Stand Structure and Development after Selective Logging with Systematically Aligned Skid Trails, Directional Felling and Climber Cutting in a Dipterocarp Rainforest in Sabah, Malaysia

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Abstract

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The tropical rainforests around the world are extremely diverse and support a huge number of timber tree species and have therefore been severely logged. One area that has produced, and still produces, large amounts of timber is Southeast Asia. In this region the most commercially important timber trees belong to the family *dipterocarpacae*, (dipterocarps). Logging is mostly carried out relatively unplanned and causes therefore great damage to the residual stand. Better planned logging and silvicultural activities, using (for instance) planned skid trails, directional felling and climber-cutting, should reduce the damage and create healthier residual stands. This study tested a logging method involving systematically aligned skid trails combined with directional felling, called supervised logging (SL) and compared it to the conventional logging (CL) practiced in the area. Both logging methods were combined with (CC) and without (NCC) climber cutting. All trees exceeding 10 cm in diameter at breast height (dbh), and a random selection of seedlings and saplings were measured before logging (1992) and for a period of eight years after logging (1993-2001).

More trees tended *(0.050 < P ≤ 0.100)* to be logged where CL was applied than in SL plots (the mean numbers of all stems and dipterocarps logged per ha were 13.0 and 12.4, respectively, in CL plots, compared to 9.4 and 6.7 in SL plots). The skid trail network applied in SL resulted in disturbance to around 7 % of the soil cover. The corresponding figure for the unplanned skid trail network in CL was higher (ca. 10 %), but not significantly different. Climber cutting resulted in four more dipterocarp trees being logged ha^{-1}, compared with NCC: a statistically significant difference *(P ≤ 0.050)*.

Basal area lost or severely damaged differed between methods for some diameter classes with mainly CL leading to greater losses. The residual stand contained statistically significantly more dipterocarp seedlings after CL than after SL, while saplings and trees showed the opposite trend, *i.e.* more individuals were left in the residual stand after SL than after CL. There were significantly (ca. 30%) more 10-29 cm dbh dipterocarp trees in the residual stand after SL than after CL. Cutting climbers had no initial effect on the residual stand in terms of densities of seedlings, saplings trees of either all species or dipterocarps.

Data collected during the subsequent period show *inter alia*, that the net basal area increased at similar rates following both logging methods, considering all species. There was also no significant difference between SL and CL in terms of dipterocarp net basal area, although this parameter grew by 1.0 m^2 ha^{-1} after SL and declined by 0.1 m^2 ha^{-1} after CL. Climber cutting significantly and positively affected net basal area growth, which amounted to 6.4 m^2 ha^{-1} and 3.3 m^2 ha^{-1} in the CC and NCC plots, respectively. The substantially higher growth associated with CC was mainly due to the growth and recruitment of small trees, mainly pioneer species.

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Contents

Appendix

Papers I-III

This thesis is based on the following studies, which will be referred to by the corresponding Roman numerals:

I. Forshed, O., Udarbe, T., Karlsson, A., & Falck, J. 2006. Initial impact of supervised logging and pre-logging climber cutting compared with conventional logging in a dipterocarp rainforest in Sabah, Malaysia. Forest Ecology and Management 221: 233 – 240.

II. Forshed, O., Karlsson, A., Larsson, E., & Falck, J. Initial impact of supervised logging and pre-logging climber cutting on the residual stands' seedlings and saplings compared with conventional logging in a dipterocarp rainforest in Sabah, Malaysia. *(Manuscript)*

III. Forshed, O., Karlsson, A., Falck, J., & Cedergren, J. Stand development after two modes of selective logging and pre-felling climber cutting in a dipterocarp rainforest, Sabah Malaysia. *(Manuscript)*

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Introduction

The tropical rainforests are like a green belt around our globe. These huge forests contain very large numbers of species; greater biodiversity than any other type of ecosystem on earth (Richards 1996). Since more or less the beginning of Man's evolutionary history, these forests have been used for subsistence, *e.g.* as sources of food and construction materials (Aiken & Leigh 1992). The rainforests have also been transformed, to varying extents, from dense forests to plantations or slash and burn patchworks, or cleared to make way for urban sprawl and/or large agro-industrial enterprises (Kammescheidt 2002). The rainforests around the equator are currently disappearing at alarming rates (Anon. 2001). For example, the forest cover has substantially decreased in the last 15 years (1990-2005) in all three of the countries with the most extensive rainforests; by 42 million ha (8 % of the forest cover in 1990) in Brazil, by 28 million ha (24 % of the forest cover in 1990) in Indonesia and by 7 million ha (5 % of the forest cover in 1990) in the Congo (Anon. 2006).

There are many causes of tropical deforestation, as discussed (*inter alia*) by Persson (1995), but for the rainforests changes to agricultural uses (large scale plantations or slash and burn regimes) have probably been the major contributors in recent decades (Bruenig 1996). However, agricultural activities are often initiated after some kind of forest degradation has occurred, *e.g.* timber exploitation (Kammescheidt 2002).

