially divided into blocks or coupes for each harvest event. This spatial extent for a major harvest operation is known as a "felling series" for uneven-aged and "regeneration blocks" in even-aged management. Consequently, the harvest interval defines the macrostructure of the regulated forests (Davis and Johnson, 1987) and is further linked to the harvest intensity (i.e., the harvest quota retrievable per unit area; see Seydack, 2000), having implications on operational management and silviculture. In effect, the harvest interval is interrelated proportionately with the spatial scale and disproportionately with the intensity of the harvest for each operational cycle (i.e., the shorter harvest interval requires a larger area and a lower harvest intensity). The harvest interval represents the frequency of the visits to a target forest that might have some silvicultural control. A short harvest interval that is associated with a more frequent harvest reentry would reduce competition, save losses from natural mortality, but expend losses from logging-induced mortality (e.g., Wright, 2000). Shorter intervals may claim recurrent economic returns, but extremely short intervals would not be economical in most cases (Crow, 1992). Accordingly, The ultimate aim of an appropriate harvest interval is to exploit the growth accumulated between harvest events with higher operational efficiency, to fulfill silvicultural requirements of the desired species and to control disturbances from logging operations. The harvest interval should therefore be selected in accordance with the above considerations within a multi-cycle time frame.

6.3.2. Harvest intensity

The harvest intensity generally refers to the amount of timber harvested per unit area at a specific harvest event (Seydack, 2002). It characterizes the microstructure (e.g., size distribution) and composition of the residual stands that affects future growth performance (Davis and Johnson, 1987). The amount of yield obtainable per unit area with a single harvest entry directly connects to economic effectiveness and efficiency of harvesting operations. Likewise, timber harvesting, even with the introduction of the Reduced Impact Logging (RIL) techniques, unavoidably causes some disruption to the forest. Harvest intensity has thus not only economic but also ecological implications. A higher harvest intensity is necessary for economic viability of the modern timber removal operations that involve high capital investments, resulting sizeable disturbances to the residual growing stock. Such a disturbance to the residual growing stock will retard the forest recovery process and insert negative impacts to long-term productivity. This points out the fact that the harvest intensity must be congruent with the natural disturbance regime, thereby inter alia allowing regeneration to take place and that it might also be relevant to restore the pre-existing conditions of the growing stock within a time frame that matches with the established harvest interval. Accordingly, the desirable harvest intensity combines the maximum use of the forest resource (i.e., economic efficiency) and minimum damage to the target stand (i.e., ecological integrity).

Generally, the yield is sustained under selective felling systems through the control of harvest intensity by numbers of trees with a minimum diameter limit. In this context, the limit is generally defined arbitrarily and it is therefore likely with a harvest guided only by minimum diameter limits to have high potential extraction rates in well-stocked forests (for example, in mixed Dipterocarp forests; Sist et al., 2003a). As a result, different harvest intensity thresholds have been proposed to use jointly with the minimum diameter limits in order to avoid such high potential extraction rates and associated unwarranted disruptions to the residual stands. The minimum seed trees to be retained, the maximum trees to be harvested (e.g., Bertault and Sist 1997; Sist et al., 1998, Sist et al., 2003b), the minimum spacing distance (e.g., Sist et al., 2003a), and permissible canopy opening have been frequently suggested to help obtain the optimal residual growing stock for sustaining growth rates and thus ensuring the sustained yield. It is obvious that short-term yield depends heavily on the initial stand and the harvesting system (i.e., proportion of trees removed from each size class), and that long-term yields depend entirely on growth rates (Vanclay, 1996). Some contemporary efforts have therefore been made to prescribe a standard diameter distribution for maintaining the residual growing stock at an optimum level.

6.3.3. Harvest tree selection criteria

In addition to the specification of the harvest interval (i.e., temporal resolution of the harvest), the associated delimitation of harvesting coupe (i.e., the spatial extent of the harvest), and the optimized harvest intensity, a yield regulation system must finally define harvest criteria to translate established tactical elements into reality or to realize a sustained yield. Trees to be harvested may be defined explicitly either by area (i.e., all trees on the particular area are to be harvested), by size (e.g., minimum harvestable diameter) or by conditional features (e.g., maturity condition criteria proposed by Seydack, 1995, Seydack et al., 1995). Under the area definition, all trees over the target area have to be felled without further control and the resulting disturbance amounts to clear-felling and the harvest interval more or less equals the rotation age. This is sometimes pertinent to the Rotation Forest management practice under a monocyclic system. In contrast, size limit definition is a commonly used criterion in selection forests for selection of trees to be harvested. Since all trees above the limit are generally cut, the limit is linked to both the available timber growing stock and the commercial productivity.

If the selection strictly follows a size limit for felling, fast-growing trees with high value may be removed prematurely, since the fastest growing trees are generally in the higher diameter classes (Rietbergen, 1989; Seydack et al., 1995) and the repeated removal of such fast growers may then have a dysgenic effect (e.g., Palmer, 1975; Weidelt, 1986; Jokers, 1987; Whitmore, 1991b; Appanah and Weinland, 1992). While the mortality of trees that reach their maturity below the minimum harvestable size cannot be harvested, the removal of trees that are not sexually mature at the defined lower harvest size limit may negatively affect seed production and hence reproduction (e.g., Weidelt, 1989). One more weakness is the fact that the minimum harvestable size limit does not assume the site differences (Seydack, 1995). For this reason, Breitenbach (1974; see also Gadow and Bredenkamp, 1992 and Sist et al., 2003c) proposed specific-specific size limit based on their population structure and density. Alder (1992) also described the method for determining the most productive size, if increment and mortality rates are known. Alternatively, Seydack (1995) and Seydack et al. (1995) proposed maturity condition criteria for harvest tree definition based on indications of advanced maturity and the remaining life expectancy.

6.4. Strategic facets of the yield regulation system

6.4.1. Stand regeneration strategies

Successful regeneration depends on the establishment space (i.e., the proximity of seed trees to spaces suitable for seedlings establishment) and recruitment space (i.e., appropriate conditions for established seedlings to survive and reach canopy positions). The regeneration space refers to the different canopy gap sizes and light requirement of recruits along the time axis in accordance with the intermediate "temperaments" of the species concerned. Bazzaz and Pickett (1980) contrasted two distinguishable reproductive strategies of species: "Gambler" and "Struggler" strategy. The Gamblers expend massive reproductive efforts through producing numerous seedlings unable to survive under the shade of overstory and sensitive to available light for rapid growth in the gaps and thus higher the chance of establishment of juvenile trees. The Strugglers spend effective reproductive attempts through producing few, but very persistent seedlings able to survive and show some growth in the densely shaded understory and thereby enhances the life expectancy of each juvenile. Stand regeneration strategies pertain to decisions aimed at the maintenance or creation of regeneration space in the effective vicinity of seed trees thereby sustaining conditions expected to result in successful regeneration (Seydack, 2000). Obviously, each stand regeneration approach is associated with a specific spatiotemporal harvest concentration. The ultimate aim of the approach is to enhance the proportion of commercially desirable species in the forest by use of timber felling as a first major silvicultural operation.

6.4.2. Yield optimization strategies

A classical goal of sustained yield management is to maximize the volume or value production per unit of time while maintaining the forest in a steady state (i.e., the stand state must be the same at the end as at the beginning of the cutting cycle; Buongiorno and Gilless, 2003). The strategies for optimizing yield therefore need to rely on the harvest removal that could result in a residual growing stock at an optimum level with a hope to retain a normal growth and balanced stand structure (i.e., age-distribution in even-aged and size-distribution in uneven-aged management). The normal growth generally refers to the maximum attainable growth for a particular species and the site. Thus, something more than mere regulation is required (Leuschner, 1984). The balanced stand structure is characterized by age-distribution in even-aged and by size-distribution in uneven-aged management. In this sense, the concept of optimized residual growing stock levels implies that the reduction of growing stock or neighbourhood crowding results in long-term productivity gain (Seydack, 2002). Accordingly, two basic tactical elements, harvest intensity and harvest tree selection criteria, must be established to guide appropriate level of growing stock reduction for optimizing the yield.

Since timber harvesting from tropical forests claims a higher operational cost, appropriate yield optimization strategies are essential for getting economic efficiency. It is most appropriate to produce large trees yielding expensive, high-quality timber for which the cost of harvesting represents only a small part of the value of the final product. It will also associate with a small disturbance to the residual growing stock. The idea of maximizing growth of individual stems of desirable species is the first approximation in the yield optimization strategy. The growth of individual trees may be maximized most often by concentrating growth onto potential crop trees with a relatively low stocking level (i.e., fewer faster growing trees strategy). This productivity enhancement requires growing stock reduction through one or more of intervention treatments such as release and refining. The level of growing stock reduction need to be adjusted the temperament of the desirable species and the nature of the prevailing disturbance pattern (fine-grained or coarse-grained). The recruitment of gap-opportunist species would requires substantial canopy opening that would congruent with a coarse-grained disturbance pattern. Since most volume and value increment of particular trees would take place only when they have achieved large dimension (Seydack, 2000) and large trees even with a slow diameter increment may have considerable volume productivity (e.g., Vooren, 1992), these faster-growing trees are to be allowed to attain comparatively large sizes. Most non-pioneer trees, and particularly the gap-opportunist emergents, sustain growth at large diameters (Seydack, 2000) and thus permitting them to accumulate growth up to retention limit (i.e., diameter of maximum volume growth) may optimize yield. Accordingly, the fewer faster growing trees strategy may be complemented by stipulating relatively high harvestable size limit.

However, optimum harvestable size not only depends on the diameter growth but also on the mortality rate, which is often higher in the larger trees (e.g., Alder, 1992). The harvest size limit has to be defined in accordance with economic maturity (where value accretion is maximized) balanced by biological maturity (where wood quality deterioration sets in). Again, while the volume productivity of individual tree progressively increases with size, the number of trees may decrease to mortality during the time required to reach the higher diameters, meaning stand productivity would drop to a certain extent. This points out that some stems are necessary to be prematurely harvested in order to save losses from natural mortality. The second strategy is to maximize stand productivity in pursuit of maximum trees per unit of growing space through specifying a balanced structure (i.e., many slower-growing trees strategy). Various experimental studies have shown that the balanced structure of an uneven-aged forest could be appropriately characterized by de Liocourt's rule, implying that the numbers of trees in successive diameter classes represents a decreasing geometric progression or a reverse J-shape curve (Meyer, 1943, 1952). Under this strategy, a part of the available space is occupied by residual trees that are kept to grow into large sizes under the selection cutting. Cancino and Gadow (2002) have shown how an appropriate stocking guide can be developed when the maximum size and the residual basal area are defined.

Manipulating two tactical elements of harvest intensity and harvest selection criteria, two fundamental yield optimization strategies could be recognized by maximizing individual tress growth and improving site occupancy. The "few faster-growing trees" strategy involves yield realization from accumulated net growth of individual trees. This may be achieved by reducing the growing stock to an early developmental stage characterized by relatively free-growing trees and a low level of mortality. The "many slower-growing trees" strategy deals with yield realization through selective mortality pre-emption. This strategy attempts to maintain a balanced growing stock and a relatively fully occupied area with stems of different developmental phases. Growth rates are moderate and possible mortality due to high density would be converted into yield through preemptive harvesting, i.e. removal of mature trees of declining vigor. The latter strategy seems to be more consistent with the natural dynamics of tropical forests and it may provide a wider scope for genetic and species conservation and a range of harvesting opportunities.

6.5. Developing a yield regulation system for Paunglaung watershed

Paunglaung watershed is located in the central part of Myanmar. It is a headwater area of the Sittung River, one of the main rivers of the country and also provides water resource for the Paunglaung multipurpose dam, which is under construction and would be the largest one in Myanmar. The dam is intended to prevent flood in downstream areas, to generate hydropower and to irrigate about 15000 ha of cultivated lands for double and triple cropping (Irrigation Department, 2003). Paunglaung watershed forms part of the Hindu-Kush Himalayas and covers an area of more than 4,000 km^2, stretching into the Mandalay Division, Shan and Kayah State (see Figure 6.1). It has an undulating topography of mountains and valleys, with the elevation ranging from 170 m to 1,000 m above sea level. A large extend of the watershed area is covered with different forest types that are a source of commercial timber production. Myanmar Timber Enterprise (MTE) of the Ministry of Forestry has been carrying out harvesting operations under the Myanmar Selection System. Some game and wildlife species including a relatively large group of wild elephants were found within the watershed (Myint, 1997, Thaung, 1998). Hundreds of thousands of people mostly ethnic minorities live within the watershed area and a small ethnic group called Kathaung is only indigenous to this area (Myint et al, 2002, Htun, 2005). These communities have practiced shifting cultivation as a traditional way of living. Collecting non-wood forest products from the forests is also an important off-farm season income generating activity (Zin et al., 2002). Therefore, Paunglaung watershed has diverse intrinsic values not only for the local and national economy but also for environmental conservation and social coherence. Since the management of the natural resources of the watershed to maintain its protective and productive functions is crucial, a yield regulation system for sustainable forest management is indispensable.

Paunglaung watershed forests have been managed under the Myanmar selection system, which adopts a 30-year felling cycle. Currently, these forests have been worked under two different Forest Management Plans that were usually developed for forest districts, following the general administrative boundaries. To be more realistic for a yield regulation, the system should follow the physical boundaries of the watershed. Species in the natural forest tend to be clustered and to follow environmental gradients. In addition, the forest is a mosaic of successional phases over scales from the small gaps resulting from fallen individual trees to some ha of areas affected by shifting cultivation. Treating a whole watershed area as if it had a homogeneous average stand table will rapidly result in an impossible conflict between management prescriptions and operational reality. Yield regulation, which links the management prescription and operations through a monitoring and regulatory process, must reflect the spatial variation. Thus, the whole watershed was divided into four zones based primarily on distinct physical features such as mountain ridges and streams. Zone 1 was further stratified into sub-zones generally based on forest types (see Figure 6.1).

6.5.1. Estimating the productive forest areas

A basic requirement of all forest management is that the land be accurately mapped and yield estimation begins with the definition and accurate quantification of the areas of forest available for timber production. A major source of error in estimating timber quantities is in estimating what proportion of the gross forest areas is harvestable (Turner, 2003). The definition of gross areas available for timber production activities is generally predetermined by the administrative process, for instance, by subtracting the forest reserves. However, on top of that there may be a zoning out of other non-productive areas. The net harvestable area normally excludes all areas, which cannot be logged for legal, logistical, environmental or social reasons. These include both areas that can be mapped, for example, stream buffers, and that cannot be mapped, for example, inoperable areas due to slopes. It is a good practice to replace the use of reduction factors with more mappable functions such as maximum operable slopes, stream buffers and then calculating the area remaining, preferably using a Geographic Information System (GIS). The process for determining the land base available for harvesting on a sustainable basis is presented in Figure 6.2.

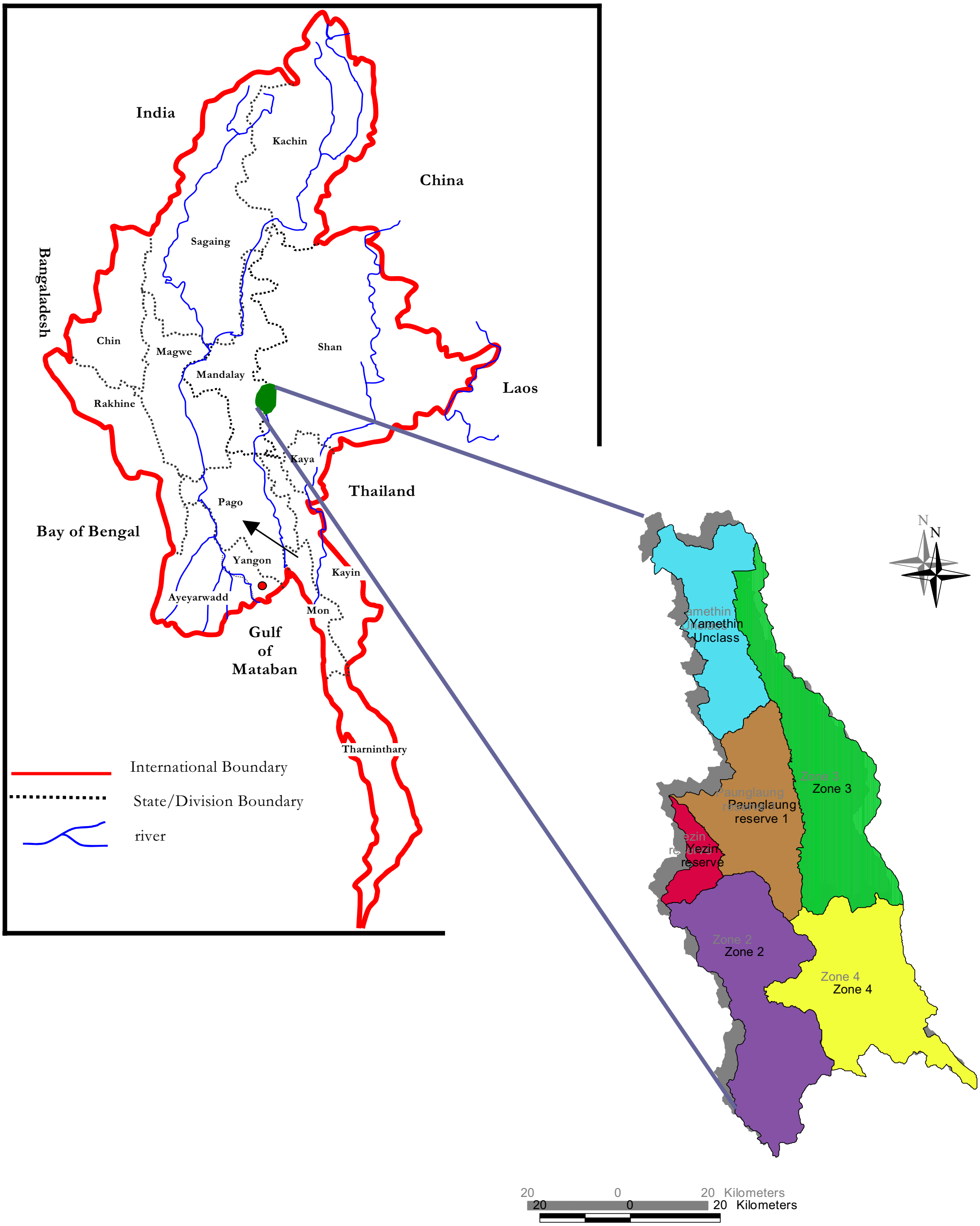


Figure 6.1 Map showing location of Paunglaug watershed with zones 1 to 4.