The modern exploitation of timber in the tropical rainforests started during colonial times (1850-1950) in most of the world's rainforests (Dawkins & Philip 1998). However, at that time the intensity was relatively light compared with intensities since the colonisation era (Breunig 1996). After the Second World War (around 1950), the extraction of timber increased dramatically. The reasons why production increased then are summarized by Dawkins & Philip (1998), the main ones being increasing global demands for wood and the more common use of machines, such as chainsaws, tractors and powerful trucks, which enabled the demands to be met. Timber exploitation in rainforests normally involves some kind of selective cutting of trees of the most commercially desirable dimensions and species. Today large areas are cut selectively in the rainforests (Asner *et al.* 2005). This kind of logging does not normally lead to clear cut areas or deforestation immediately. It is when the areas are repeatedly logged with too short cutting cycles, or converted for use in other ways that deforestation occurs.

One area that has produced, and still produces, large amounts of tropical timber is Southeast Asia, including countries such as Thailand, Indonesia, Malaysia, Vietnam and The Philippines. This region has been, and to some extent still is, covered by forests dominated by trees belonging to the family *Dipterocarpaceae,* commonly called dipterocarps. The *Dipterocarpaceae* family includes approximately 500 different species that can be found in both dry and moist areas (Maury-Lechon & Curtet 1998). The forests that are richest in dipterocarp species are the moist forests in the Malesian region, and the highest concentration of dipterocarp species is found in Borneo, where there are 267 species (Maury-Lechon & Curtet 1998). Many of these dipterocarps are excellent timber trees

(Burgess 1966, Meijer & Wood 1979). Dipterocarp forests are divided into several categories on the basis of geographical and ecological criteria, *e.g.* swamp, lowland and hill dipterocarp forests (Fox 1978, Meijer & Wood 1979). Dipterocarp forests are generally mixed rather than pure dipterocarp forests, since the majority of species are often non-dipterocarps, and up to ca. 80-180 different species per ha (including dipterocarps) have been found in them (Sist & Saridan 1999, Cedergren *et al.* 2002a). Several non-dipterocarps in these mixed forests are also considered to be valuable timber trees (Burgess 1966, Anon. 1999).

The basal area in dipterocarp forests is generally around 28-35 m^2 ha^{-1} (Newbery *et al.* 1999, Cedergren *et al.* 2002a, Verburg & van Eijk-Bos 2003), the major contributors being dipterocarps (Ashton 1998), which can account for around 50% of the total basal area (Garcia & Goh 1995, Sist & Saridan 1999). Trees in this kind of forest, especially the dipterocarps, have inverted J-shaped diameter curves (which are typical for natural forests), with plenty of seedlings and small trees, and only a few individuals with large diameters (Manokaran & Swaine 1994, Sist *et al.* 2003a).

In the Southeast Asian region the main timber producers are Indonesia and Malaysia (Anon. 2001). Borneo, the large island that is shared by Indonesia, Malaysia (and Brunei) accounts for a major part of the production. The studies that this PhD-thesis is based upon were carried out in the Malaysian state Sabah in the northern part of Borneo (Figure 1).

Figure 1. Map of Southeast Asia with Borneo in the centre, showing state boundaries in Borneo and the location of the experimental plot.

In Borneo the logging industry arrived with the colonisers. Great Britain administered North Borneo, which now is Sabah, and there were also British rulers ("Rajahs") in Sarawak, which nonetheless retained independence, for ca. 100 years. Kalimantan was administrated by the Netherlands. In the early 1900s rattan, jelotong and other non-timber forest products (NTFP) were important products from these forests and timber was sometimes a secondary product (Lundqvist 1949, Dawkins & Philip 1998). Timber logging was restricted to a few species and thus relatively low volumes were extracted (Nicholson 1979). The logging was mainly carried out along the coasts by man and animal power, and the impact on the forest was relatively low. However, timber harvesting gradually increased over the following decades and larger coupes or areas were designated for logging. In Sabah, for example, 14 million m^3 was produced in the late 1970s (Nicholson 1979). The production peaked during the 1970s and 1980s (Anon. 1989a) and today Sabah produces around 3.5 – 5.4 million m^3 of round logs per year (Anon. 2000, Anon. 2004).

The modern management and silvicultural regimes in Sabah, and the rest of Borneo, have been strongly influenced by the "Malayan Uniform System" (MUS) (Nicholson 1979). The MUS, which is intended to create a more or less uniform forest in terms of age, species and size, is a tropical version of the monocyclic clear felling system applied in northern Europe (among other places) followed by natural regeneration. Various treatments have been included to meet the aims of the MUS, such as poison-girdling of unwanted species and natural regeneration of wanted species (Wyatt-Smith 1995).