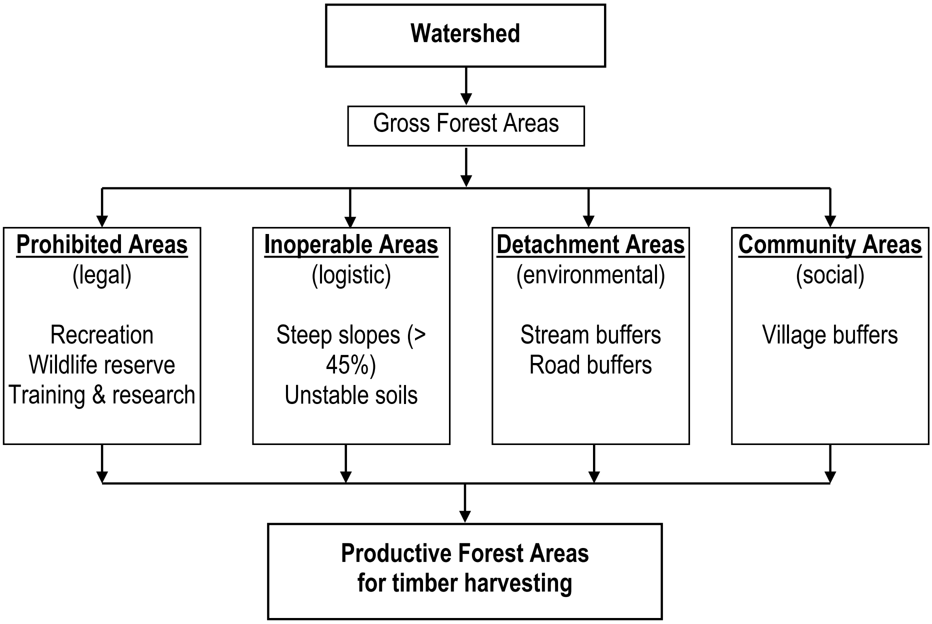


Figure 6.2 Process for determining productive forest areas suitable for timber harvesting

Firstly, the gross forest areas of a particular sub-zone were identified based on the land cover map of the watershed produced by the GIS section of the Forest Department in 1995. The original land cover map was developed from Landsat TM images taken in January 1995 and recoded into four different land cover types (forest, agriculture, shifting cultivation, and water body) in the ArcView GIS environment. Then other exclusion areas for legal, logistic, environmental, and social reasons were identified through GIS analyses. Steep slopes (i.e., > 45%) were considered appropriate to use as a reduction factor to specify areas for keeping aside from harvesting for logistic and environmental reasons. These areas were identified from the Digital Elevation Model (DEM) developed by the GIS section of the Forest Department based on 1:63360 scale topographic maps and 80 m contour intervals. 50 m buffers were defined for major streams. Nearly one hundred villages existed within the watershed and some areas need to be allocated for subsistence living and community development activities. Local communities have for a long time practiced shifting cultivation for subsistence living by clearing nearby forests around their villages and the areas around human settlements are mostly under the shifting cultivation cycle and not available for timber management. Most recently, they established permanent agriculture like horticultural farms and low land rice cultivation for commercialization process.

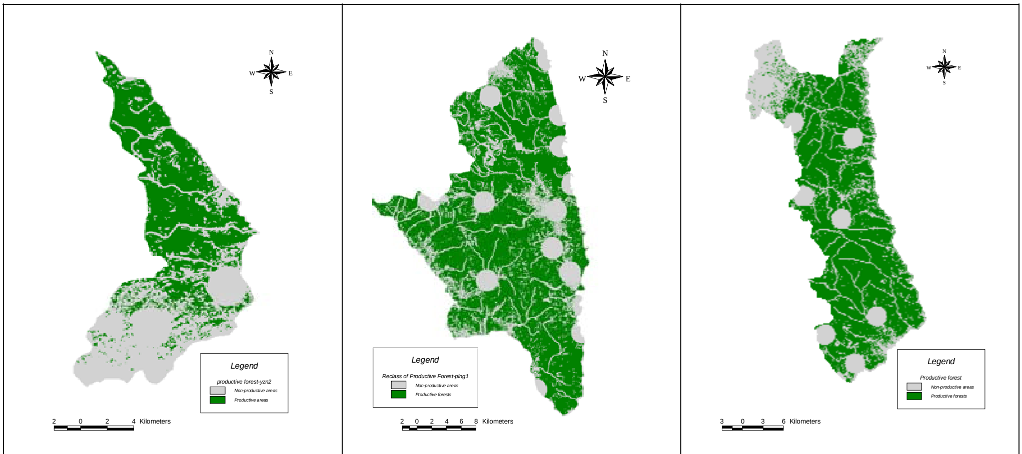
Therefore, a buffer with a 2 km radius was, based on finding of Zin et al., (2002), specified for each village for communities' activities. Finally, net forest areas (or productive forest areas) available for timber harvesting were derived by excluding these unproductive areas from the gross forest areas. The resulting productive forest areas for sub-zones and zones are given in Table 6.1 and Figure 6.3.

Table 6.1 Productive forests areas of different zones of Paunglaung watershed (in ha)

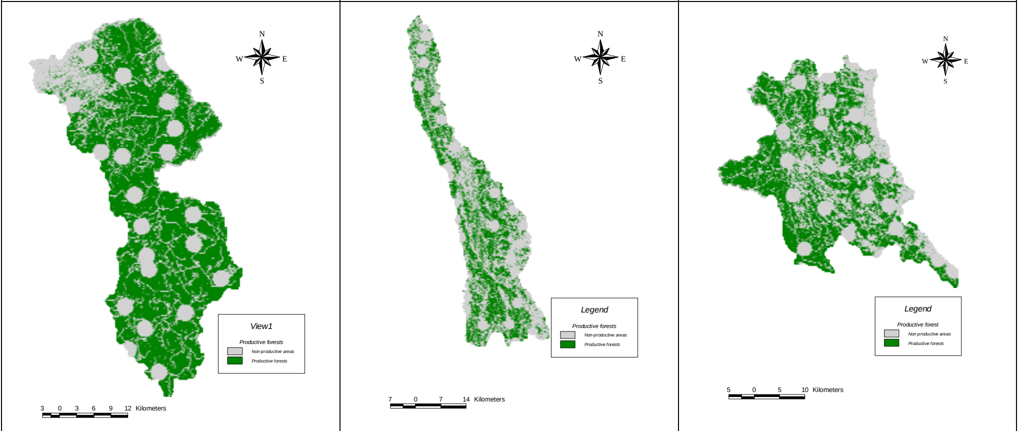
	Watershed zones	Gross forest areas	Un-productive areas	Productive forest areas
1	Zone 1			
	a) Yezin	9818	2045	7773
	b) Yamethin unclass	48910	9703	39207
	c) Paunglaung 1	64418	15613	48805
2	Zone 2	94375	22139	72236
3	Zone 3	65810	22960	42850
4	Zone 4	67887	21272	46615
	Total	351218	93732	257486

6.5.2. Prediction of sustainable timber yields

In the Myanmar Selection System, a harvest level is generally prescribed by the number of trees with a specified minimum allowable size. The Annual Allowable Cut (AAC) is, according to the formula introduced by Brandis in 1857, defined to maintain a sustained harvest from a particular forest. The formula consists of two parts: calculation of the Annual Rate of Recruitment (ARR) and a correction factor. The correction factor is introduced to save the working stock (i.e., the number of stems above a prescribed size limit) at a desirable level that is defined as the ARR times ½ felling cycle. The surplus working stock compared with the desirable working stock has to be liquidated over a given period (usually two felling cycle). When the actual working stock is less than the desirable level, the AAC become less than the ARR for restoring the existing stock. The Brandis method of AAC calculation has therefore been said to be a good one when used properly. However, it uses information of the stems from the size class just below the size limit that is quite often prescribed for an aggregate of species and provides only a final yield (Thein, 1991). It does not consider the diameter distribution that is usually used to characterize the structure of the target forests.



Yezin reserve **Paunglaung reserve portion 1** **Yamethin unclass forests**



Zone 2 **Zone 3** **Zone 4**

Figure 6.3 Productive forests of different zones of the Paunglaung watershed

It is more realistic to use a simple spread-sheet method (so-called "cutting cycle analysis") for predicting a sustainable yield (e.g., Alder, 1992, Vanclay, 1996, Vanclay and Turner, 2001). The procedural steps for developing a spreadsheet model have been discussed in section 5.5. This method offers a way to estimate the allowable harvest from data that are rather basic such as nominal cutting cycle, the initial stand tables, and some data on growth, recruitment and mortality. It is also possible to carry out a sensitivity analysis for exploring more appropriate harvest intervals and intensities (Vanclay, 1996). It involves the projection of current stand tables with certain simplifying assumptions: 1) trees are uniformly distributed within the class; 2) the increment rates are assumed to be the same in all size classes of a particular species group; 3) the mortality rates are not related to species groups or tree sizes; 4) increment, mortality and recruitment are not affected by stand density; 5) outgrowth from the class 1 (i.e., 20-30 cm dbh class) is replaced by an equivalent number of recruits; and 6) harvesting induced damages are negligible. Although these assumptions are unsatisfactory in some sense, they are typical of assumptions commonly made in many yield forecasts and AAC calculation (e.g., Vanclay, 1996).

Since no permanent plot has been installed in the area, the growth rates for commercial species groups were extrapolated from the Pago mountain ranges (see Table 5.1). Teak, the most commercially important species, is considered as a separate group. Commercial timber group 1 comprises hardwood species that are essential in construction while group 2 possesses species with timber applicable for interior use. Group 3 contains timber trees that are useful in local use whereas match and box wood species are in the group 4. Group 5 is to represent non-commercial species and other remaining species. The outgrowth (i.e., the number of stems moving up to a larger dbh class) is estimated as a movement ratio (i.e., the ratio between the dbh class interval and average growth rate). The average mortality rate of 1.25% per annum is considered reasonable for trees of 20 cm dbh and above for all species groups. Inventory data (collected in 1994 and 1997) for each zone (and for each sub-zone in zone 1) were categorized into in 10 cm dbh classes to develop stand tables for different commercial timber species groups. The sampling design and procedure have been given detailed in section 4.2. The prescribed harvest size for all species in the watershed areas is reported as 60 cm dbh (see Myint, 1997, Thaung, 1998). Depending on the extrapolated growth rates for a given species group, commercial group 1 can have a total diameter growth of 15.6 cm for the adopted felling cycle of 30 years while the other groups have around 10 cm. Therefore, trees under the current diameter classes of 40-50 cm and larger ones of the commercial group 1 can be potential crop trees for the next harvest while stems of 50-60 cm dbh class and above of other groups are assumed to up-grow to harvestable size.

Within the watershed, the current inventory data indicated that some species were present, but locally rare. Such species should be kept aside from harvesting to enhance biodiversity conservation and to reduce the risk of species extinction. Accordingly, species with the growing stock of less than 50 stems (of $\geq$ 20 cm dbh) per km^2 were considered rare and proposed to be protected as reserved trees. The proposed reserved trees for respective sub-zones and zones are given in Table 6.2. Again, to keep a proper density of reproductive trees for maintaining sufficient seed sources, preventing genetic erosion and conserving ecological integrity, one per cent of the largest trees of commercial species are to be retained as seed sources. Table 6.3 represents a current stand table of the commercial species group 1 for Yezin sub-zone of the watershed zone 1.

Table 6.2 Proposed reserved tree species for conservation in specific localities of Paunglaung watershed.

Zone 1 (Yezin sub-zone)	**Zone 1 (Yamrthin unclass)**	**Zone 1 (Paunglaung reserve 1)**
Shorea oblongifolia (thitya)	*Xylia xylocarpa (pyinkado)*	*Pterocarpus macrocarpus* (padauk)
Pentacme siamensis (ingyin)	*Mitragyna rotundifolia* (binga)	*Dalbergia oliveri* (tamanlan)
Albizzia odoratissima (thit-magyi)	*Cedrala multijuga* (taungtama)	*Mitragyna rotundifolia* (binga)
Cedrala multijuga (taungtama)	*Protium serrata* (thadi)	*Adina cordifolia* (hnaw)
Chukrasia tabularis (yinma)	*Mangifera caloneura* (tawthayet)	*Albizzia odoratissima* (thit-magyi)
Dalbergia cultrata (yindaik)	*Swintonia floribunda* (taung-thayet)	*Cedrala multijuga* (taungtama)
Dipterocarpus tuberculatus (in)	*Terminalia tomentosa* (taukkyan)	*Dalbergia cultrata* (yindaik)
Gmelina arborea (yamane)	*Terminalia chebula* (panga)	*Melanorrhoea usitata* (thitsi)
Mitragyna rotundifolia (binga)	*Duabanga grandiflora* (Myaukngo)	*Pentace griffithii* (thitsho)
Pentace griffithii (thitsho)	*Lennea grandis* (nabe)	*Millettia pendula* (thinwin)
Anogeissus acuminata (yon)	*Salmalia insignis* (didu)	*Baccaurea sapida* (kanoso)
Cordia fragrantissima (sandawa)	*Spondis pinnata* (gwe)	*Lagerstroemia speciosa* (pyinma)
Gardenia coronaria (yingat-gyi)		*Mangifera caloneura* (tawthayet)
Lagerstroemia speciosa (pyinma)		*Swintonia floribunda* (taung-thayet)
Mangifera caloneura (tawthayet)		*Anogeissus acuminata* (yon)
Terminalia tomentosa (taukkyan)		*Anisoptero scaphula* (kaung-hmu)
Terminalia chebula (panga)		*Duabanga grandiflora* (Myaukngo)
Salmalia insignis (didu)		*Garuga pinnata* (chinyok)
Salmalia malabarica (letpan)		*Lennea grandis* (nabe)
Wendlandia glabrata (thitpyu)		*Salmalia insignis* (didu)
Firmiana colorata (wetshaw)		*Spondis pinnata* (gwe)
		Salmalia malabarica (letpan)
		Sandoricum koetjape (thitto)
Zone 2	*Terminalia chebula* (panga)	*Artocarpus calophyla* (taung-pein)
Pterocarpus macrocarpus (padauk)	*Lennea grandis* (nabe)	*Gardenia coronaria* (yingat-gyi)
Hopea helferi (thingan-net)	*Salmallia anceps* (kokhe)	*Lagerstroemia speciosa* (pyinma)
Shorea oblongifolia (thitya)	*Sterculia foetida* (letkok)	*Melanorrhoea usitata* (thitsi)
Dalbergia oliveri (tamanlan)	*Salmalia insignis* (didu)	*Millettia pendula* (thinwin)
Adina cordifolia (hnaw)	*Salmalia malabarica* (letpan)	*Protium serrata* (thadi)
Albizza lebbek (kokok)	*Wendlandia glabrata* (thitpyu)	*Cedrala multijuga* (taungtama)
Albizzia odoratissima (thit-magyi)	*Firmiana colorata* (wetshaw)	*Cinnamomum inunctum* (karawe)
Cedrala multijuga (taungtama)		*Dalbergia cultrata* (yindaik)
Cedrela toona (thitkado)		*Albizzia procera* (sit)
Chukrasia tabularis (yinma)	**Zone 3**	*Pentace burmanica* (thitkha)
Cinnamomum inunctum (karawe)	*Pterocarpus macrocarpus* (padauk)	*Baccaurea sapida* (Kanoso)
Dalbergia cultrata (yindaik)	*Hopea helferi* (thingan-net)	*Terminalia chebula* (panga)
Dipterocarpus tuberculatus (in)	*Dalbergia oliveri* (tamanlan)	*Mangifera caloneura* (tawthayet)
Dipterocarpus alatus (kanyin)	*Mitragyna rotundifolia* (binga)	*Salmallia anceps* (kokhe)
Gmelina arborea (yamane)	*Adina cordifolia* (hnaw)	*Sterculia foetida* (letkok)
Melanorrhoea usitata (thitsi)	*Albizzia odoratissima* (thit-magyi)	*Salmalia insignis* (didu)
Michelia champaca (sagawa)	*Chukrasia tabularis* (yinma)	*Lennea grandis* (nabe)
Pentace griffithii (thitsho)	*Cedrala multijuga* (taungtama)	*Wendlandia glabrata* (thitpyu)
Anogeissus acuminata (yon)	*Cedrela toona* (thitkado)	*Firmiana colorata* (wetshaw)
Artocarpus calophyla (taung-pein)	*Dipterocarpus tuberculatus* (in)	*Spondis pinnata* (gwe)
Terminalia tomentosa (taukkyan)	*Anogeissus acuminata* (yon)	*Tetrameles nudiflora* (baing)

The data in table 6.3 reveals that two species *Shorea obtusa* (thitya) and *S. siamensis* (ingyin) are found to have less than 50 stems per km² and they are proposed to be conserved as reserved trees in the Yezin sub-zone for species diversity. Generally, trees of ≥ 40-50 cm dbh classes of this group can perhaps be realized as potential crop trees for the next cycle. Thus a total of 218 trees [177 (80.8%) stems of *X. xylocarpa*, 30 (13.7%) stems of *P. macrocarpus*, 12 (5.5%) stems of *S. siamensis* (ingyin)] are potential crop trees for the coming cycle. However, *S. siamensis* (ingyin) needs to be retained for species conservation. Only 207 stems (94.5%) of the total potential crop trees of 218 stems can roughly be available for a harvest before adjusting for mortality and future reproduction of these species. The numbers of available trees for harvest need to be discounted by the anticipated mortality rate (here, 1.25% annually) and then 1% of the largest trees have to be retained from these potential harvestable stems. Consequently, the sustainable yield is taken as the number of the potential crop trees minus the reserved trees to be retained that is further discounted by the mortality rate and reduced by the factor for reproductive purpose. Estimation of sustainable yields for a particular zone was made by the model separately developed in MS EXCEL. An example calculation of a sustainable yield for commercial species group 1 for Yezin sub-zone is presented in Table 6.4. The zone-wide estimations of sustainable yield for different species groups are given in Table 6.5.

Table 6.3 Stand table for the commercial species group 1 of Yezin sub-zone (zone 1) of Paunglaung watershed (stems / km²).

Species		Diameter classes (cm)						
Scientific name	Local name	20-30	30-40	40-50	50-60	60-70	70+	Total
1. *Xylia xylocarpa*	pyinkado	94	94	65	59	12	41	365
2. *Pterocarpus macrocarpus*	padauk	47	6	6	12	6	6	82
3. *Shorea siamensis*	ingyin	29	6	6	0	6	0	47
4. *Shorea obtusa*	thitya	29	0	0	0	0	0	29
Total		**200**	**106**	**76**	**71**	**24**	**47**	**523**

Source: Forest Resource Division, Forest Department. (based on data collected in 1994)

Table 6.4 Calculation of sustainable yield for commercial timber group 1 of Yezin sub-zone of Paunglaung watershed zone1.

Particulars	Diameter classes (cm)						
	20-30	30-40	40-50	50-60	60-70	70+	Total
Present stocking (stems / km^2)	200	106	76	71	24	47	523
Increment (cm /year)	0.55	0.55	0.55	0.55	0.55	0.55	0.55
Annual mortality (%)	1.25	1.25	1.25	1.25	1.25	1.25	1.25
Future stocking (stems /km^2)	137	134	116	82	54	94	616
Reserved trees (stems / km^2)	-	-	-	-	30	52	82
Mother trees (stems / km^2)	-	-	-	-	5	9	14
Sustainable yield (stems / km^2)	-	-	-	-	19	33	52

Table 6.5 Estimated sustainable yields for different species groups of different zones of Paunglaung watershed (stems / km²)

Watershed zones	Teak	Group 1	Group 2	Group 3	Group 2	Group 5	Total
Zone 1							
a) Yezin	21	52	103	43	89	-	308
b) Yamethin unclass	-	83	102	33	7	-	225
c) Paunglaung 1	-	-	173	62	1	-	235
Zone 2	15	76	19	7	90	-	207
Zone 3	-	7	43	26	64	-	140

6.5.3. Silvicultural treatments for enhancing regeneration and growth

In the Yezin area and zone 2 of the watershed, there are mixed deciduous forests here Teak and other valuable associates are grown. The diameter distribution of Teak in these areas is shown in Figure 6.4. As Teak provides premium wood of high commercial value, its development should be given priority in these forests. Teak is a pronounced light-demander, intolerant of shade and requiring complete overhead light. Its seedlings are very sensitive to suppression by weeds and further development is hampered by shade from seed-trees; its crown requires freedom on all sides for proper development (Kadambi, 1972). Large openings may support plenty of natural regenerations from dormant seeds in the soil (e.g., Troup, 1921). It seems therefore to be not adequate for its regeneration and development under gaps resulted from single-tree felling. Many observations (e.g. Thwin and Han, 1991; Keh, 1993; Keh and Aung, 1995; Keh and Kyaw, 1995; Keh, 1997; Forest Department, 1998; Oo, 2000, Lwin, 2001, Kyaw, 2003) indicated a lack of teak regeneration in various forests in the country. Teak is generally girdled three years prior to felling with a view to season the wood naturally, to be floatable for least-cost transportation and reduce felling damages. It has been questioned whether gradual opening resulted from dying girdled Teak is the cause of inadequate regeneration. Dry Teak (1960) however strongly recommended not to stop the girdling practice of Teak for economic reasons in timber processing while pointing out certain silvicultural drawbacks.

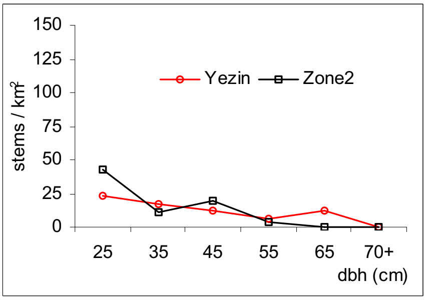


Figure 6.4 Current diameter distributions of Teak in Yezin reserve and Zone 2 of Paunglaung watershed.

Deciduous Dipterocarp forests are confined to the Yamethin sub-zone where *Shorea obtusa* (thitya) and *S.siamensis* (ingyin) are abundant. The diameter distribution of these species in the area is given in Figure 6.5. These two species are categorized under the commercial timber group 1 due to their high quality timber with economic values. They are matrix invaders (i.e., large-sized species occupying the upper and emergent canopy positions) and behave like gap-opportunists such that, once established, saplings are able to persist for a number of years within the forest matrix under heavy shade, but they need moderate to high light intensity for rapid growth. They produce flowers at irregular intervals of several years, usually 2-5 years, with varying intensity, though gregariously; seed dispersal is usually only over short-distance from mother trees, generally not more than 30 m; mycorrhizae that is inactivate under prolonged exposure to full light is essential for optimal growth of their seedlings and they can survive best in intermittent sunlight; species grow slowly (e.g., Soerianegara and Lemmens, 1993). Accordingly, under selective cutting system with a systematic felling, it can be expected to outcome a good natural regeneration of these species, at least locally. Since they need protection from nurse trees in the early stages of development, special care is required in attempts to manipulate over-topping forest matrix species to enhance the growth of well-established saplings. If natural regeneration is found inadequate, enrichment planting using 20-25 cm high seedlings is recommended.

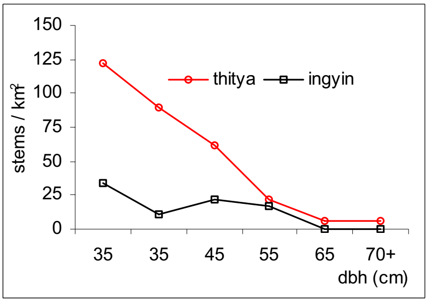


Figure 6.5 **Current Diameter distribution of *S.obtusa* (thitya) and *S. siamensis* (ingyin) in Yamethin unclass forest areas of Paunglaung watershed.**

The areas of Paunglaung reserve portion 1 and zone 3 of the watershed are covered generally with evergreen forests dominated by *Dipterocarpus spp.* (kanyin), producing valuable timbers suitable for construction, which are categorized under the commercial timber group 2. The diameter distribution of *Dipterocarpus spp.* in these areas is presented in Figure 6.6. They are really gap-opportunist species with a tendency to form gregarious cohorts in the upper canopy or emergent strata. They are reported to flower and fruit annually; Their seeds germinate without dormancy; seedlings need mycorrhizae and shade for establishment in the forest matrix and well-established seedlings are sensitive to direct light for the extended growth to large stature over-topping the forest matrix; stems therefore reach large bole sizes in a comparatively short time (e.g., Soerianegara and Lemmens, 1993). Disturbances induced by felling of scattered stems may not be adequate to enhance the growth of established seedling within the forest matrix. If prevailing seedlings are seen to be adequate in the stands, release operations are advisable to help support the extended growth of these seedlings. With their biological influences, species would regenerate well only in primary forests and thus enrichment planting after selective cutting is recommended.

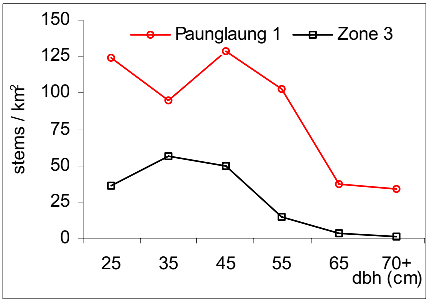


Figure 6.6 **Current Diameter distributions of *Dipterocarpus spp.* in Paunglaung reserve portion 1 and Zone 3 of Paunglaung watershed**

7. Conclusions

This study addresses several problems that are of great practical relevance for the management of complex forest ecosystems. The scientific approach is based on proven as well as newly developed methodology. Different levels of resolution are applied. Tree-based analysis of forest structure is complemented by tree-based growth prediction and growth and mortality modelling on the cohort and stand level. Regional data then provide the basis for yield regulation.

7.1. Analysis of stand structure and diversity

Tropical forests are species-rich spatially complex systems. The structural modifications caused by silvicultural operations need to be made transparent if sustainable forest management is to be meaningful. The examples presented in the case study (chapter 3) illustrate the utility of spatial indices and statistical functions applied to interpret three important aspects of the stand structure at different spatial scales. Neighbourhood-based variables and point process statistics are applied for analysing the complex structure of tropical forests of different types within the Paunglaung watershed: effectiveness in describing stand structure and usefulness in evaluating management impacts.

The neighbourhood variables that are used to describe spatial forest structures can be assessed easily in the field without the necessity to measure distances between trees. In contrast, the point process requires a map of tree positions in field assessments, which is considerably expensive in practical forestry. In an attempt to apply these methods in the analysis of the complex structure of tropical forests, neighbourhood-based variables provide information on a fine scale, enabling detailed monitoring of silvicultural interventions by detecting subtle structural changes. Point pattern analyses with spatial statistics also provide detailed information, as structure is investigated as a function of inter-tree distances. Both approaches offer opportunities which are basic to developing single-tree models that are believed to be fundamental of contemporary timber management planning. Neighbourhood-based variables reveal what happens within the immediate vicinity of a given reference tree while point process statistics represent structure as a function of distance, including distances beyond the immediate neighbourhood. Both kinds of analyses have specific strengths and the results are often compatible and even complementary in describing the stand structure.

In fact, describing the forest spatial structure and diversity in a straightforward way is necessary for simplifying the process of measuring, understanding, and manipulating forests and hence making objective decisions in management planning. However, with the rapid development of theoretical statistical methods and computer technology, it is possible to mimic complex structures of tropical forests with neighbourhood-based variables and point process statistics. The study has shown that neighbourhood-based variables are sensitive to minor structural changes involving the spatial distributions of species, tree sizes and tree positions and hence are suitable for short-term monitoring with low-cost sampling. Point pattern analyses are appropriate for long-term monitoring of management impacts using datasets with known tree positions.

7.2. Modelling individual tree diameter growth of naturally grown Teak

The potential-modifier approach was proposed for developing an individual-tree diameter growth model for naturally grown Teak, the most commercially significant timber species of Myanmar. The model presented in this study is based on some inherent assumptions: (1) the growth of an individual tree cannot exceed its potential growth- it equals the potential growth only when there is no competition; (2) the individual-tree diameter growth rate for a given dbh class decreases as competition increases; (3) as competition increases, the individual-tree diameter growth rate for a given dbh asymptotically approaches zero. One basic problem in this approach is defining a best subset of growth data for developing the potential function that needs a partially subjective process. Since the goal was to fit an idealized response curve to a biologically plausible relationship between tree size and growth potential, some bias was unavoidable. When the modifier function was incorporated into the model, both indices- BAL and GD could sensibly explain the growth reductions from the potentials due to competition. The BAL index function with a smaller magnitude of the bias can explain the observed growth marginally more effectively than the GD index.

Although some of the variability in the annual diameter growth of the individual Teak trees can be explained by the stand and tree variables contained in this model, the remaining variability is due to other unknown factors, probably involving micro-site conditions. Model predictions in a complex biological system like a forest will never be perfect, because the environmental conditions within which that system resides continue to change and cannot be predicted with certainty. The ultimate aim of the modelling presented in this study is not to imitate the system, but to predict the system performance with a reasonable accuracy. It is concerned with how well the model predicts change relative to alternative models. In conclusion, it can be stated that the literature currently does not appear to offer diameter growth models for naturally grown Teak which offer a better accuracy than the model presented in this study. The modelling approach presented here offers a good potential for use in similar conditions. A crucial aspect is in future modelling endeavours is the improvement of the database.

7.3. Modelling stand development for all species

Since a forest stand is managed as a single unit, a comprehensive knowledge on stand development is essential in forecasting the growth and yield of individual stands for management planning. The ideas of the stand projection is to represent the dynamics of forest stands that is the results of an array of interactions of many factors by some parameters through simplification and generalization. The basic input data to stand projection consist of: a stand table, increment, mortality, and ingrowth (new recruits). Myanmar introduced the concept of stand projection one and half centuries ago. A dynamic inventory system was also initiated at a national scale in the early 1980s for monitoring the growth dynamics of different forest types. Unfortunately, this case study (chapter 5) brings out deficiencies in the data for used as input for updating inventory with higher accuracy. The specific information on recruitment, growth and mortality is still limited. This is a result of difficulties for remeasuring permanent sample plots (PSPs) in inaccessible forests, limited departmental resources for maintaining installed PSPs over extensive forest areas and lack of sufficient expertise for analyzing collected data.

If meaningful improvements are to be made in modelling stand development of tropical forests of the country, various aspects need to be revised in the dynamic inventory system and the data compiling system for practical management applications. The first condition is to improve the PSP system. From the data currently available in the database, it is not possible to quantify site productivity, which is known to have considerable influence on diameter growth rates and non-suppression mortality. Moreover, PSPs were set up to investigate management effects, but not for growth studies. Therefore, growth plots should be established in different forest types with the standard requirements of stand dynamic studies. On the other hand, it is reportedly known that the mortality problem is further compounded by damages to the residual stands caused by selective logging. The impact of selective logging should also be monitored with appropriate research plots. An important question that was addressed in this study is how to reduce the data sets of hundreds of species into groups meaningful for growth projection. The cohort modelling approach is recommended for use, but this requires more specific information.

7.4. A yield regulation system for sustainable watershed management

Yield regulation is a means to achieve sustainable forest management (SFM), a standard approach to conservation of tropical forest watersheds assuming intrinsic values with pronounced temporal and spatial effects. Even though the concept of SFM necessarily draws a wider attention on economic, ecological, and emotional objectives, the principle of sustained yield (i.e., a non-declining even-flow of timber) is still one of the overriding objectives. The process of yield regulation translates management prescriptions into operational reality. Under the Myanmar Selection System of forest management, timber yield has been regulated by the Brandis' method for more than a century. Though the original method has proved to be sound enough in estimating the allowable cut, inappropriate modification of this method in view of obtaining economic harvests leads to over-estimation of yields. In fact, effective timber management claims a more reliable approach in yield regulation in so far as to integrate sustained yield principles into overall objectives of watershed conservation. Accordingly, a yield regulation system was proposed as an effective timber management tool for integrated resource management of Paunglaung watershed.

A proper yield regulation system needs to be devised to bring conservation principles into harmony with profitable timber harvest on a sustainable basis. Estimation of productive forests available for timber harvest constrained by logistic, operational, environmental and social factors is an indispensable sub-component of the system. A geographic information system plays a critical role in area estimations. The availability of specific information on growth and mortality is essential for developing proper growth and yield models. In addition, pre- and post-harvest inventories need to be incorporated with suitable sampling designs for assessing timber resources, planning timber harvests, monitoring harvest impacts, and revising silvicultural treatments. It is rather obvious that modern yield regulation systems with a more conservation-oriented approach calls for greater attention on all ecosystem components than only on potential crop trees of commercial species. It appears, based on the current study, that the accurate projection of the complex tropical forest resource is beyond the capability of any one country in the tropical region. The Forest Department of Myanmar especially Forest Resource Division needs to enhance its capacity to organize and maintain a large number of installed PSPs and to compile the data already at hand. It is proposed to pool resources by launching bilateral and multilateral collaboration programs.

8. Summary

Myanmar is a country situated in continental Southeast Asia and still endowed with natural forests that cover more than half of the country's territory. Most parts of the country are highlands forming as watersheds of drainage systems of the country. These highland watersheds are usually clad with forests of different types providing productive and protective functions essential for sustainable development of the country. Accordingly, sustainable forest management has to be adopted as a standard approach for effective watershed conservation whereas timber production guided by sustained yield principles would be one of the overriding objectives. It has been officially recorded that scientific forest management started in 1856 with the introduction of the Brandis management system, which has been known as the first systematic silvicultural management system of the tropics, although forest management in Myanmar could be traced back over centuries. The original Brandis Selection System was modified into the Burma Selection System in 1920, which is still in use and known as the Myanmar Selection System (MSS), in efforts to be more compliant with country forests. Even though Myanmar has been said to enjoy a reputation for good forest management and the quality of the MSS has been tested for 150 years, it has become discernable that this long-standing practice of forest management needs to meet a number of challenges to retain its reputation for excellence. Two serious threats for the sustainability of the forest resources can be identified, namely deforestation and degradation. Deforestation is one of the management problems that needs to be addressed on the political-social level while degradation is a silvicultural problem that claims proper technical solutions. As an effort to resolve some technical problems of the prevailing strategic challenges, four case studies were conducted with the motivation of following objectives:

1. To gain a deeper insight into the structure of some forest types in support to designing proper silvicultural interventions and monitoring impacts of management practices.
2. To explore a consistent modelling strategy, based on the existing data structure, for developing individual tree growth models that can be incorporated in a general growth projection system for updating forest inventories.