The MUS system, which was mainly developed for lowland dipterocarp forests in Peninsular Malaysia, was later considered inappropriate for hilly forests (Appanah 2001). The main reason for this was the insufficient regeneration of desirable species, which led to the development in both Peninsular Malaysia and Sabah of the modified Malayan Uniform System (MMUS). The MMUS further opened up the residual canopy to encourage natural regeneration, but also included planting seedlings of desired species, which was one of its main new features (Appanah 1998). MMUS, in its original form, allowed very hard felling and relied entirely on the establishment and growth of seedlings and saplings, together with the planted seedlings, to form the next harvestable crop (Appanah 1998). Medium-sized trees were left without any particular value. This system was not as productive as expected since the regeneration was still low (Appanah 2001) and, probably, because the "unproductive" harvesting cycles seemed to be unnecessarily long. Therefore, a polycyclic "modified" form of MMUS was developed, sometimes called the Stratified Uniform System (SUS) (Appanah 1998) but more commonly referred to as just MMUS, where the medium sized trees were partially relied on to create the next harvestable crop, as well as the seedlings, saplings and (if necessary) planted seedlings (Appanah 1998, Dawkins & Philip 1998). The use of poison-girdling decreased, and diameter cutting limits were introduced, in Sabah for instance the over-riding rule for cutting dipterocarps and most other species was that their diameter at breast height (dbh) had to exceed 60 cm (Anon. 1989b). This version of MMUS, or SUS, has been the most widely applied logging system in Sabah since the 1970s (Anon. 1989a, Anon. 1989b, Appanah 1998) and is hereafter referred to as the conventional logging system.

Similar selective diameter cutting regimes are also practiced in the surrounding states and countries, like Peninsular Malaysia, Kalimantan and The Philippines (Anon. 1989b, Appanah 1998, Dawkins & Philip 1998).

Since the medium-sized trees became valuable when the diameter cutting felling rule was introduced, concerns about felling damage to the residual stand were raised in the late 1970s (Chai & Udarbe 1977), because felling and skidding trees caused considerable collateral damage – up to ca. 50-60 % of the remaining trees were destroyed (Nicholson 1958, Burgess 1971, Anon. 1989a). Both Chai and Udarbe (1977) and Lee (1982) pointed out that applying post-felling treatments would be pointless, throughout Sabah, if damage could not be controlled. In the surrounding areas too, Kalimantan for instance, similar concerns were raised (Abdulhadi *et al.* 1981). The cited authors also proposed that alternative, less damaging, logging methods should be developed.

To ensure that there was acceptable regeneration, the focus on post-felling treatments had to be changed to consider the actual logging as a major part of the regeneration process. Several proposed adjustments to the logging process were then recommended to reduce the damage level. These suggestions mainly concerned two important steps: the felling of the trees and their extraction (*cf.* Mattson-Mårn, & Jonkers 1981, Appanah & Weinland 1990; Vanclay 1993; Ong *et al.* 1996). When a large tree is felled its crown and stem crush smaller trees and break the branches of other large trees (Burgess 1971). To avoid this problem directional felling and climber cutting were suggested.

Directional felling means felling tress in a predetermined direction to minimise damage to the stand and potential crop trees (PCTs). Directional felling has been successfully tested by several authors, *e.g.* Mattson-Mårn & Jonkers (1981), who concluded that directional felling was feasible and that it could help minimise damage. Pinard *et al.* (1995) found that the fellers could fell trees within 10 degrees of the marked direction, but did not record whether this single measure actually reduced damage. However, it must be assumed that if it is possible to fell a tree in a predetermined direction, damage to the surrounding trees could be reduced. It is also known that directional felling in combination with other measures, such as the use of planned skid trails, can reduce damage (Pinard *et al.* 2000b).

Directional felling rules and a checklist were presented in Klasson & Cedergren (1996). Following these rules in a subsequent study (Cedergren *et al.* 2002b) found that most (78%) of the harvested trees could be felled within 20º of the desired lay, and only 10 % of them fell > 60 º outside the desired lay. In the same experiment it was also found that 94 % of the trees selected for retention could be saved. In addition, directional felling facilitates skidding since the extraction distances can be shortened (Marsh *et al.* 1996). The safety of the forestry workers, which is a major problem in tropical forestry (Blombäck 2001), can also be enhanced by using directional felling.

The second main suggestion for reducing the damage caused by felling was to cut vines and/or climbers. Vines, climbers, or lianas are important structural components of a tropical rainforest (Kellman & Tackaberry 1997). Climbers are

10

numerous and abundant in tropical forests, but account for a relatively small proportion of the total biomass, around 5% (Hegarty & Caballé 1991). In Borneo more than 300 species of climbers are found (Fox 1968). The frequency of vines per ha varies, depending on the site and definitions, but in dipterocarp forests around 2500 liana stems per ha can be found (Hegarty & Caballé 1991) if lianas of all diameter classes are counted, representing around 4 % of all woody stems. In studies where only vines or lianas over 2 cm dbh in dipterocarp forests were counted, Cambell & Newbery (1993) found around 900 stems of woody vines per ha, while Appanah & Putz (1984) found almost 400 stems per ha (Peninsular Malaysia) and Cedergren *et al.* (2002a) around 190 stems per ha.

Climbers seem to be more common in lowland areas than in hill forests, while rattan palm climbers are more numerous in hilly areas (Appanah *et al.* 1993). However, climbers have been regarded as major problems or nuisances for the management of tropical forests (Putz 1991). Climbers infest large trees and bind their crowns together (Richards 1996), creating numerous problems for the loggers and the residual forest for several reasons. Firstly, climbers are dangerous when felling since large parts of broken climbers can fall unpredictably and trees can be dragged by hanging climbers in unwanted directions (Klasson & Cedergren 1996, Dawkins & Philip 1998). Secondly, when logging, damage to the residual surrounding forest is caused by the climbers since they create a tangled mat of vegetation in the crowns, so when one tree is felled other trees and big branches also break and follow the felled tree down (Fox 1968, Marsh *et al.* 1996). Thirdly, climbers are known to suppress the growth of trees and to deform stems (Putz *et al.* 1984, Putz 1991).

Several logging experiments have included climber-cutting treatments, but did not separate the climber-cutting effects from those of other types of logging damage, making them difficult to evaluate (*cf.* D'Oliveira & Braz 1995, Bertault & Sist 1995, Pinard *et al.* 1995, Pinard & Putz 1996). Climber cutting seems to have been assumed to be an effective treatment to minimize damage without evidence to support it. However, some experiments have separated the effects of the treatments and cutting lianas prior to logging, preferably at least a year ahead of harvesting operations, has reportedly reduced felling damage levels in some experiments (Fox 1968, Putz & Appanah 1984). These experiments were carried out in areas with relatively abundant climbers > 2 cm in dbh.

In contrast, some studies have found no evidence that cutting climbers reduces logging damage. For instance, in a forest in Cameroon that contained many lianas (around 5000 per ha, of which at least 100 were > 5 cm in dbh) Parren & Bongers (2001) found that cutting them resulted in no improvements in terms of gapsizes, tree mortality or damage levels. Cedergren *et al.* (2002b) also found no evidence that cutting climbers either reduced damage or affected the lay of felled trees at a site studied in Sabah (however, this was in a hilly forest, and probably contained a relatively small number of lianas; Cedergren *et al.* 2002a)

Although it is doubtful that pre-felling of climbers can reduce felling damage it may have other effects on the residual stand, such as improving the growth of large trees and accelerating the regeneration of trees. Large trees can be quite extensively infested with vines after logging (Pinard & Putz 1994), which affects

the formation and growth of their trunks (Putz *et al.* 1984). The presence of numerous climbers in gaps also increases competition for light, which in turn probably affects the regeneration and growth of seedlings of several species (Ashton 1995, Pinard *et al.* 1996, Whitmore & Brown 1996, Bebber *et al.* 2002). Several studies have shown that cutting climbers can reduce vine infestation after logging both in gaps and on trees (Alvira *et al.* 2004, Schnitzer *et al.* 2004). Other experiments have also shown that cutting climbers prior to logging can increase the growth rates of the residual trees (Putz *et al.* 1984, Grauel & Putz 2004).

Although felling trees *per se* clearly damages forests, the harvesting step that follows felling, extraction of the tree trunks by skidding, is the largest contributor to overall logging damage (Nicholson 1958, Elias 1995, Sist *et al.* 1998). Conventional skidding in selective management systems is essentially uncontrolled and unplanned. Normally, tractors and bulldozers are called in after felling and the operators have to go searching for felled trees (Martyn 1966, Mattson-Mårn & Jonkers 1981, Appanah 1998). Such unplanned skidding can open up large areas in the search for logs; reported soil disturbance levels vary substantially, but up to 40-50 % of the forest area may be affected (Fox 1968, Chai & Udarbe 1977, Nicholson 1979). However, such high levels of disturbance have seldom been found in recent studies, which generally report levels, of around 10-30 %, that are probably more up to date and typical of current conventional forest operations (Mattson-Mårn & Jonkers 1980, Okimoro & Matius 2000, Pinard *et al.* 2000a). However, such systems still clearly cause unnecessary damage to both residual trees and the forest floor (van Gardingen *et al.* 1998), and also compact and destroy the soil surface (Ilstedt 2002).

Improved skidding systems have been devised for Southeast Asian conditions, the main features being that they are planned before felling takes place. A system following the actual stocking of commercial trees and the local topography, such as ridges and ravines, has been suggested by Heinrich and Dykstra (1996) in the FAO Model Code for Forest Harvesting Practices, and also by several other authors (*e.g.* Marsh *et al.* 1996, Sist 2000). The basic rationale of this system is that only the tracks needed to reach commercial trees should be constructed, and that the tracks should avoid areas that are prone to heavy erosion, *e.g.* steep slopes and ravines (Heinrich & Dykstra 1996, Marsh *et al.* 1996, Sist 2000).