3. To develop a general growth projection system for providing more precise information in estimating an allowable harvest for sustainable management of particular forest areas.
4. To modify the prevailing yield regulation system for improving productivity and ensuring sustainability of timber resources of the tropical forest watershed in order to establish a trade-off between increasing demands for timber and growing concerns for environmental conservation.

Stand structure, one of the characteristics conventionally used to interpret forest conditions, is usually thought of as both a product and driver of ecosystem processes and diversity. Therefore, the knowledge of variations in forest structure over time (i.e., successional patterns) and space (i.e., physical horizontal and vertical organization of stems) can serve as the basis for designing silvicultural interventions and evaluating management impacts. Accordingly, various indices and functions have been proposed to describe the stand structure for simplifying the process of measuring, understanding, and manipulating forests and hence making objective decisions in management planning. In fact, it is necessary to consider various aspects at different scales of the stand structure in order to interpret structural heterogeneity, complexity and diversity. Thus a case study was conducted with a view to gain a deeper insight into structural complexity of tropical forests of different types to assist in designing and evaluating management interventions.

Three 1-ha research plots were set up at different forest types (deciduous forests, typical evergreen and hill evergreen forests) inside the Paunglaung watershed, one of the critical watersheds of the country. All stems with > 20 cm dbh inside these stands were identified, measured for diameter and height, and their positions were recorded. Neighbourhood-based variables (contagion, mingling and differentiation) and point process statistics (pair correlation function, L-function and marked correlation function) were comparatively applied to describe the complex structure of these stands for three important aspects (spatial distribution of stems, species mixture and size differentiation) at two different spatial scales. Comparisons were made for two intuitive questions: effectiveness in describing stand structure and usefulness in evaluating management impacts. Different neighbourhood variables applied in the study could mimic structure of the stands effectively on a finer scale while point process statistics provided more detail structural information as a function of inter-tree distances. The concepts, calculation processes and field assessments for neighbourhood-based indices are rather simple compared to spatial statistics. It was however found that both analyses have their own strengths and the results were almost comparable and actually complementary in describing stand structure of all research plots. Since tree-based indices of contagion, mingling and differentiation were assessed according to nearest neighbours at their immediate vicinities, these indices may be sensitive to even subtle changes in the stands. In contrast, spatial statistics were calculated based on the distribution of inter-tree distances within each plot, minor structural changes may not have serious effects on their values. With recent developments in spatial statistics for forestry applications and computer technology, both analyses are useful for describing complex structures of tropical forests at different scales. It is also recommended that neighbourhood-based variables are suitable for short-term analyses while point process statistics are appropriate for long-term monitoring of management interventions if data are available with recorded tree positions.

The second case study dealt with the development of an individual tree diameter growth model for naturally grown Teak which is one of the most valuable timber species in the world, but indigenous only to four Asian countries including Myanmar. However, dense natural forests with large and premium quality teak have degraded and shrunk so rapidly that at present they are confined to Myanmar and to some parts of India. Natural teak has now almost become an endangered species. The study of growth and yield of naturally grown Teak seemed to be initiated by Brandis who is known to as the father of tropical forestry since 1857. Some others, but limited studies were also conducted to explain the growth of natural Teak using tree age as a main independent variable. The use of age as an independent variable in a growth model for Teak will not be consistent with the requirements of other species. It will therefore not be possible to use an age-based model in a growth projection system supporting the size-limit-based forest management practice and inventory data structure of Myanmar. In this context, an age-independent individual tree model is considered to be the only suitable option for modelling growth under the specific conditions in Myanmar, featuring a large variation in species composition and stand structure. Consequently, the case study was organized with the motivation to explore a consistent modelling strategy, based on the existing data structure, for developing individual tree growth models that can be incorporated in a general growth projection system for updating forest inventories.

The data used in this study were collected in permanent inventory plots located in the Bago mountain ranges, which was once renowned as the “true home of Teak”. The study covered a total of 46 plots and 297 growth observations. A potential * modifier type model was chosen as an appropriate basis for estimating individual tree growth of naturally grown Teak. A Potential Relative Increment (PRA) approach was adopted to develop the potential function and two distance-independent competition indices – BAL (Basal-Areas-of-Larger-trees) and GD (Basal area-Diameter competition index)- were used to explain the reduction of the potential growth due to competition. Both indices could sensibly explain the growth reduction in response to the competition, but the BAL index proved marginally more precise and had marginally lower bias estimates. The model can be incorporated into the growth projection system for the Teak bearing forest of Myanmar, but parameter estimates should be improved in the future using an extended database of observed growth rates. In the meantime, applications of the model should be limited to the range of calibrated data set and conditions similar to the area of study.

In forest management, a forest stand is considered as a single unit. A comprehensive knowledge on stand development therefore is essential in estimating growth and yield of individual stands for effective management planning. Hence, a third case study was conducted to develop a general growth projection system for providing more precise information in estimating an allowable harvest for sustainable management of particular forest areas. Among others, a stand projection approach was adopted to modelling of stand development for all species. The idea of the stand projection is to represent the dynamics of a particular forest stand by some parameters through simplification and generalization. The basic data consist of: an initial stand table, and estimates of increment, mortality and new recruits. Actually, Myanmar introduced the concept of stand projection for modelling stand development for yield estimation one and half centuries ago. A dynamic inventory system was also initiated at a national scale in early 1980s for monitoring the growth dynamics of different forest types.

This study used data from the national forest inventory database of the Forest Department of Myanmar, which were collected in 1994 and 1997 for the Paunglaung watershed. A spreadsheet-based stand projection model was developed in MS EXCEL in order to update inventory data for making yield predictions for next felling cycle. Different stand tables representing number of stems per km^2 classified by 5 cm dbh classes were developed for each timber group currently used in timber management in the country. Specific movement ratios were applied to estimate upgrowth to larger diameter classes. However, as three are no permanent sample plots in this watershed, specific information on growth parameters were not available. Average growth rates of each timber groups were extrapolated from PSPs established on the Bago mountain ranges. For Teak, an empirical mortality function was available and incorporated into its projection system, but mortality rates for other hardwood groups were estimated through theoretical assumptions. Ingrowth (i.e., the number of stems recruited into smallest diameter classes) was not considered in the present system that was intended to use only for short-term projection. This system provides yield estimates for the next cycle with a certain degree of accuracy. Finally, some suggestions were made for revisions on current dynamic inventory and a data compiling system for making meaningful improvements in modelling stand development of tropical forests of the country. Further research needs were also highlighted and a cohort modelling approach was recommended to introduce more accurate estimates if relevant data are available.

Sustainable forest management (SFM) is realized as a standard approach to effective conservation of tropical forest watersheds that provide economic, environmental, and social functions with pronounced temporal and spatial effects. Even though the concept of SFM necessarily draws a wider attention on economic, ecological, and political objectives, the principle of sustained yield (i.e., a non-declining even-flow of timber) is still one of the principal objectives. The process of yield regulation translates management prescriptions into operational reality and therefore is a mean to SFM. Under the SFM concepts, sustainable yield is distinguishable from sustained yield: sustainable yield is meant as a long-term goal of overall forest resource development whereas sustained yield is referred to as a short-term objective, a means to achieve this end. In practice, sustained yield is realized as an allowable harvest for a given period through manipulation of three tactical elements namely interval, intensity of and trees selection criteria for harvest. Traditionally, allowable harvest was estimated based virtually on limited information. Contemporary approaches have developed a number of data intensive yield prediction systems such as stand projection and simulation.

In fact, effective timber management claims a more reliable approach in yield regulation in so far as to integrate sustained yield principle into the overall objectives of watershed conservation. A proper yield regulation system needs to be devised to bring conservative principles into harmony with profitable timber harvest on a sustainable basis. The final case study was therefore motivated by the objective to modify the prevailing yield regulation system for improving productivity and ensuring sustainability of timber resources of the tropical forest watershed. Accordingly, a yield regulation system was proposed as an effective timber management tool for integrated resource management of Paunglaung watershed of the country.

The first attempt for integration was to define the spatial boundaries of the timber management system according to the watershed boundaries that can be topographically delineated. The watershed area was then differentiated into spatial zones according to forest types to reflect site variations, following distinct topographic features. The proposed system includes two components: a productive forest areas estimation sub-system and a yield prediction sub-system. Geographic information system was applied to exclude non-productive areas for logistic, environmental and social reasons from gross forest areas in estimating effective forests for timber harvesting. The yield prediction sub-system employed the stand table projection to update inventory data of different zones. The presently used felling cycle of 30 years was adopted as harvest interval of the proposed system. Harvest intensity was controlled basically by tree numbers prescribed in terms of the minimum harvest size-limit. No particular specification was set to maintain the residual growing stocks at a optimum level for getting maximum growth, balanced structure and composition, but various conditions complemented by maximum harvest specification (e.g., retaining seed-trees, maximum number of trees to be harvested and permissible canopy opening) were also set to control harvest intensity. The rareness of the species was used as an indicator for defining reserved species to prevent locally rare commercial species from extinction. Sustainable yields were estimated for each commercial timber group for the Paunglaung watershed. The population structures characterized by diameter class distributions of the most desirable commercial species were used as implicit guides to design silvicultural treatments for inducing regeneration and enhancing growth for particular stands.

The study pinpointed the urgent needs for developing specific growth models and mortality functions for a yield estimation sub-system to provide more accurate estimates. It also called for incorporating resource assessment sub-system in line with establishment of a pre- and post-harvest inventory guided by appropriate designs for assessing timber resources, planning timber harvests, monitoring harvest impacts, and revising silvicultural treatments. In fact, the problem of estimating growth and yield in mixed tropical forests with sufficient accuracy is very demanding and beyond the resources of any one country in the tropical region. It is a general conclusion that the Forest Department of Myanmar especially the Forest Resource Division needs to enhance its capacity to reorganize and maintain a large number of installed PSPs and to compile the data already in hand. Then, an available alternative would be to pool resources by launching bilateral and multilateral collaboration programs.

9. Zusammenfassung

Myanmar ist ein besonders waldreiches Land innerhalb des kontinentalen Südostasien. Immer noch bedecken Naturwälder etwa 50% der Landesfläche. Der größte Teil des Landes ist geprägt durch waldreiche Hochlagen. Die Wassereinzugsgebiete der Bergregion, die mit unterschiedlichen Waldformationen bedeckt sind, sind unabdingbar für die nachhaltige Entwicklung des Landes, da sie vielfältige Schutz- und Nutzfunktionen erfüllen. Daher ist die Anwendung der Methoden der nachhaltigen Waldnutzung eine Voraussetzung für den effektiven Schutz der Wassereinzugsgebiete, wobei die Holzproduktion als primäres Ziel angesehen wird.

Die wissenschaftlich begründete Waldnutzung begann in Myanmar offiziell im Jahre 1856 mit der Einführung des sog. *Brandis Management Systems*, benannt nach dem deutschen Forstwissenschaftler v. Brandis. Das Brandis Management System gilt als das erste systematische Forsteinrichtungssystem für Tropenwälder, obwohl die Waldnutzung in Myanmar schon damals bereits auf eine mehrhundertjährige Tradition zurückblicken konnte. Das ursprüngliche *Brandis Selection System* wurde 1920 weiterentwickelt zum *Burma Selection System* und ist heute bekannt als das *Myanmar Selection System* (MSS). Myanmar ist bekannt für eine lange Waldbautradition; das MSS wird seit 150 Jahren erfolgreich angewandt. Trotzdem ist das Land heute zunehmend von Entwaldung und Bodendegradation bedroht. Diese neuen Herausforderungen machen eine Anpassung bisheriger Nutzungspraktiken und eine Weiterentwicklung der Forsteinrichtungsmethoden dringend notwendig.

Die Entwaldung ist ein Problem, das auf der politischen Ebene gelöst werden muss. Die Übernutzung mit nachfolgender Bodendegradation erfordert dagegen technische Lösungsansätze, die in vier konkreten Fallstudien beispielhaft entwickelt werden. Die speziellen Ziele dieser Untersuchung sind:

1. Ein besseres Verständnis komplexer Waldstrukturen zu erlangen. Dieses Verständnis soll dazu beitragen, unterschiedliche Waldbauprogramme besser beurteilen und die Auswirkungen von Management-Praktiken besser überwachen zu können.

2. Schätzfunktionen für das Wachstum von Einzelbäumen zu entwickeln. Auf der Basis der verfügbaren Datensätze sollen Einzelbaum-Modelle entwickelt werden, die in einem System für die Fortschreibung von Inventurdaten Verwendung finden können.
3. Schätzfunktionen für Mortalität und Einwuchs von Einzelbäumen zu entwickeln. Zusammen mit den Wachstumsfunktionen bilden diese Hilfsmittel die Basis für die Beurteilung unterschiedlicher Nutzungsstrategien in ungleichaltrigen Mischwäldern.
4. Die Methoden der nachhaltigen regionalen Nutzungsplanung und Steuerung zu verbessern. Das bestehende *yield regulation system* im Wassereinzugsgebiet Paunglaung soll weiterentwickelt werden, unter Abwägung ökonomischer und ökologischer Beschränkungen.

Die Bestandesstruktur ist ein wesentliches Merkmal des Waldzustandes; sie ist sowohl das Ergebnis als auch die Ursache für Diversität und Ökosystemdynamik. Daher ist die Kenntnis der Veränderung von Waldstrukturen, sowohl in zeitlicher (Muster der Sukzession) als auch in räumlicher Auflösung (horizontale und vertikale Raumbesetzung durch Bäume) geeignet, um Nutzungsstrategien zu entwerfen und die unmittelbaren Auswirkungen von Management-Eingriffen zu bewerten. Dementsprechend wurden neue quantitative Hilfsmittel verwendet, um das Verständnis komplexer räumlicher Strukturen zu verbessern. Im Einzelnen war es notwendig, die Waldstruktur in unterschiedlicher Auflösung und auf unterschiedlichen Ebenen zu untersuchen, um die Heterogenität, Komplexität und Diversität zu interpretieren. Die zu diesem Zweck bearbeiteten Fallstudien ermöglichen ein besseres Verständnis der Strukturvielfalt.

Drei Versuchsflächen von je 1 ha wurden in unterschiedlichen Waldformationen (*deciduous forest, typical evergreen forest, hill evergreen forest*) innerhalb des Paunglaung Wassereinzugsgebietes angelegt. Das Paunglaung Wassereinzugsgebiet ist eines der wichtigsten Wassereinzugsgebiete in Myanmar. Die Brusthöhendurchmesser, Höhen und Koordinaten aller Bäume mit einem BHD > 20 cm wurden in diesen drei Flächen erfasst. Bekannte Maße der räumlichen Statistik (pair correlation function, L-function, marked correlation function) und Nachbarschafts-Variablen (Aggregation, Durchmischung, Dimensionsdifferenzierung) wurden verwendet, um die Raumstruktur der Flächen mit unterschiedlicher Auflösung zu beschreiben.

Die Verfahren der Strukturanalyse wurden aufgrund von drei Kriterien beurteilt: Effektivität der Strukturbeschreibung, Brauchbarkeit für die Beurteilung forstlicher Eingriffe und Erfassungsaufwand im Gelände. Mit Hilfe der Verteilungen der Nachbarschaftsvariablen konnten komplexe Strukturen sehr effektiv im Detail beschrieben werden, während die Punktprozesse die Strukturen besser als Funktion der Baumabstände beschreiben konnten. Die Berechnung und Erfassung der Nachbarschaftsvariablen war erheblich einfacher und kostengünstiger im Vergleich mit den Punktprozessen. Allerdings wurde festgestellt, dass beide Ansätze Vorzüge aufweisen und dass die Anwendungen sich ergänzen. Die Werte der Nachbarschaftsvariablen Aggregation, Durchmischung und Dimensionsdifferenzierung reagierten bereits empfindlich auf kleine Änderungen in der Bestandesstruktur. Die Punktprozesse dagegen wurden nicht sehr stark durch Strukturveränderungen beeinflusst. Sie scheinen für Monitoringsysteme geeignet zu sein, die über Daten mit bekannten Baumkoordinaten verfügen, während die Nachbarschaftsvariablen auch dann eingesetzt werden können, wenn solche Daten nicht verfügbar sind.

Die zweite Fallstudie befasst sich mit der Entwicklung eines Einzelbaummodells für Teakbäume, eine besonders wertvolle Baumart, deren natürliche Verbreitung auf vier Länder in Asien beschränkt ist, u.a. auf Myanmar. Leider sind Naturwälder mit starken und hochwertigen Teakbäumen kaum noch vorhanden, die letzten Reste finden sich in Myanmar und Indien. Selbst dort sind die natürlichen Vorkommen gefährdet. Brandis hatte bereits vor etwa 150 Jahren erste Untersuchungen zu Wachstum und Ertrag natürlich vorkommender Teakbäume durchgeführt. Darüber hinaus gab es einige kleinere Arbeiten, in denen das Wachstum als Funktion des Alters untersucht wurde. Leider ist das Alter bei den meisten Baumarten eine unbekannte Größe, daher musste ein altersunabhängiger Ansatz als einzige praktikable Lösung gewählt werden. Die Fallstudie war daher darauf ausgerichtet, ein konsequentes Modellkonzept zu entwerfen, unter Berücksichtigung des verfügbaren Datenfundus und der benötigten Prognoseauflösung bei der Fortschreibung von Inventurdaten.

Die in dieser Untersuchung verwendeten Daten stammen aus permanent markierten Inventurflächen im Berggebiet von *Bago*. Insgesamt 46 wiederholt aufgenommene Versuchsflächen mit 297 Wachstumsintervallen waren verfügbar. Ein *Potential-Modifyer*-Modelltyp erwies sich als besonders geeignet. Zunächst wurde der potentielle relative Zuwachs geschätzt. Zwei Konkurrenzindizes, der *BAL* (Basal-Areas-of-Larger-trees) and *GD* (Basal area-Diameter competition index) konnten die konkurrenzbedingte Wachstumsreduktion erklären, wobei die Schätzgenauigkeit des BAL-Index marginal besser ausfiel. Es ist bereits im jetzigen Stadium möglich, das Modell im Prognosesystem der Teakwälder in Myanmar zu verwenden. Allerdings sollten die Parameterschätzwerte in Zukunft verbessert werden, sobald die Datenbasis erweitert werden kann. Bis zu diesem Zeitpunkt sind Anwendungen des Modells auf die Variationsbreite der beobachteten Messwerte zu beschränken.

Eine Waldlandschaft besteht aus Einzelbeständen mit ganz bestimmten Merkmalen. Da Nutzungseingriffe bestandesweise durchgeführt werden, können die Merkmale benachbarter Bestände erhebliche Unterschiede aufweisen. Prognosen der Landschaft sind daher nur realistisch, wenn sie als Summe der Bestandesprognosen konzipiert sind. In einer dritten Fallstudie wurde ein dynamisches Bestandesmodell entwickelt, das für eine bekannte Durchmesser-Ausgangsverteilung die Zuwächse, die Mortalität und die Einwüchse schätzt. Diese Art der dynamischen Fortschreibung realer Bestandesdaten wird bereits seit 150 Jahren in Myanmar praktiziert, allerdings auf der Basis sehr einfacher Schätzverfahren. Die Daten für diese Untersuchung stammen aus dem Einzugsgebiet Paunglaung und wurden im Rahmen der Nationalinventur in den Jahren 1994 und 1997 erhoben. Das hier entwickelte dynamische Bestandesmodell stellt eine erhebliche Verbesserung der bisherigen Ansätze dar.

Für die praktische Anwendung wurde ein Tabellenkalkulationsprogramm unter MS EXCEL entwickelt. Mit diesem Programm können Ertragsprognosen für den nächsten Nutzungszeitpunkt geschätzt werden. So wurden auf der Basis der Daten aus der Waldinventur in Paunglaung und bekannten Wachstumsraten aus dem Bago-Gebiet für mehrere Baumartengruppen durchschnittliche Wechsleranteile (Anteil der Bäume, die in einem bestimmten Zeitraum aus einer BHD-Klasse in die nächst höhere Klasse wechseln) in 5cm Durchmesserklassen berechnet. Zusätzlich wurden Mortalitätsraten für Teak und weitere Baumartengruppen geschätzt. Einwuchs in die geringste Durchmesserklasse konnte wegen der unzureichenden Datenbasis nicht ermittelt werden. Das System für die Fortschreibung von Inventurdaten ist daher vorläufig nur für kurzfristige Prognosen geeignet. Schließlich wurden Empfehlungen für die Verbesserung der gegenwärtigen Datenerhebungs- und Auswertungsmethoden formuliert.

Das Prinzip der nachhaltigen Waldnutzung (Sustainable Forest Management, *SFM*) wird allgemein anerkannt als Grundlage für den Erhalt der vielfältigen Schutzfunktionen der Tropenwälder und ihrer Einzugsgebiete. Obwohl das Prinzip heute nicht nur ökonomische, sondern auch ökologische und soziale Ziele umfasst, bildet die Nutzungsbeschränkung bzw. der dauerhafte Erhalt einer bestimmten Vorratshöhe die Grundlage für das Postulat der Nachhaltigkeit. Dieses Postulat erfordert eine Umsetzung der Theorie in praktische Handlungsanweisungen.

Das langfristig angelegte Ziel der Nachhaltigkeit wird kurz- und mittelfristig erreicht durch die Kontrolle der zulässigen Nutzung. In der Praxis wird die Nutzung für einen gegebenen Zeitraum durch drei Größen bestimmt, die sich gegenseitig beeinflussen:

- Eingriffsintervall,
- Eingriffstärke und
- Auswahl der zu entnehmenden Bäume.

Bislang beruhte die Schätzung der zulässigen Nutzung auf unzureichenden Daten. Mit der Erweiterung des Datenfundus ist es möglich geworden, die Auswirkungen unterschiedlicher Eingriffstrategien abzuschätzen. In der vierten Fallstudie wurde daher das derzeitige Verfahren zur Bestimmung der nachhaltigen Nutzung kritisch bewertet und an die neuen Anforderungen angepasst.

In einem ersten Schritt wurden die durch die Topografie bestimmten Grenzen des Einzugsgebietes Paunglaung identifiziert. Das Einzugsgebiet wurde sodann je nach Waldtyp und Topografie weiter untergliedert. Mit Hilfe von Informationen aus einem Geografischen Informationssystem wurde die produktive Waldfläche bestimmt. Unzugängliche und unproduktive Waldflächen wurden ausgeklammert und so der potentiellen Nutzung entzogen. Diese Schutz- und Rückzugsgebiete werden nicht erschlossen und haben daher eine große Bedeutung für den Erhalt unbeeinflusster Waldentwicklungen.

Für die produktive Waldfläche wurde der bestehende 30-jährige Nutzungsintervall übernommen. Die Eingriffstärke wird durch die Anzahl der Bäume bestimmt, die einen bestimmten unteren Grenzdurchmesser aufweisen. Diese Information wird auf Basis der vorliegenden Inventurdaten und mit Hilfe der Fortschreibung für den Eingriffszeitpunktes bestimmt. Ein optimaler Residualvorrat wurde für das Einzugsgebiet Paunglaung nicht festgelegt, da die hierfür benötigten Daten noch fehlen. Allerdings wurde die Eingriffstärke durch erweiterte Nutzungsbeschränkungen kontrolliert (maximale Anzahl von Bäumen, minimaler Kronenschluss und minimale Anzahl der Samenproduzenten pro Flächeneinheit). Die relative Häufigkeit einer Baumart wurde als Indikator für die Definition sog. *Reservierter Baumarten* verwendet, um das Aussterben seltener Baumarten zu verhindern.

Für jede Baumartengruppe im Einzugsgebiet Paunglaung wurde die nachhaltige Nutzung bestimmt. Die erfassten Populationsstrukturen der kommerziell bedeutenden Baumarten bilden die Grundlage für den Entwurf der Nutzungsstrategien, die u.a. darauf abzielen, die Verjüngung zu fördern und das Wachstum anzuregen. Die gegenwärtige Waldzustandserfassung in den meisten tropischen Regionen ist verbesserungswürdig. Unter anderem fehlt oft ein effektives Nutzungsimpakt-Monitoring. Präventive Kontrollverfahren, wie zum Beispiel die für Mitteleuropa vorgeschlagenen Eingriffsinventuren, sind noch kaum im Einsatz. Die Datenerfassung und Entwicklung verbesserter Wachstumsmodelle sind kostenaufwendige Aktivitäten, die die Ressourcen eines einzelnen Landes wie Myanmar übersteigen. Daher wird eine internationale Kooperation und Koordination der Waldforschung immer wichtiger.

10. References

Albert, M., 1999. Analyse der eingriffsbedingten Strukturveränderung und Durchforstungs-modelleirung in Mischbeständen. Ph.D. Dissertation, Falculty of Forestry Science. George-August-University, Göttingen, Germany.

Albert, M., and Gadow, K.v., 1998. Assessing biodiversity with new neighbourhood-based parameters. In Laumonier, Y., King, B., Legg, C. and Rennolls, K. (eds.). Procd., FIMP-INTAG International Conference, October 26-29, 1998, Jakarta, Indonesia.433-445.

Alder, D., 1979. A distance independence tree model for exotic conifer plantation in East Africa. For. Sci. 25(1): 69-71.

Alder, D., 1992. Simple methods for calculating minimum diameter and sustainable yield in mixed tropical forest. In, Miller, F.R. and Adam, K.L. (eds.) Wise Management of Tropical Forests. Proc. Oxford Conference on Tropical Forests, Oxford Forestry Institute. 189-200.

Alder, D., 1995. Growth Modelling for Mixed Tropical Forests. Oxford Forestry Institute, Oxford Uni., Oxford. 231 p.

Alder, D., 2000. Some issues in the yield regulation on moist tropical forests. In Procd. Workshop on Humid and semi-humid tropical forest yield regulation with minimal data heald at CATIE; Turrialba, Costa Rica, 5-9 July, 1999.

Alder, D., 2002. Simple diameter class and cohort modelling methods for practical forest management. Paper presented to: ITTO Workshop on Growth and Yield, Kuala Lumpur, 24-28 June 2002. 16 pp.

Alder; D and Silva, J.N.M., 2000. An empirical cohort model for management of Terra Firme forests in the Brazilian Amazon. For. Ecol. Manage. 130: 141-157.

Alder; D, Baker, N. and Wright, H.L., 2002. MYRLIN: Simple tools for yield regulation in natural tropical forests. Working Doc., Oxford Forestry Institute, Oxford. (www.myrlin.org)

Alder, D., Oavika,F., Sanchez, M., Silva, J.N.M., van Der Hout, P. and Wright, H.L., 2003. A comparison of species growth rates from four moist tropical forest regions using increment size ordination. International For. Rev. 4(3):196-205.

Alvarez, G. J. G, Castedo, D. F., Ruiz, G.A.D, Lopez, S.C.A., and Gadow, K.v., 2004. A two step mortality model for even-aged stands of *Pinus radiata* D. Don in Galicia (Northwestern Spain). Ann. For. Sci. 61:1-10.

Amelung, T. and Diehl, M., 1992. Deforestation of Tropical Rain Forests- economic causes and impact on development. J.C.B. Mohr (Paul Siebeck), Tübingen. 157 p.

Angelsen, A.**,** 1997. Tropical Agriculture and Deforestation- economic theories and a study from Indonesia. Ph.D. dissertation, Norwegian School of Economic and Business Administration, Berge. 251 p.

Appanah, S. and Weinland, G., 1992. Will the management systems for hill Dipterocarp forests stand up ?. J. Trop. For. Sci. 3(2): 140-158.

Appanah, S. and Weinland, G., 1993. Planning Quality Timber Trees in Peninsular Malaysia: a review. Malay For. Rec. No.38. FRIM, Kuala Lumpur, Malaysia. 221 p.

Armitage, I., 1998. Guideline for the Management of Tropical Forests: the production of wood. Forestry Paper 135, FAO, Rome. 293 p.

Arney, J.D., 1972. Computer simulation of Douglas-fir tree and stand growth. PhD. Thesis, Oregon State Uni., Corvallis. 88 p.

Arney, J.D., 1974. An individual tree model for stand simulation in Douglas-fir. In Fries, J. (ed.) Growth Models for Tree and Stand Simulation. 38-46.

Arney, J.D., 1985. A modelling strategy for the growth projection of managed stands. Can. J. For. Res. 15:511-518.

Ashton, P.S., 1988. Dipterocarp biology as a window to understanding of tropical forest structure. Ann. Rev. Ecol. Sys. 19: 347-370.

Assmann, E., 1970. The Principles of Forest Yield Study. Pergamon Press, New York. 506 p.

Atta-Boaten, J. and Moser, J.W., 1998. A method for classifying commercial tree species of uneven-aged mixed species tropical forest for growth and yield model construction. For. Ecol. Manag. 104: 89-99.

Augirre, O., Hui, G., Gadow, K.v. and Jimenez, J., 2003. An analysis of spatial forest structure using neighbourhood-based variables. For. Ecol. Manage. 183: 137-145.

Baddeley, A. and Turner, R., 2005. Spatstat: an R package for analyzing spatial point patterns. Journal of Statistical Software 12:1-42.

Barbier, E.B., Burgess, J.C. and Folke, C., 1994. Paradise Lost? The ecological economic of biodiversity. Earthscan, London.

Bawa, K.S. and Dayanandan, S., 1998. Causes of tropical deforestation and institutional constraints to conservation: In Goldsmith, F.B. (ed.) Tropical Rain Forest- a wider perspective. Conservation Biology Series. Chapman and Hall, Landon.175-198.

Bazzaz, F.A., 1991. Regeneration of tropical forests: physiological responses of pioneer and secondary species. In Gomez-Pompa, A., Whitmore, T.C. and. Hadley, M. (eds.) Rain Forest Regeneration and Management. Man and the Biosphere Series, Vol. 6. UNESCO. Parthenon Publishing Group, Paris. 181-207.

Bazzaz, F.A. and Pickett, S.T.A., 1980. the physiological ecology of tropical succession: a comparative review. Ann. Rev. Ecol. Sys. 11:287-310.

Belcher, D.M., Holdaway, M.R. and Brand, G.J., 1982. STEMS: the Stand and Tree Evaluation and Modeling System. USDA Forest Service, GTR-NC-79. 18 p.

Bella, I.E., 1971. A new competition model for individual tree. For. Sci. 17: 364-372.

Bertalanffy, L. v., 1957. Quantitative laws in metabolism and growth. Quart. Rev. Biol. 32: 217-231.

Bertault, J.G. and Sist, P., 1997. An experimental comparison of different harvesting intensities with reduced-impact and conventional logging in East Kalimantan, Indonesia. For. Ecol. and Manage. 94: 209-218.

Bertault, J.G., Dupuy, B. and Maitre, H.F., 1993. Silvicultural research for sustainable management of rain forest. In Wood P.J., Vanclay, J.K. and Wan Razali, W.M. (eds.) Procd., The Tropical Silviculture Workshop at the IUFRO Centennial Conference in Berlin, 1-3 September, 1992. FRIM, Kuala Lumpur, Malaysia.1-14.

Bertault; J.G., Dupuy, B. and Maitre, H.F., 1995. Silviculture for Sustainable Management of Tropical Moist Forest. Unasylva 181:

Besag, J.E., 1977. Comments on Ripley's paper. J. Roy. Stat. Soc. B39:193-195.

Besag, J.E. and Diggle, P.J., 1977. Simple Monte Carlo tests for spatial pattern. Appl. Stat. 26:327-333.

Biging, G.S. and Dobertin, M., 1995. Evaluation of competition indices in individual tree growth models. For. Sci. 41: 360–377.

Bilsborrow, R. and Geores, M., 1994. Population, landuse and the environment in developing countries: what can we learn from cross-national data?. In Brown, K. and Pearce, D.W. (eds.) The Causes of Tropical Deforestation: the economic and statistical analysis of factors giving rise to the loss of the tropical forests. University College Press, London. 106-133.

Blanford, H.R., 1956. Highlights on one hundred years of forestry in Burma, The Burmese Forester vol. 6(1).

Borota, J., 1991. Tropical Forests- some African and Asian case studies of composition and structure. Elsevier, Amsterdam. 274 p.

Bossel, H., Krieger, H. and Mohren, G.M.J., 1994. Simulation of multispecies tropical forest dynamics using a vertically and horizontally structured model. For. Ecol. Manage. 69: 123-144.

Botkin, D.B., 1993. Forest Dynamics: an ecological model. Oxford Uni. Press, Oxford. 309 p.

Botkin, D.B., Janak, J.F. and Wallis, J.R., 1972. Some ecological consequences of a computer model of forest growth. J. Ecol. 60: 849-873.

Boxman, O., De Graaf, N.R., Hendrison, J., Jonkers, W.B.J., Poels, R.H.L., Schmidt, P. and Tjon Lim Sang, R., 1985. Towards sustained timber production from tropical rain forests in Suriname. Netherlands J. Agri.Sci. 33:125-132.

Brack, C.L. and Wood, G.B., 1996. Electronic Resources for Forest Mensuration. (http:/www. anu.edu. au:80 /forestry/mensuration)

Bragg, D.C., 2001. Potential relative increment (PRI): a new method to empirically derive optimal tree diameter growth. Ecol. Model. 137: 77-92.

Bragg; D.C. 2003. Optimal diameter growth equations for major tree species of the Midsouth. Southern J. Applied For. 27(1): 5-10.

Brandis, D. 1896. The Burma Teak Forest. Garden and Forest vol II.

Brasnett, N.V., 1953. Planned Management of Forests. George, Allen & Unwin Ltd., London.

Bravo, F., Hann, D.W. and Maguire, D.A., 2001. Impact of competitor species composition on predicting diameter growth and survival rate of Douglas-fir trees in southwestern Oregon. Can, J. For. Res. 31: 2237-2247.

Breitenbach, F. v., 1974: Southern Cape Forests and trees. The Government Printer, Pretoria: 328 p.

Brokaw, N.V.L. and Lent, R.A., 1999. Vertical structure. In Hunter, M.L., Jr. (ed.) Maintaining Biodiversity in Forest Ecosystems. Cambridge Uni. Press, Cambridge, United Kingdom. 373–399

Bruenig, E.F., 1996. Conservation and Management of Tropical Rainforests: an integrated approach to sustainability. CAB International. 339 p.

Bryant, R.L, 1993. Contesting the Resource: the politics of forest management in colonial Burma. Ph.D. Dissertation, School of Oriental and African Studies, Uni. of London. 372 p.