This kind of skid trail alignment, in combination with other damage-reducing measures, such as directional felling and climber cutting, has been tested and evaluated by several research teams (Bertault & Sist 1995, Pinard *et al.* 1995, Pinard *et al.* 2000b, Sist 2000). Systems combining all these damage-reducing techniques are often classed as "Reduced impact logging" (RIL) regimes. The acronym RIL is now applied to almost any system that includes a "rational" approach to timber harvesting in the tropics. However, using the RIL concept proposed by the cited authors, skid trail disturbance can be substantially reduced. In experiments reported by Pinard *et al.* (2000b) in Sabah, for instance, the skid trail area was reduced from around 12 % with conventional logging to 3.5 % with RIL, using planned skid trails based on stocking and topographic maps at one of the experimental sites. However, in the same experiment, but at another site, soil disturbance after RIL was found to be higher than after conventional logging.

Nevertheless, the overall conclusion was that the skid trail area could be reduced from 13 % to 9 % (Pinard *et al.* 2000b). In an experiment in Eastern Kalimantan Bertault & Sist (1995) found that use of RIL reduced the skidding area by 10%, resulting in ca. 14 % disturbed soil surface in the least disturbed areas.

Using this stocking and topographic map system to align skid trail reduces not only the actual soil disturbance, but also the damage to trees and seedlings *etc*. For example, Bertault & Sist (1997) found that the number of dead and injured trees could be substantially lowered; from 48.1 % with conventional logging to 30.5 % with RIL. Pinard *et al.* (2000b) found similar figures for damaged trees (50% with conventional and 28 % with RIL). However, these figures reflect the effects on the whole RIL approach, including the effects of several measures, such as planned skid trails, directional felling *etc*. It could be argued that it would be better to assess the effects of each component of a logging system individually, but since it is always difficult to separate and evaluate single factors, it is probably more useful to evaluate the overall effects of these RIL approaches. If we do so there is no doubt that RIL, as defined in Bertault & Sist (1995) and Pinard *et al.* (1995), substantially reduces the overall damage.

However, these kinds of RIL systems are associated with several problems, *e.g.* they have been regarded as being less productive than conventional systems since they avoid steep slopes and, thus, harvestable trees on such slopes cannot be reached (Marsh *et al.* 1996, Pinard *et al.* 2000b). In addition, both creating stocking maps for aligning the skid trails and climber cutting have been found to be very expensive (Pinard *et al.* 1995). Sist *et al.* (1998, 2003a, 2003b) recognised that these measures are insufficient for sustainable management since damage to the residual is also strongly (and unsurprisingly) correlated to the numbers of logged trees (Sist *et al.* 1998, Okimoro & Matius 2000). Therefore, Sist *et al.* (1998, 2003a) suggested that at most eight stems per ha should be cut when RIL systems are applied, claiming that if more stems are cut, damage will not be reduced by following RIL guidelines and the residual stand will become depleted.

Other planned skid trail systems have also been tried and tested. In Sarawak a skid trail network, using parallel aligned tracks, has been tested by Mattsson-Mårn & Jonkers (1981). Distances between tracks depended on the stocking density, but were normally around 100-150 m. In addition, secondary skid trails with a maximum length of 50 m were allowed where necessary to reach the logs. Here, too, directional felling was implemented to make extraction as easy as possible. The data acquired showed that the level of soil disturbance caused by skidding was the same as in conventional logging, but there was 33 % less damage to the residual stand. The authors concluded that the only measure that effectively reduced damage in the tested system was the directional felling (Mattsson-Mårn & Jonkers 1981). Cedergren *et al.* (1996a) described a similar way to align skid trails, except that there were smaller distances between the tracks, and secondary skid trails were not permitted. The systematically aligned skid trail network was also combined with directional felling and climber cutting and experimental plots established in the cited study, in 1992, were evaluated in the studies underlying this thesis.

Similar "RIL" issues to those outlined above have been debated, and various RIL systems have been trialled and/or applied in other rainforest areas around the world. In South America, for instance, the CELOS-system developed in Suriname has been tried and evaluated over several decades and seems to work quite well (de Graaf 1999). In addition, several experiments have shown that RIL can reduce damage levels in Brazil (*e.g.* D'Oliveira & Braz 1995, Johns *et al.* 1996), and Vanclay (1993) described a similar system that is intended to reduce damage when logging in the Australian rainforests.