Buchman, R.G., Pederson, S.P., and Walter, N.R., 1983. A tree survival model with application to the Great Lakes region. Can. J. For. Res. 13:601-608.

Budowski, G., 1988. Is sustainable harvest possible in the tropics ? American Forest 94(11 & 12): 34-37, 79-80.

Bunogiorno, J. and Gilless, J.K., 2003. Decision Methods for Forest Resource Management. Academic Press, Amsterdem. 439 p.

Burgess, P.F, 1989. Asia. In Poore, D., Burgess, P, Rietbergen, S. and Synnott, T. (eds.) No Timber without Trees: sustainability in the tropical forests. Earthscan, London.117-153.

Cancino, J and Gadow, K.v., 2002. Stem number guide curves for uneven-aged forests-development and limitations. In Gadow, K.v., Nagel, J. and Saborowski, J. (eds.) Continuous Cover Forestry. Kluwer Academic Publishers, London. 163-174.

Canham, C.D., Finzi, A.C., Pacala, S.W. and Burbank, D.H., 1994. Causes and consequences of resource heterogeneity in forests: Interspecific variation in light transmission by canopy trees. Can. J. For. Res. 24:337–349.

Cao, Q.V. and Baldwin, V.C., 1999. A new algorithm for stand table projection model. For. Sci. 45: 506-511.

Champion, H.G., 1936. A preliminary survey of the forest types of India and Burma. Indian Forest Record (Silviculture) 1(5), Dehra Dun, India.

Cheah, L.C., 1991. Sustained yield natural forest management in Peninsular Malaysia: opportunities for more effective forest practices. Malaysia Forestry and Forest Products Research. Procd. FRIM; Kuala Lumpur. 1-15.

Clark, D.A. and Clark, D.B, 1999. Assessing the growth of tropical rain forest trees: issues for forest modeling and management. Ecol. Application 9(3): 981-997.

Clark, D.B. and Clark, D.A., 1987. Population ecology and microhabitat distribution of *Dipteryx panamensis*, a neotropical rain forest emergent tree. Biotropica 19(3): 236-244.

Clark, P.J. and Evans, F.C., 1954. Distance to nearest neighbour as a measure of spatial relationships in populations. Ecology 35:445–453.

Cleuren, H., 2001. Paving the Road for Forest Destruction: key factors and driving forces of tropical deforestation in Brazil, Ecuador and Cameroon. Liden Development Studies, New Series Vol. 1. Research School of Asian, African, and Amerindian Studies (CNWS), University of Leiden, the Nerthlands. 266 p.

Clutter, J.L., Fortson, J.C., Pienaar, L.V., Brister, G.H. and Bailey, R.L., 1983. Timber Management: a quantitative approach. Wiley, N.Y. 333 p.

Condit, R., Hubbell, S.P. and Foster, R.B., 1996. Assessing the response of plant functional types in tropical forests to climate change. J. Vegetation Sci. 7: 405-416.

Cox, D.R. and Isham, V., 1980. Point Process. Chapman and Hall.188 p.

Cressie, N., 1993. Statistics for Spatial Data, rev. ed. Wiley, New York.

Crow, T.R., 1992. Stocking level, stand structure, cutting cycle and growth rates. Northern hardwood notes No., 4.06. North Central Forest Experiment Station, USDA Forest Service. 4 p.

Cummings, W., Jones, E., Reed, D. and Drummer, T., 2001. Frontier function analysis to estimate the maximum relative growth rate of Red pine (*Pinus resinosa*, Ait.) in northern Michigan. In Proc. IUFRO S4.11 conference on Forest Biometry, Modelling and Information Science, 25-29 June 2001, Uni. of Greenwich, London, U.K.

Dah, S. E., 2004. Teak and forest management in Myanmar. ITTO Tropical Forest Update 14(1). 12-13.

Daniels, R.F., 1976. Simple competition indices and their correlation with natural Loblolly Pine Trees. Can. J. For. Res. 16:1230-1237.

Daniels, R.F., Burkhart, H.E. and Clason, T.R., 1986. A comparison of competition measures for predicting growth of loblolly pine trees. Can. J. For. Res. 16: 1230-1237.

Davis, L.S. and Johnson, K.N., 1987. Forest Management (3rd ed,). McGraw-Hill.790 p.

Dawkins, H.C., 1958. The management of natural tropical forest with special reference to Uganda. Oxford Forestry Institute, Institute Paper No. 34. 155p.

Dawkins, H.C., 1959. The volume increment of natural tropical high-forest and limitations on its improvement. Emp. For. Rev. 38(2):188-191.

Dawkins H.C. and Philip, M.S., 1998. Tropical Moist Forest Silviculture and Management: a history of success and failure. CAB International, New York. 359 p.

De Graaf, N.R., 1986. A Silvicultural System for Natural Regeneration of Tropical Rain Forest in Suriname. Agri. Uin., Wageningen. 250.

Diggle, P. J., 1983. Statistical Analysis of Spatial Point Patterns. Academic Press, London.

Diggle, P. J., 2003. Statistical Analysis of Spatial Point Patterns. Academic Press, London.

Dobbertin, M. and Biging, G.S., 1998. Using the non-parametric classifier CART to model forest tree mortality. For. Sci. 44:507-516.

Dovciak, M., Frelich, L.E and. Reich, P.B., 2001 Discordance in spatial patterns of white pine (*Pinus strobus*) size-classes in a patchy near-boreal forest. J. Ecol. 89:280-291.

Dry Teak, 1960. Stop girdling of Teak ? Burmese Forester vol. X (6). 26-28.

Eba'aAtyi, R., 1997. Potential of cluster analysis for the aggregating tree species from African tropical forest. In Foli, E.G., Vanclay, J.K. and Ofosu-Asiedu, A. (eds.) Procd. IUFRO conference on growth studies in tropical moist forest in Africa, 11-15 Nov., 1996. Forest Research Institute, Kumasi, Ghana. 170-176.

Eba'aAtyi, R., 2000. TROPFOMS: a decision support model for sustainable management of south Cameroon's rainforest. Thesis, Waginengen Uni., Tropenbos-Cameroom series 2. 203 p.

Ehrlich, P. and Ehrlich, A., 1990. Overpopulation. In Ehrich, P. and Ehrlich, A. (eds.) The Population Explosion. Simon and Schuster, New York. 37-40.

Ek, A.R., 1974. Nonlinear models for stand table projection in northern hardwood stands. Can. J. For. Res. 4: 23-27.

Ek, A.R. and Monserud, R.A., 1974. FOREST: A computer model for simulating the growth and reproduction of mixed species forest stands. Uni. Wisconsin. Sch. Nat. Resour. Res. Rep. R2635. 84 p.

Emborg, J., 1998. Understorey light conditions and regeneration with respect to the structural dynamics of a near-natural temperate deciduous forest in Denmark. For. Ecol. Manage. 106:83–95.

Emmingham, W.H. and Elwood, N.E., 1983. Thinning: an important timber management tool. USDA Forest Service, OP-PNW-184. 8 p.

FAO, 1989a. Management of Tropical Moist Forests in Africa. Forestry Paper 88, FAO, Rome. 165 p.

FAO, 1989b. Review of Forest Management Systems of Tropical Asia: case studies of natural forest management for timber production in India, Malaysia and the Philippines. Forestry Paper 89, FAO, Rome. 228 p.

FAO, 1993. The Challenge of Sustainable Forest Management: what future for the world forests. FAO, Rome. 128 p.

FAO, 1997. State of the World's Forests 1997. FAO, Rome.

FAO, 2001. State of the World's Forests 2001. FAO, Rome.

FAO/UNEP, 1981. Tropical Forest Resource Assessment Project.Tech. Rep.1-3. FAO, Rome.

Ferrari, J.B., 1999. Fine-scale patterns of leaf litterfall and nitrogen cycling in an old-growth forest. Can. J. For. Res. 29:291–302.

Finegan, B., Camacho, M. and Zamora, N., 1999. Diameter increment patterns among 106 tree species in a logged and silvicultural treated Costa Rican rain forest. For. Ecol. Manage. 121: 159-176.

Forest Department, 1985. Field Instructions (second revision): National Forest Survey and Inventory Burma. FO: BUR/79/011, Field Document 4. Forest Dept., Rangoon, Burma.79 p.

Forest Department, 1998. Management of natural Teak forest in Myanmar. In Proc. Second Regional Seminar on Teak: Teak for the Future, 29 may-3 June, 1995, Yangon, Myanmar. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand. 201-209.

Forest Department, 2000. Management of Teak Forests in Myanmar. Occasional Report. Forest Dept., Myanmar. 11 p.

Forest Department, 2003. Forestry in Myanmar. Forest Dept., Myanmar, Yangon. 28 p.

Forest Department, 2004. Project Proposal for Conservation of Pago Yoma. Forest Dept., Yangon, Myanmar. 12 p.

Fox, J.E.D., 1976. Environmental constraints on the possibility of natural regeneration after logging in tropical moist forest. Proc. Division 1, XVI IUFRO World Congress, Norway. Forest Research Institute. 512-538.

Franklin, J.F., Cromack Jr. K., Denison, W., McKee, A., Maser, C., Sedell, J., Swanson, F. and Juday, G., 1981. Ecological Characteristics of old-growth Douglas-Fir Forest. USDA Forest Service; GTR-PNW-118.

Fridman, J., and Stahl, G., 2001. A three-step approach for modeling tree mortality in Swedish forests. Scan. J. For. Res. 16: 455-466.

Füldner, K., 1995. Strukturbeschreibung von Buchen-Edellaubholz-Mischwäldern. Dissertation, Fakultät für Forstwissenschaften und Waldökologie, Georg-August-University Göttingen, Cuvillier, Göttingen. 146 p.

Gadow, K.v., 1980. The principle of sustainable yields in forestry planning. S. Afr. For. J., No. 114: 25-28.

Gadow, K.v., 1984. The Relationship between diameter and diameter increment in *Pinus patula*. Proc. IUFRO Conference « Site and Productivity of Fast-growing plantation», Pretoria 1984. Vol 2: 741-751.

Gadow, K.v., 2001. Orientation and Control in CCF system. Paper presented at the seminar in Bangor,Wales. 13 p.

Gadow, K. v., 2003. Waldstruktur und Wachstum. Universitätsdrucke Göttingen.

Gadow, K.v. and Bredenkamp, B, 1992. Forest Management. Academica. Hatfield, Pretoria. 151 p.

Gadow, K.v., and Füldner, K., 1992. Zur Methodik der Bestandesbeschreibung. Vortrsg anlaesslich der Jahrestagung der AG Forsteinrichtung in Klieken b. Dessau.

Gadow K.v. and Hui, G., 1999: Modelling Forest Development. Kluver, Amsterdem, the Nerthlands. 213 p.

Gadow, K.v., Hui, G.Y., 2002. Characterizing forest spatial structure and diversity. Manuscript prepared for the conference " sustainable Forestry in Temperate Region". Organized by SUFOR, University of Lund, Sweden, 7-9 April, 2002.

Gadow, K.v., Hui, G.Y., and Albert, M., 1998 Das Winkelmass—ein Strukturparameter zur Beschreibung der Individualverteilung in Waldbesta¨nden. Centralblatt fu¨ r das gesamte Forstwesen 115(1): 1–9.

Geldenhuys, C.J. and Maliepaard, W., 1983. The causes and sizes of canopy gaps in the southern Cape forests. S. Afr. For. J. 124: 50 –55.

Gertner, G.Z., 1989. The need to improve models for individual tree mortality. In procd. 7th Central Hardwood Conference. USDA Forest Service, GTR-NC-132. 59-61.

Gompertz, B. 1825. On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. Phil. Transac. Roy. Soci. London. 115: 513-585.

Goodall, D. W., 1952. Some considerations of the use of point quadrats for the analysis of vegetation. Aust. Jour. Sci. Res. Ser. Bull. 5:1-41.

Gourlet-Fleury, S. and Houllier, F., 2000. Modelling diameter increment in a lowland evergreen forest in French Guiana. For. Ecol. Manage. 131: 269-289.

Graz, P., 2002. The behaviour of the Species Mingling Index M_{sp} in relation to species dispersal, unpublished manuscript.

Guan, B.T. and Gertner, G., 1991. Modelling red pine tree survival with an artificial neural network. For. Sci. 37(5): 1429-1440.

Gyi, K.K, 1972. An Investigation of Factors Relevant to Development of Teak Plantation in South-east Asia with Particular Reference to Burma. M.Sc. Thesis. Aus. Nat. Uni.

Gyi, K.K. and Tint, K., 1998: Management Status of Natural Teak Forests. In Proc. Second Regional Seminar on Teak: Teak for the Future, 29 may-3 June, 1995, Yangon, Myanmar. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand. 27-48.

Hahn, J.T. and Leary, R., 1979. Potential diameter growth functions. In Generalized Forest Growth Projection System applied to the Lake State Region. USDA Forest Service GTR-NC-49. 22-26.

Hahn-Schilling, B., Heuvelop, J. and Palmer, J., 1994. A comparative study of evaluation systems for sustainable management. In Heuvelop, J. (ed.) Assessment of Sustainable Tropical Forest Management. Kommissions Verlag, Humburg. 37-165.

Hamilton, D.A., 1986. A logistic model of mortality in thinned and unthinned mixed conifer stands of northern Idaho. For. Sci. 32:989-1000.

Hamilton, D.A., 1990. Extending the range of applicability of an individual tree mortality model. Can. J. For. Res. 20:1212-1218.

Hamilton, D.A. and Edwards, B.M., 1976. Modelling the Probability of Individual Tree Mortality. USDA Forest Service, RP-INT-185. 22 p.

Hansen, A.J., Spies, T.A, Swanson, F.J. and Ohmann, J.L., 1991. Conserving biodiversity in managed forests. BioScience 41: 382-392.

Harmon, M.E., Franklin, J.F., Swanson, F., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack. Jr., and Cummins, K.W., 1986. Ecology of coarse woody debris in temperate ecosystems. In MacFadey, A. and Ford, E.D. (eds.) Advances in Ecological Research Vol (15), Academic Press, Orlando, Fla. 133-302.

Harms, W.R., 1983. An empirical function for predicting survival over a wide range of densities. In procd. Second Biennial South Silvicultural Research Conference, 4-5, Nov., 1982, Atlanta, Ga. USDA Forest Service, GTR-SE-22. 334-337.

Hasse, W.D. and Ek, A.R., 1981. A simulated comparison of yields for even- versus uneven-aged management of northern hardwood stands J. Envi. Manage. 12: 235-246.

Hegyi, F. 1974. A simulation model for managing jack pine stands. In Fries, J (ed.) Growth Models for Tree and Stand Simulation. Royal Coll. For. Res. Notes 30. 74-90.

Hendrick, R.L., 2001. Forest Types and Classification. In Evans, J (ed.) The Forest Handbook. Vol. 1. Blackwell Science Ltd., Malden, USA. 23-64.

Higman, S., Bass, S., Judd, N., Mayers, J. and Nussbaum, R., 1999. The Sustainable Forestry Handbook: a practical guide for tropical forest managers on implementing new standards. London, Earthscan. 289 p.

Hilt, D.E., 1983. Individual Tree Diameter Growth Model for Managed, Even-aged Upland Oak Stands. USDA Forest Service, RP-NE-533. 15 p.

Holdaway, M.R., 1984. Modelling the Effects of Competition on Tree Diameter Growth as Applied in STEM. USDA Forest Service GTR-NC-094. 9 p.

Holdaway, M.R., 2000. The AFIS tree growth model for updating annual inventories in Minnesota. In Hansen, M.H. and Burk, T.E. (eds.) Integrated Tools for Natural Resource Inventories in the 21st Century: Proc. IUFRO conference, 16-20 August, 1998, Boise. USDA Forest Service GTR-NC-212. 507-514.

Htun, A.A., 2005. Local communities use of medicinal plants in Paunglaung watershed area. Research Paper presented at the School Family Day, 30 Dec 2004-1 Jan, 2005. University of Yangon, Yangon, Myanmar. 12 p.

Hui, G.H. and Hu, Y.B., 2001. Measuring species spatial segregation in mixed forest. Forest Res. 14(1): 23-27

Hui, G.Y., and Gadow K.v., 2002. Das Winkelmass—Theoretische Überlegungen zum optimalen Standardwinkel. Allgemeine Forst u. Jagdzeitung, in press.

Hui, G.Y., Albert, M., Gadow, K.v., 1998. Das Umgebungsmaß als Parameter zur Nachbil-dung von bestandesstrukturen. Forstwissenschaftliches Centralblatt 117 (1): 258–266.

Hutchinson, I. D., 1987. Silvicultural treatments. Improvement thinning in natural tropical forests: Aspects and institutionalization. In Mergen, F. and Vincent, J. R. (eds.) Natural Management of Tropical Moist Forests: Silvicultural and Management Prospects of Sustained Utilization. Yale School of Forestry and Environmental Studies, New Haven, CT.

Hutchinson, I.D., 1988. Point of departure for silviculture in humid tropical forests. Comm. For. Rev. 67(3): 223-230.

Irrigation Department, 2003. Progress Report on Paunglaung Multi-purpose Dam Project. Construction (5), Pyinmana, Myanmar. 15 p.

Jaehne, S and Dohrenbusch, A., 1997. Ein Verfahren zur Beurtielung der Destandesdivertität. Summary: a method to evaluate forest stand diversity. Forstwissenshaftliches Centralblatt 116: 333-345.

Jogiste, K., 2000. A basal area increment model for Norway spruce in mixed stands in Estonia. Scan. J. For. Res. 15: 97-102.

Johnson, E.W., 1973. Relationship between Point Density and Growth. Agric. Exp. Stn., Auburn Uni., Bull. 447.

Johnson, N. and Cabarle B., 1993. Surviving the Cut: natural forest management in the humid tropics. World Resource Institute, Washington DC. 71 p.

Jonkers, W.B.J., 1987. Vegetation Structure, Logging Damage and Silviculture in a Tropical Rain Forest in Suriname. Agricultural Uni., Wageningen. 172 p.

Jonkers,W. and Foahom, B., 2004. Sustainable Management of Rainforest in Cameroon. Cameroon series 9.Tropenbos International, Wageningen, the Netherlands. 74 p.

Kadambi, K., 1972. Silviculture and Management of Teak. Bull. 24. School of Forestry, Stephen F. Austin Uni., Nacogdoches, Texas. 137.

Kaosa-ard, A., 1981. Teak: its natural distribution and related factors. Natural History Bulltin, Siam Society. 29: 55-74.

Keh, S.K., 1993. The problems of natural regeneration of Teak in the lower reaches of Bago Yoma particularly in the Sourth Zamayi and North Zamiyi reserved forests. For. Sci. research paper, Forest Research Institute, Forest Dept., Yezin, Myanmar.

Keh, S.K., 1997. The problem of the natural regeneration of Teak in the tropical high rainfall area. TEAKNET newsletter No. 8. Yangon, Myanmar.

Keh, S.K. and Aung, M., 1995. A critical review of the silvicultural treatments of the teak bearing forests of the Bago Yoma with some suggested remedial treatment. For. Sci. research paper. Forest Research Institute, Forest Dept., Yezin, Myanmar.

Keh, S.K. and Kyaw, S., 1995. A general study of the growing stock of Teak in the Bago Yoma: some suggested redress. The Teak Symposium, 28-29 March, 1995, Central Forestry Development Training Centre (CFDTC), Forest Dept., Myanmar.

Kenkel, N.C., 1988. Pattern of self-thinning in jack pine: testing the random mortality hypothesis. Ecol. 69: 1017-1024.

Kenkel, N. C., Hoskins, J. A. and Hoskins, W. D., 1989. Local competition in a naturally established jack pine stand. Can. J. Bot. 2630–2635.

Kermode, C.W.D. 1964. Some Aspects of Silviculture in Burma. Central Press, Rangoon, Burma. 158 p.

Kimmins, J.P., 1990. Modelling the sustainability of forest production and yield for a changing and uncertain future. For. Chron. 66: 271-280.

Kint, V., Meirvenne, M.V, Nachtergale, L., Geuden, G. and Lust, N., 2003. Spatial methods for quantifying forest stand structure development: a comparison between nearest-neighbour indices and variogram analysis. For. Sci. 49(1): 36-49.

Korsgaard, S., 1992. An Analysis of Growth Parameters and Timber Yield Prediction Based on Research Plots in the Permanent Forest Estate of Sarawak, Malaysia. Council of Department of Research, Copenhagen. 134 p.

Kuuluvainen, T. and Pukkala, T., 1987. Effect of crown shape and tree distribution on the spatial distribution of shade. Agri. For. Meteo. 40: 215-231.

Kyaw, N.N., 2003. Site Influence on Growth and Phenotype of Teak (*Tectona grandis* Linn. f.) in Natural Forest of Myanmar. PhD Dissertation. Faculty of Forestry Science, George-August-University, Göttingen. Cuvillier Verlag, Göttingen, Germany. 163 p.

Kyaw, S., 2000. Historical review of Teak forestry in Myanmar. Paper presented in 3rd Regional Seminar on Teak: Potential and opportunities in marketing and trade of plantation Teak. Yogyakarta, Indonesia, July 31-August 4, 2000.

Lamprecht, H., 1989. Silviculture in the Tropics. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), Eschborn, Germany. 296 p.

Lanly, J.P., 1982. Tropical Forest Resources. Forestry Paper 30, FAO, Rome. 106 p.

Lanly, J.P., 1995. Sustainable forest management: lessons of history and recent developments. Unasylva 46(182): 38-45.

Lawrence, A., 2003. No forest without timber ? Intl. For. Rev. 5(2): 87-96.

Leary, R.A., 1979. Design: In Generalized Forest Growth Projection System applied to the Lake State Region. USDA Forest Service GTR-N49. 5-15.

Leary, R.A. and Holdaway, M.R. 1979. Modifier functions. In Generalized Forest Growth Projection System applied to the Lake State Region. USDA Forest Service GTR-N49. 22-26.

Lee, Y.J., 1971. Predicting mortality for even-aged stands of lodgepole pine. For. Chron. 47: 29-32.

Leech, J.W., Correll, R. and Aung-Kyaw-Myint, 1991. Use of Hotelling's T^2 and principal coordinate analysis to assist in aggregating species for volume table construction. For. Ecol. Manage. 40: 279-288.

Leibundgut, H., 1960. Die waldbauliche Planning als Mittle zur Erhöhung Forstzeitschrift 24:686-690.

Lessard, V.C., 2000. Calibration of the STEMS diameter growth model using FIA data. In Hansen, M.H. and Burk, T.E. (eds.) Integrated Tools for Natural Resource Inventories in the 21st Centuary: Proc. IUFRO conference, 16-20 August, 1998, Boise. USDA Forest Service, GTR-NC-212. 507-514.

Leuschner, W.A., 1984. Introduction to Forest Resource Management. J. Wiley and Sons, New York. 298 p.

Lieberman, M. and Lieberman, D., 1994. Patterns of density and dispersion of forest trees. In McDade, L., Bawa, K.S., Hartshorn, G.S. and Hespenheide, H. (eds) La Selva: Ecology and Natural History of a Neotropical Rain Forest. Uni. of Chicago Press. 106-119.

Lieberman, D., Lieberman, M., Peralta, R. and Hartshorn, G.S., 1985. Mortality pattern and stand turnover rates in a wet tropical forest in Costa Rica. J. Ecol. 73(3): 915-924.

Lin, J. Y., 1970. Growing space index and stand simulation of young western hemlock in Oregon. D.F. Thesis. Duke Uni., Durham, North Carolina.

Lotwick, H.W. and Silverman, B.W., 1982. Methods for analyzing spatial processes of several types of points J. Roy. Stat. Soc. B 44:406-413.

Lugo, A.E., 1995. Tropical Forests: their future and our future. In Lugo, A.E. and Lowe, C. (eds.). Tropical Forests: management and ecology. Ecological studies 112, Springer-Verlag, Berlin. 3-17.

Lwin, K., 2001. Natural Regeneration of Teak in Moist Deciduous Forests on Eastern and Western Exposure of the Bago Yoma in Myanmar. M.Sc. Thesis, Faculty of Forestry Science, George-August-University, Göttingen, Germany. 69 p.

Maini, J.S., 1992. Sustainable development of forests. Unasylva 43(169):3-8.

Maitre, H.F., 1987. Natural forest management in Cote d'Ivoire. Unasylva 39: 53-60.

Manokaran, N., 1990. Ecological and environmental dimensions/problems of integration of forestry into regional development. In Kohler V. (ed.) Integration of Management of Tropical Forests into Regional Development. Germen Foundation for International Development (DSE/ZEL), Feldafing, Germany. 47-55.

Marcon, E. and Puech, F. 2003. Generalizing Ripley's K function to inhomogeneous populations. (in press)

Martin, G.C. and Ek, A.R., 1984. A comparison of competition measures and growth models for predicting plantation red pine diameter and high growth. For. Sci. 30(3): 731-743.

Mateu, J., Uso, J.L. and Montes, F., 1998. The spatial pattern of a forest ecosystem. Ecol. Model. 108:163-174.

McComb, W.C., Spies, T.A., and Emmingham, W.H., 1993. Douglas-fir forests: managing for timber and mature forest habitat. J For. 91(12): 31-42

Meyer, H.A., 1943. Management without rotation. J. Forestry, 41: 123-132

Meyer, H.A., 1952. Structure, growth, and drain in balanced uneven-aged forest. J. For. 50:85-92.

Midgley, J., Seydack, A., Reynell, D. and McKelly, D., 1990. Fine-grain pattern in southern Cape plateau forests. J. Veg. Sci. 1: 539-546.

Mladenoff, D.J. and Pastor, J., 1993. Sustainable forest ecosystems in the northern hardwood and conifer forest region: Concept and management. In Aplet, G.H., Johnson, N., Olson, J.T., and Sample, V.A. (eds.). Defining Sustainable Forestry. Island Press, Washington DC. 145-180.

Moeur, M., 1993. Characterizing spatial patterns of trees using stem-mapped data. For. Sci. 39(4):756-775

Monserud, R.A., 1975. Methodology for Simulating Wisconsin Northern Hardwood Stand Dynamics. Ph.D. Thesis, Uni. Wisconsin-Madison. 173 p.

Monserud, R.A. 1976. Simulation of forest tree mortality. For. Sci. 22: 438-444.

Monserud, R.A., 2003. Evaluating forest models in a sustainable forest management context. FBMIS, vol. 1:35-47.

Monserud; R.A. and Sterba, H., 1996. A basal area increment model for individual trees growing in even- and uneven-aged forest stands in Austria. For. Ecol. Manag. 80:57-80.

Monserud, R.A. and Sterba, H., 1999. Modelling individual tree mortality for Austrian forest species. For. Ecol. Manage. 113: 109-123.

Moser, J.W., 1972. Dynamics of an even-aged forest stand. For. Sci. 18:184-191.

Munro, D.D., 1974. Forest growth models: a prognosis. In Fries, J. (ed.) Growth Models for Tree and Stand Simulation. Royal College Forest Research Note 30. 7-21.

Murphy, P.A. and Sheldon, M.G., 1996. An individual-tree basal area growth model for loblolly pine stands. Can. J. For. Res. 26: 327-331.

Myers, N., 1994. Tropical deforestation: rate and patterns. In Brown, K. and Pearce, D.W. (eds.) The Causes of Tropical Deforestation: the economic and statistical analysis of factors giving rise to the loss of the tropical forests, University College Press, London. 27-40.

Myint, T., 1997. Forest Management Plan: Taunggyi District, Shan State (1996-97 to 2005-2006). Forest Dept., Myanmar.

Myint, W.W., Mon, M.S. and Kyi, K.M., 2002. Sustainability of natural resources through NWFP based income Generation activities in Paunglaung watershed area. In Proceeding “Annual Research Conference 2002”, Myanmar Academy of Agricultural, Forestry, Livestock and Fishery Sciences, Yangon, Myanmar. 152-174.

Neil, P.E., 1981. Problems and Opportunities in Tropical Rain Forest Management. Occasional paper No. 16, Commonwealth Forestry Institute, Oxford. 127 p.

Nepal, S.K. and Somers, G.L., 1992. A generalized approach to stand table projection. For. Sci. 38: 120-133.

Newman, M.F., Burgess P.F. and Whitmore, T.C. 1996. Manuals of Dipterocarps for Foresters: Sumatra Light Hardwoods. GBP15, Bogor, Indonesia

Newnham, R.M., 1964. The development of a stand model for Douglas-fir. Ph.D. Thesis, Univ. of B.C., Vancouver. 201 p.

Newton, P.F., and Jolliffe, P.A., 1998. Assessing processes of intraspecific competition with spatially heterogeneous black spruce stands. Can. J. For. Res. 28:259-275.

NIST/SEMATECH, 2004. e-Handbook of Statistical Methods. (http://www.itl.nist.gov/div898/handbook).

Nyland, R.D., 2002. Silviculture: concept and application (2nd ed.). MaGraw-Hill, New York. 682 p.

Oliver, C.D. and Larson B.C., 1990. Forest Stand Dynamics. Biological Resources Management Series. McGraw Hill, New York. 467 p.

Oo, T.S., 2000. Structure and Composition of a Teak Bearing Moist Deciduous Forest near Moeswe, Yemethin District, Myanmar. M.Sc. Thesis, Faculty of Forestry Science, George-August-University, Göttingen, Germany. 78 p.

Palmer, J.R., 1975. Towards more reasonable objectives in tropical high forest management for timber production. Comm. For. Rev. 54:273-289.

Parren, M.P.E., 2000. Latest trends in West African natural forest management aimed at timber production. In Seydack, A.H.W., Vermeulen, W.J. and Vermeu, C. (eds.). Toward Sustainable Management Based on Scientific Understanding of Natural Forests. Proc. Natural Forests and Savana Woodland symposium II, Knysna, South Africa. 5-9 Sep., 1999.

Parry, B.T., Vaux, H.J. and Dannis, N., 1983: Changing conception on sustained yield policy on the national forests. J. For. 81:150-154.

Pearce, D. and Brown, K., 1994. Saving the world's tropical forests. In Brown, K. and Pearce, D.W. (eds.) The Causes of Tropical Deforestation: the economic and statistical analysis of factors giving rise to the loss of the tropical forests, University College Press, London. 2-26.

Pelz, D. and Luebbers, P., 1998. Quantifying biodiversity: the effect of sampling method and intensity on diversity indices. In Environmental Forest Science. Extented Abstract Volume of Proceedings. IUFRO Division 8 Conference, 19-23 October, 1998, Kyoto, Japan. 189-190.

Penttinen, A., Stoyan, D. and Henttonen, H.M., 1992. Marked point process in forest statistics. For. Sci. 38:806-824.

Perresol; B.R. 1995. Basal area growth for 15 tropical tree species in Puerto Rico. For. Ecol. Manage. 73: 211-219.

Peterson, C.J. and Squiers, E.R., 1995. An unexpected change in spatial pattern across 10 years in an aspen-white pine forest. J. Ecol. 83:847-855.

Phllips, P.D. and Van Gardingen, P.R., 1999. Ecological species grouping for forest management in east Kalimantan. Project report. Berau Forest Management Project

Pielou, E.C., 1977. Mathematical Ecology. Wiley, New York. 384 p.

Pommerening, A., 2002. Approaches to quantifying forest structures. For. 75 (3): 305–324.

Poore, D., Burgess, P, Rietbergen, S. and Synnott, T. (eds.) No Timber without Trees: sustainability in the tropical forests. Earthscan, London.

Pretzsch, H., 1995. Zum Einflß des Baumvertielungsmusters auf den Bestandszuwachs. Allg. Forst u J.Ztg. 166:190-201.

Primack, R.B., Chi, E.O.K., Tan, S.S. and Lee, H.S., 1987. The silviculture of Dipterocarp trees in Sarawak, Malaysia II: Improvement felling in primary forest stands. Malaysia Forester 50 (1):43-61.

Quicke, H.E., Meldahl, R.S. and Kush, J.S., 1994. Basal area growth of individual trees: a model derived from a regional longleaf pine growth study. For. Sci. 40(3): 528-542.

Reed, D., Tome´, M., Arau´jo, M.C. and Jones, E., 2001. A re-examination of potential * modifier dimensional growth model. In Proc. IUFRO S4.11 conference on Forest Biometry, Modelling and Information Science, 25-29 June 2001, Uni. of Greenwich, London, U.K.

Reineke, L. H., 1933. Perfecting a stand density index for even-aged forests. J. of Agri. Res. 46(7):627-638.

Repetto, R. and Gillis, M., 1998. Public Policies and the Misuse of Forests Resources. Cambridge University Press, Cambridge.

Revington, J., 1992. The Causes of Tropical Deforestation. NEW Renaissance Vol. 3(2), Renaissance Universal, Mainz, Germany. (http://www.ru.org/32defore.html)

Richards, P.W., 1996: The Tropical Rain Forest (2nd ed.): an ecological study. Cambridge Uni. Press, Cambridge. 575 p.

Rietbergen, S., 1989. Africa. In Poore, D., Burgess, P, Rietbergen, S. and Synnott, T. (eds.) No Timber without Trees: sustainability in the tropical forests. Earthscan, London. 40-74.

Ripley, B. D., 1976. The second-order analysis of stationary point processes. J. Appl. Probab. 13:255–266.

Ripley, B. D., 1977. Modelling spatial patterns (with discussion). J. Roy. Statist. Soc. Ser. B 39:172–212.

Ripley, B. D., 1981. Spatial Statistics. Wiley, New York.

Ripley, B. D., 1984. Edge corrections for spatial processes. In Ambartzumian, R. V. and Weil, W. (eds.) Stochastic Geometry, Geometrical Statistics, Stereology. Teubner, Leipzig, 144-153.

Ripley, B. D., 1988. Statistical Inference for Spatial Processes. Cambridge Univ. Press.

Rombouts, J., 1998. Species grouping based on diameter increment in east Kalimantan. GTZ Sustainable Forest Management project, Samarinda, Kalimantan Timor. 47 p.

Rouvinen, S. and Kuuluvainen, T., 1997. Structure and asymmetry of tree crowns in relation to local competition in a natural mature Scots pine forest. Can. J. For. Res. 27:890-902.

Ruggiero, L.F., Jones, L.C. and Aubry, K.B., 1991. Plant and animal habitats associations in Douglas-fir forests of the Pacific Northwest: An overview. In Ruggiero, L.F., Aubry, K.B., Carey, A.B. and Huff, H.M. (Technical coordinators) Wildlife and Vegetation of Unmanage Douglas-fir forest. USDA Forest Service, GTR-PNW-285. 447-462.

Schmidt, R.C., 1987: Tropical rainforest management: A status report. Unasylva 156(39): 2-17.

Schmidt, R.C., 1991: Tropical rainforest management: A status report. In Gomez-Pompa, A., Whitmore, T.C. and. Hadley, M. (eds.) Rain Forest Regeneration and Management. Man and the Biosphere Series, Vol. 6. UNESCO. Parthenon Publishing Group, Paris. 181-207.