How then will these "RIL"-forests grow, regenerate and develop? Do the damage-reducing factors, mentioned above, effectively create healthier and more productive forests in the long run? Since the forests in which RIL-management has been applied are still relatively young, these questions are not easily answered as yet. Indeed, long-term assessments of dipterocarp forests after any kind of logging are extremely scarce. Thus, the recently introduced logging cycles and cutting limits are more or less based on qualified guesses. It is also very difficult to estimate growth parameters in these kinds of forests, for various reasons, including the substantial variations in growth both between and within the hundreds of species present in the Southe ast Asian rainforests (Kennedy & Swaine 1992, Manokaran & Swaine 1994, Appanah 1998, Delissio *et al.* 2002), and the relatively high level of local variations (Sist *et al.* 2003a). Ideal cutting cycles and subsequent growth parameters also depend on the desired features of the residual stand, *e.g.* whether a forest similar to the primary forest stage is desired, or a forest with a greater abundance of commercial species, for instance with higher proportions of dipterocarps. Most studies have focused on the next harvestable crop of currently high value timber, *i.e.* the growth of dipterocarps and various other species.

The growth of stands in heterogeneous forests such as dipterocarp forests is affected by three main factors; recruitment, actual increment (diameter and height) of living trees and mortality (Korsgaard 2002). It is very important to consider all of these factors simultaneously, and their correlations and interactions, when attempting to determine net growth parameters of the forests. In primary dipterocarp forests the net growth rate is close to zero (Manokaran & Swaine 1994, Whitmore 1998), albeit with large local variations (Newbery *et al.* 1999), but primary forests are generally considered to be in equilibrium or in a climax stage (Richards 1996). A timber harvest disturbs that balance, leaving the forest area to a large extent open for recruitment and advanced growth.

Initial responses in the first few years to selective cutting in dipterocarp forests include increased growth of the residual trees (*cf.* Sist & Nguyen –Thé 2002, East Kalimantan, and Korsgaard 2002, Peninsular Malaysia). Increases in growth occur among most species, including the dipterocarps, which seem to respond by growing more rapidly than several other tree species (Sist & Nguyen –Thé 2002). Mortality rates are also higher in the first few years after logging than in undisturbed forest, but the rates also seem to return to the same level as before logging after some years (Sist & Nguyen –Thé 2002). However, mortality can still differ several years after logging (Brearley *et al.* 2004).

14

Recruitment will also increase during the first few years following logging. Light-demanding pioneer species, *e.g. Macaranga spp.*, mainly establish in the first few years (Nussbaum *et al.* 1995, Pinard *et al.* 1996, Kuusipalo *et al.* 1996), but the recruitment of other species, including dipterocarps, is also enhanced by openings in the forest (Tuomela *et al.* 1996). Of course, the regeneration of desired species is essential, since they will create the next harvestable crop in the future.

The effects of these factors and harvest cycling periods have been examined in several simulations, resulting in various recommendations. For instance, in Sabah Ong & Kleine (1995) suggest that intervals of around 60-80 years are required when using conventional logging for the forest to return to a state similar to a primary forest. In contrast, Huth & Ditzer (2001), who included low impact methods in their simulations, estimated that 80-100 years intervals were required to promote the conservation of species. Shorter intervals could jeopardise the balance and lead to overexploitation of the forest. Huth and Ditzer suggest that 60-year cycles should be combined with low impact logging methods, as a compromise between ecological and economic interests. The cited authors concluded that reduced impact or low impact methods help to promote long-term growth of the residual stand. Based on data from East Kalimantan, simulations led to recommendations for cycles that are substantially shorter than those currently applied in Sabah (Sist *et al.* 2003c), and van Gardingen (2003) recommend cycles of 35-45 years in combination with RIL and a maximum harvest of eight trees per ha. There seem to be different strategies in the Sabah and the East Kalimantan simulations. In East Kalimantan the no. of harvested trees are fewer compared with Sabah, which probably then result in shorter cycles, while the opposite; larger no. of trees are cut and longer cutting cycles are suggested for Sabah. However, all of the simulation studies come to the conclusion that cutting cycles can be shortened if RIL techniques are applied (Huth & Ditzer 2001, Sist *et al.* 2003c, van Gardingen *et al.* 2003).

Although RIL has been proven to reduce damage and improve the residual stand it is not widely implemented in routine logging practices (Applegate *et al.* 2004). With few exceptions logging continues to be done in the same way that it has since the 1980s in this region (Appanah 1998). There are many reasons for the low interest in adopting RIL (Applegate *et al.* 2004), but the over-riding concern is the demand for "fast" returns (Rice *et al.* 1997). The individual countries demand of fast economical growth and the widespread system of selling concession rights combined with using numerous logging contractors' leaves the forest without strict governance, no incitements for long term sustainability is created. Similar trends developed in the northern European countries from 1850 to 1950, when large areas of primary old growth forest were selectively logged and severely damaged (Östlund *et al.* 1997, Kardell 2004).

In addition, implementing RIL is not straightforward, and requires well-qualified personnel (Marsh *et al.* 1995, Applegate *et al.* 2004). Furthermore, preparing the stock and topographic maps is time-consuming and expensive (Pinard *et al.* 2000b). Thus, although aligning skid trails following stocking maps certainly seems to help minimise damage, this measure may be one (but by no means the only) obstacle to the introduction of more careful logging regimes.

In the studies underlying this thesis another way of aligning the skid trials was evaluated, in combinations with directional felling and climber-cutting. The inspiration for this skid trail alignment system came from the strip-road networks seen in the boreal zone, *e.g.* in Sweden and Finland, where strip-roads are often aligned parallel to one another, following only natural borders such as rivers and are mainly used for thinning operations (Silversides & Sundberg 1989). The parallel strip-road system is considered an efficient way of aligning skid trials for extraction, and is also widely accepted and used by the forest operators (Silversides & Sundberg 1989, Sidbäck 1993).

Although substantially smaller trees are handled in thinning with parallel strip-roads in boreal forests than the large, logged timber trees in dipterocarps forest, a similar type of network may be appropriate in the tropical rainforest. Timber trees in dipterocarp forests are not generally as evenly distributed as in a boreal forest or a plantation. However, they are tall and could be reached and winched out if they are directed towards a skid trail when they are felled, even if they stand as far as 30 metres away from it (Cedergren *et al.* 1996a). Therefore, a systematic alignment with 60-metre spacing between the trails was introduced and tested; the systematic alignment for its ease of implementation, and the 60 metre spacing in order to allow all harvestable trees to be reached. Theoretically, this alignment should leave large parts of the forests undisturbed by tractors, and thus minimise soil disturbance or concentrate it along the trails. In addition, it should leave wide, continuous tracts of relatively undisturbed forest land following logging, except of course for the missing felled trees, and accompanying felling damage.

In addition to this alignment, directional felling was used in an attempt to lay the trees in desired orientations to facilitate their extraction. This logging approach is hereafter called "Supervised logging" (SL) while "Conventional logging" (CL) refers to the standard logging approach routinely practiced in the area (see *Material and methods* for further details). As mentioned above, climber cutting was also included in the design, to evaluate whether it could help (alone, or in combination with SL) to reduce logging damage to the residual stand and improve subsequent stand development.

Objectives

The questions addressed in the studies underlying this thesis, based on the considerations discussed above, were:

- Are there differences between Supervised logging and Conventional logging, with respect to initial logging damage and subsequent stand dynamics?

- Does cutting climbers prior to logging affect initial logging damage to the stand and subsequent stand dynamics?

16

Materials and Methods

The study was carried out at Mile 41 in the Gunung Rara Forest Reserve in Sabah, Malaysia (approximately 4º 33' N, 117º, 02' E). The elevation here ranges from 300 to 610 m a.s.l. and the soils are Haplic Acrisols (Cedergren *et al.* 1996a) (Ultisol, USDA Soil Taxonomy). The climate in the region is very wet, with monthly rainfall exceeding 100 mm and long-term mean annual rainfall ranging from 2,000 to 4,000 mm (Whitmore 1998). Pre-logging, the vegetation was primary tropical rainforest dominated by the *Dipterocarpaceae* family, which accounted for half of the basal area (Study I).

The experimental design was a randomised 2 x 2 factorial complete block design, to evaluate the initial impact of two modes of selective harvesting, and cutting climbers versus not cutting them. The study area comprised four blocks and 16 treatment plots (Figure 2) defined here as gross plots of 5.76 ha (240 x 240 m) except for one measuring 200 x 240 m. In the centre of each gross plot a net plot of 1 ha (100 x 100 m) was established. In addition, four non-treated plots (virgin forest) of the same size, one per block, were established and considered as control plots. The control plots were not included in the 2 x 2 factorial complete block design. The blocking factor was based on average ground inclination within the net plots. Logging methods were randomly assigned to the plots within the blocks. Block 1 (mean = 22º, standard deviation, SD = 3º) was the steepest followed by Block 2 (mean = 11º, SD = 3º), Block 3 (mean = 8º, SD = 1º) and finally Block 4 (mean = 6º, SD = 1º).
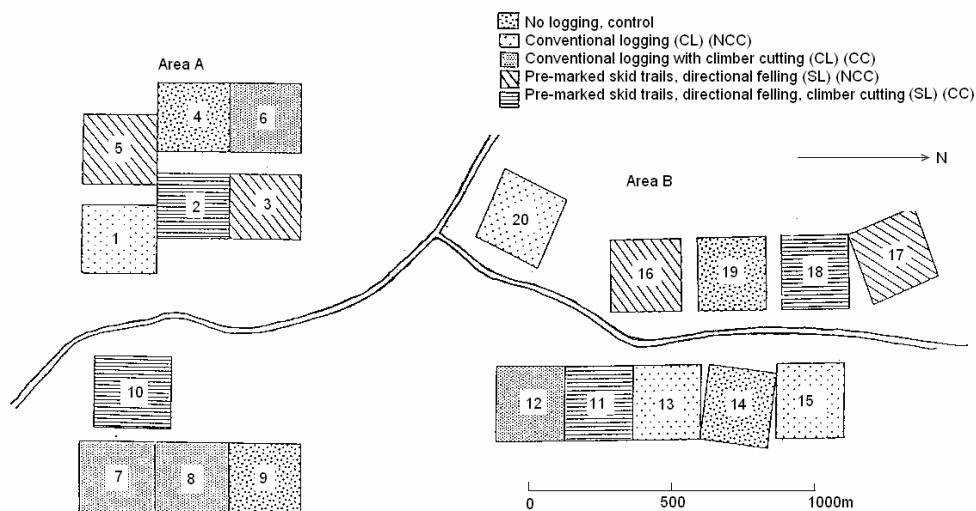

Figure 2. Experimental design and plot layout.