Schreuder, H.T. and Williams, M.S., 1995. Assessing measures of tree competition using fixed-area, variable-radius, and horizontal plot sampling. Can. J. For. Res. 25: 1578-1582.

Schröder, J. and Gadow, K. v., 2000: Testing the performance of the BAL-index on maritime pine in Northwest Spain. In Schröder J.: Analyse der Wuchsdynamik von Pinus pinaster Ait. In Nordwest-Spanien. Ph.D. Dissertation. Faculty of Forestry Science. George-August-University, Göttingen, Germany.

Seydack, A.H.W., 1995. An unconventional approach to timber yield regulation for multi-aged, multi-species forests I. Fundamental considerations. For. Ecol. Manage. 77: 139-153.

Seydack, A.H.W., 2000. Theory and practice of yield regulation systems for sustainable management of tropical and subtropical natural forests. In Gadow, K.v., Pukkala, T. and Tome, M., (eds.). Sustainable Forest Management. Kluwer Academic Publishers, London. 257-317.

Seydack, A.H.W., 2002. Continuous cover forestry system in tropical and subtropical forests: current state and future perspectives. In Gadow, K.v., Nagel, J. And Saborowski, J. (eds.) Continuous Cover Forestry. Kluwer Academic Publishers, London. 309-334.

Seydack, A.H.W., Vermeulen, W.J., Heyns, H., Durrheim, G., Vermeulen, C., Willems, D., Ferguson, M., Huisamen, J. and Roth, J., 1995. An unconventional approach to timber yield regulation for multi-aged mutispecies forests. II Application to a South African forest. For. Ecol. Manage. 77: 155-168.

Shannon, C.E., 1949. deutsch 1976: Die mathematische Theorie der Kommunickation. In Shannon, C.E. and Weaver, W. 1949. 1976. Mathematische Grundlagen der Informationtheorie. Oldenbourg: 41-143.

Shifley, S.R., 1987. A Generalized System of Models Forecasting Central State Growth. USDA Forest Service RP-NC-279. 10 p.

Shifley, S.R. and Brand, G.J., 1984. Chapman-Richard growth function constrained for maximum tree size. For. Sci. 30(4): 1066-1070.

Silva, J.N.M., 1989. The behavior of the tropical rainforest of the Brazilian Amazon after logging. D. Phil. Thesis, Oxford University. 302 p.

Silva, J.N.M., de Carvalho, J.O.P.; Lopes, J. do C.A., de Almeida, B.F., Costa, D.H.M., de Oliveria, L.C., Vanclay, J.K., Skovsgaard, J.P., 1995. Growth and yield of a tropical rain forest in the Brazilian Amazon 13 years after logging. For. Ecol. Manage. 71(3): 267-274

Sist, P., Dystra, D.P. and Fimble, R., 1998. Reduced-impact logging guidelines for lowland and hill Dipterocarp forests in Indonesia. CIFOR Occasional Paper 15, Bogor, Indonesia. 19 p.

Sist, P., Fimble, R., Shell, D., Nasi, R. and Chevallier, M.H., 2003a. Towards sustainable management of mixed Dipterocarp forests of Southeast Asia: moving beyond minimum diameter cutting limits. Environmental Conservation 30(4): 364-374.

Sist, P., Sheil, D., Kartawinata, K. and Priyadi, H., 2003b. Reduced-impact logging and high extraction rates in mixed Dipterocarp forests of Borneo: the need of new silvicultural prescriptions. For. Ecol. and Manage. 179: 415-427.

Sist, P., Picard, N. and Gourlet-Fleury, S. 2003c. Sustainable cutting cycle and yields in a low land mixed Dipterocarp forest of Borneo. Ann. For. Sci. 60: 803–814

Smith, D.M., Larson, B.C., Kelty, M.J. and Ashton, P.M.S., 1997. The Practice of Silviculture: applied forest ecology (9th ed.). John Wiley & Son, New York. 537 p.

Soebiato, P., 1990: Country report: Indonesia. In Kohler V. (ed.) Integration of Management of Tropical Forests into Regional Development. Germen Foundation for International Development (DSE/ZEL), Feldafing, Germany. 86-91.

Soerianegara; I. and Lemmens, R.H.M.J., 1993. Timber Trees: major commercial timbers. Plant resource of South-east Asia No. 5(1). Pudoc Scientific Publisher, Wageningen, the Netherlands. 610 p.

Somers, G.L., Oderwald, R.G., Harm, W.R. and Langdon, O.G., 1980. Predicting mortality with a Weibull distribution. For. Sci. 26: 291-300.

Spellmann, H. 1995.Vom strukturarmen zum strukturreichen Wald. Forst u. Holz, 50(2): 35-44.

Spies, T.A., 1997. Stand structure, function, and composition. In Creating a Forestry for the 21st century: The science of Ecosystem management. Oxford Uni. Press.

Spies, T.A., 1998. Forest Structure: A key to the ecosystem. Northwest Sci. 72, special issue No.2:34-39.

Spies, T.A., Franklin, J.F. and Klopsch, M., 1990. Canopy gap in Douglas-fir forests of the Cscade Mountains. Can. J. For. Res. 20: 649-658.

Spies, T.A., Tappeiner, J., Pojar, J. and Coates, D., 1991. Trends in ecosystem management at the stand level. Transactions of 56th North American Wildlife and Natural Resources Conference 56: 628-639.

Staupendahl, K., 2001. Das fla¨chenbezogene Winkelmass Wf–Ein Index zur quantitativen Beschreibung der horizontalen Baumverteilung. In: Akca, A., et al. (Eds.), Waldinventur, Waldwachstum und Forstplanung—Moderne Technologien, Methoden und Verfahrensweisen. Festschrift K. von Gadow. Zohab, Göttingen, pp. 101–115.

Stoyan, D. and Penttinen, A., 2000. Recent applications of point process methods in forest statistics. Statistical Sci. 15(1):61-78.

Stoyan, D. and Stoyan, H., 1994. Fractals, Random Shapes and Point Fields. John Wiley, Chichester.

Swaine, M.D. and Whitmore, T.C., 1988. On the definition of ecological species groups in tropical rain forest. Vegetatio 75: 81-86.

Synnott, T., 1980. Tropical Rain Forest Silviculture. Commonwealth Forestry Institute, Occasional Paper No. 10. Department of Forestry, Oxford Uni., Oxford. 454.

Synnott, T.J. and Kemp, R.H., 1976. Choosing the best silvicultural system. Unasylva 112-113.

Szwagrzyk, J. and Czerwczak, M., 1993. Spatial patterns of trees in natural forests of East-Central Europe. J. Veg. Sci. 4: 469-476.

Tang, H.T., 1987. Problems and strategies for regenerating Dipterocarp forests in Malaysia. In Mergen, F. and Vincent J. R. (ed.). Natural Management of Tropical Moist Forests- silvicultural and management prospects of sustained utilization. School of Forestry and Environmental Studies, Yale Uni., New Haven, USA. 23-41.

Teck, R.M. and Hilt, D.E., 1991. Individual-Tree Diameter Growth Model for the Northeastern United States. USDA Forest Service,RP-NE-649. 11 p.

Thang, H.C., 1987. Forest management system for tropical high forest with special reference to Peninsular Malaysia. For. Ecol. Manage. 21: 3-20.

Thaung, M., 1998. Forest Management Plan: Yamethin District, Mandalay Division (1996-97 to 2005-2006). Forest Dept., Myanmar.

Thein, P., 1991. Review on Forest Management in Myanmar. Occasional Paper, Forest Dept.,Yangon, Myanmar. 31 p. (in Myanmar).

Thwin, B. and Han, S. 1991. Management of Teak and Hardwoods Stands for Sustainable Production. Occasional paper, Forest Dept., Myanmar. 31 p.

Thwin, S., 2003. Deforestation Analysis in Eastern and Western Myanmar. PhD Dissertation. Faculty of Forestry Science, George-August-University, Göttingen. Cuvillier Verlag, Göttingen, Germany. 128 p.

Tint, K. and Schneider, T.W., 1980. Dynamic Growth and Yield Models for Burma Teak. Kommissionsverlag. Humburg. 93 p.

Tome´, M. and Burkhart, H.E., 1989. Distance-dependent competition measures for predicting growth of individual trees. For. Sci. 35(3): 816-831.

Tomppo, E., 1986. Models and methods for analyzing spatial patterns of trees. Comm. Inst. Forestalis Fennicae 138.

Troup, R.S., 1921. The Silviculture of Indian Trees vol. II. Clarendon Press, Oxford.

Troup, R.S,. 1928. Silvicultural Systems. Clarendon Press, Oxford. 199 p.

Troup, R.S., 1952. Silvicultural Systems (2nd ed.). Clarendon Press, Oxford. 216 p.

Tuomela, K., Kuusipalo, J., Vesa, L., Nuryanto, K., Sagal, A.P.S. and. Adjers, G. 1996. Growth of dipterocarps seedlings in artificial gaps: an experiment in a logged-over rainforest in South Kalimantan, Indonesia. For. Ecol. Manage. 81: 95–100.

Turner, B., 2003. Why sustained yield can be anything you want it to be (almost): Good practice in its calculation. In Mason, E.G. and Perley, C.J. (eds.). Proc. Joint Australia and New Zeland Institute of Forestry Conference, April-May 2003, Queenstown, NZ. Ministry of Agri. and For., Wiilington, NZ .157-615.

Turner, I.M., 2001. The Ecology of Trees in the Tropical Rain Forest. Cambridge Uni. Press, Cambridge. 298 p.

Vanclay, J.K., 1990. Effects of selection logging on rainforest productivity. Australian For. 53: 200-214.

Vanclay, J.K., 1991. Aggregating tree species to develop diameter increment equations for tropical rain forests. For. Ecol. Manage. 42: 143-168.

Vanclay, J.K., 1992a. Consultancy Report for National Forest Inventory Project. Forest Dept., Myanmar.

Vanclay; J.K.,1992b. Consultancy Report for National Forest Inventory Project. Forest Dept., Myanmar.

Vanclay, J.K., 1994. Modelling Forest Growth and Yield: application to Mixed Tropical Forests. CAB International, UK. 312 p.

Vanclay, J.K., 1995. Growth models for tropical forests: a synthesis of models and methods. For. Sci. 41:7-42.

Vanclay, J.K., 1996. Estimating sustainable timber production from tropical forests. Working Paper No. 11, CIFOR, Bogor, Indonesia. 17 p.

Vanclay; J.K. and Turner, B., 2001. Evaluation of Data and Methods for Estimating the Sustainable yield of Sawlogs in Vactoria. Report of the expert data reference group. Minister for Environment and Conservation, Victoria, Australia. 94 p.

Vanclay; J.K., Gillison, A.N. and Keenan, R.J., 1997. Using plant functional attributes to quantify site productivity and growth patterns in mixed forests. For. Ecol. Manage. 94(1):149-163.

Verhulst, P.F., 1838. A note on population growth. Correwspondence Mathematiques et Physieues. 10: 113-121. (in French).

Vooren, A.P., 1992. Harvest criteria for tropical forest trees. In Cleaver, K., Munasinghe, M., Dyson, M., Egli, N., Peuker, A., and Vencelius, F. (eds.). Conservation of West and Central African Rainforests. Env. Paper No. 1. Work Bank, Washinton D.C. 134-140.

Wadsworth, F.H., 1983. Production of usable wood from tropical forests. In Golley, F.B. (ed.) Tropical Rain Forest Systems: structure and functions. Elsevier, Amsterden. 279-288.

Wadsworth, F.H., 1987. Applicability of Asian and African silvicultural systems to naturally regenerated forests of the Neotropics. In Mergen, F. and Vincent, J.R. (eds.) Natural Management of Tropical Moist Forests: silvicultural and management prospects of sustained utilization. School of Forestry and Environmental Studies, Yale Uni., New haven. 93-111.

Wan Razali; W.M., 1988. Modelling the tree growth in mixed tropical forests i.use of diameter and basal area increments. FRIM publication. Vol. 1(2).

Wan Razali, W.M., 1993. Silvicultural management issues limiting the quest for sustainability of natural tropical forests. In Wood P.J., Vanclay, J.K. and Wan Razali, W.M. (eds.) Procd. Tropical Silviculture Workshop at the IUFRO Centennial Conference in Berlin, 1-3 Septemper, 1992. FRIM, Kuala Lumpur, Malaysia.15-24.

Wan Razali, W. M. and Rustagi K. P., 1987. Development of a generalized growth model for mixed tropical forests of peninsular Malaysia. In Ek. R., Shirley, S.R., and Burk, T.E. (eds.) proc. IUFRO Conference: Forest Growth Modelling and Prediction. Vol. 1. USDA Forest Service GTR-NC-120. 167-174.

WCED (World Commission for Environment and Development), 1987. Our Common Future. Oxford Uni. Press, Oxford.

Weidelt, H.J., 1986. Die Auswirkung waldbaulicher Pflegemassnahmen auf die Entwicklung exploitierter Dipterocarpaceen-Wälder. Göttinger Beiträge zur Land-und Foestwirtschaft in den Tropen und Suntropen, vol. 19, George-August-Universität, Göttingen. 166 p.

Weidelt, H.J., 1989. Die nachhaltige Bewirtshaftung des tropischen Feuchwaldes. Möglichkeiten und Grenzen. Forstarchiv 60: 100-108.

Weiner, J., 1990. Asymmetric competition in plant population. Trends Ecol. Evol. 5: 360-364.

West, P.W., 1980. Use of diameter increment and basal increment in tree growth studies. Can. J. For. Res. 10: 71-77.

Whitmore, T.C., 1978. Gaps in the forest canopy. In Tomlinson, P.B. and Zimmermann M.H. (eds.) Tropical Trees as Living System. Cambridge Uni. Press, Cambridge. 639-655.

Whitmore, T.C., 1984. Tropical Forests of the Far East. Clarendon Press, Oxford.

Whitmore, T.C., 1991a. An Introduction to Tropical Rainforests. Oxford University Press, Oxford.

Whitmore, T.C., 1991b. Tropical rain forest dynamics and its implications for management. In Gomez-Pompa, A., Whitmore, T.C., and Hadley, M. (eds.) Rain Forest Regeneration and Management. Man and Biosphere Series, vol. 6, UNESCO/Parthenon Publishing Group, Paris. 67–89.

Whitmore, T.C., 1998. An Introduction to Tropical Rain Forest. Oxford Uni. Press, Oxford.

Whitmore, T.C. and Burnham, C.P., 1984. Tropical Rain Forests of the Far East (2nd ed.). Oxford Uni. Press, Oxford. 352 p.

Wiegand, T. and Moloney, K. A., 2004. Rings, circles, and null-models for point patter analysis in ecology. Oikos 104: 209-229.

Willan, R.L., 1965. Natural regeneration of high forest in Tanganyika. E. Afr. Agri. For. J. 31:31-43.

Wilson, F.G., 1951. Control of stocking in even-aged stands of conifers. J. For. 49:692-695.

Woodall, C.W., Fiedler, C.E. and Milner, K.S., 2003. Intertree competition in uneven-aged ponderosa pine stands. Can. J. For. Res. 33: 1719-1726.

World Bank, 1998: World Development Report 1998/99. World Bank, Washington.

Wright, H., 2000. Yield determination in tropical moist forest. In Proc. "Workshop on Humid and semi-Humid Tropical Forest Yield Regulation with Minimal Data" held at CATIE, Turrialba, Costa Rica 5-9 July 1999. Oxford Forestry Institute, Uni. of Oxford. 49-53.

Wyatt-Smitt, J., 1987a: The Management of Tropical Moist Forest for the Sustained Production of Timber: some issues. IUCN/IIED Tropical Forest Policy Paper No. 4. IUCN, Cambridge. 20 p.

Wyatt-Smitt, J., 1987b. Problems and prospects for natural management of tropical moist forests. In Mergen, F. and Vincent J. R. (eds.) Natural Management of Tropical Moist Forests: silvicultural and management prospects of sustained utilization. School of Forestry and Environmental Studies, Yale Uni., New Haven, USA. 5-22.

Wykoff, W.R., 1990. A basal area increment model for individual conifers in the northern Rocky Mountain. For. Sci. 36(4): 1077-1104.

Wykoff, W.R. and Monserud, R.A., 1988. Representing site quality in increment models: a comparison of methods. In Ek, A.R., Shifley, S.R. and Burk, T.E. (eds.) Forest Growth Modelling and Predicting. USDA Forest Service, GTR-NC-120. 184-191.

Wykoff, W.R., Crookston, N.L. and Stage, A.R., 1982. Users' Guide to the Stand Prognosis Model. USDA Forest. Service. GTR-INT-133. 112 p.

Yao, X., Titus, S.J. and MacDonald, S.E., 2001. A generalized logistic model for individual tree mortality for aspen, white spruce, and loge pine in Alberta mixed forests. Can. J. For. Res. 31:283-291.

Yoda, K., Kira, T., Ogawa, H. and Hozumi, K. 1963. Self-thinning in overcrowded pure stands under cultivated and natural conditions. J. Biol. Osaka City Univ. 14:107–129.

Zeide, B., 1993. Analysis of growth equations. For. Sci. 39(3): 594-616.

Zenner, E.K. and Hibbs, D.E., 2000: A new method for modelling the heterogeneity of forest structure. For. Ecol. Manage. 129:75-87.

Zin, M.T., Htun, N.Z, Aye, M.M., Win, K.N.C. and Sein, C.C., 2002. Assessing extension needs for community forestry development in Paunglaung watershed. In Proceeding "Annual Research Conference 2002", Myanmar Academy of Agricultural, Forestry, Livestock and Fishery Sciences, Yangon, Myanmar. 175-196.

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