Plot establishment, including climber cutting, was conducted from March 1992 to June 1992. The first measurement of the plots was carried out at the same time. Harvesting commenced in June 1993 and was completed in August 1993. The plots were then re-measured, after harvesting, in October-November every second year from 1993 to 2001.

The net plots were divided into 100 sub-plots (10 x 10 m), which were marked out on the ground for convenience. During the first measurement (before logging) all trees, defined as woody species with a dbh of at least 10 cm, within each sub-plot were recorded and marked with an individual, 5-cm aluminium number tag that was buried in the soil at the base of the tree. Recorded variables for each tree were: its ID number; distance (in dm) and bearing (determined using a compass) from the centre of the sub-plot; species; and diameter (measured with a tape, in cm) at breast height (dbh) if possible, otherwise 0.3 m above the highest buttress. For each sub-plot the slope elevation in degrees was recorded.

In addition to these tree measurements, seedlings and saplings were surveyed in 40 randomly selected sub-plots per plot (Figure 3) as follows. Saplings were inventoried in a circular area of the sub-plot, with a radius of 3 m, and seedlings in a circular area with a radius of 2 m (Figure 3). In both cases the circles were centred on the middle of the sub-plot. Seedlings were defined as plants taller than 30 cm with a dbh up to 2.49 cm, and saplings were defined as plants taller than 30 cm with a dbh ranging from 2.50 cm to 9.99 cm. Recorded data were the species and numbers of (i) all seedlings, (ii) all saplings, (iii) dipterocarp seedlings and (iv) dipterocarp saplings (see below).
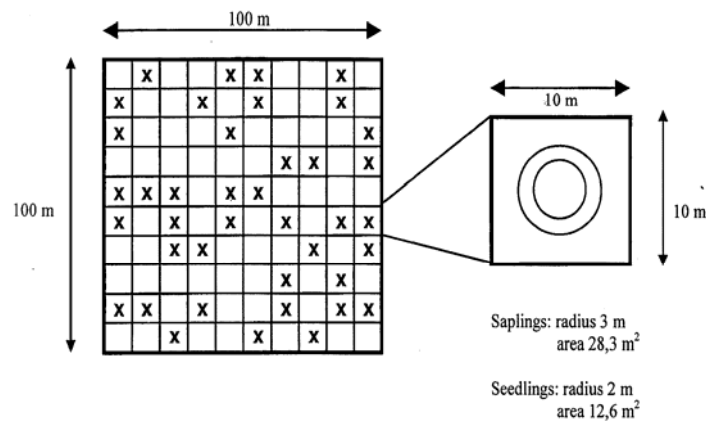

Figure 3. Schematic diagram of the 100 x 100 m net plot that was divided into 100 sub-plots, 40 of which were randomly assigned as enumeration plots for seedlings and saplings.

Tree, seedling and sapling species were identified in the field by professional inventory rangers. All individuals were, if possible, identified to species level. Seedlings, saplings and trees that could not be identified were classified as Other

18

Timbers (OT). The individuals were also grouped into dipterocarps (all individuals belonging to the *Dipterocarpaceae* family) and non-dipterocarps (all other tree species).

The enumeration procedure after logging was similar to the one applied before logging, except that a subjective assessment of skid-trail cover was introduced, where each sub-plot was given an estimation in percentage of the skid-trail cover (0 – 100 %). No measurement of slope was carried out. However, damage to individual trees was scored in three classes: 1 = Undamaged, no visual damage; 2 = Minor injury, minor visual damage that probably won't harm the individual in the long term; 3 = Major injury, substantial visual damage that will probably affect the individual's growth or eventually kill it. The diameter (dbh) was measured with a measuring tape in mm. A metal detector was used to find the tree number tags.

Tree data from all 100 sub-plots per plot were used to analyse the initial impact of the treatments on the stand (Study I). However, after following the trees for several years (Study III) the amount of data that had been gathered had become very large, so samples of sub-plots were selected to assess growth dynamics; 30 sub-plots per net plot for the ≥ 45.0 cm dbh trees, and 10 sub-plots per net plot for the 10.0 – 44.9 cm dbh trees. The chosen sub-plots were selected from a layout in which the sub-plots were evenly distributed over the whole net plot (Figure 4). Within these sub-plots all trees were individually followed inventory by inventory and all new trees that appeared, that died or changed to a larger diameter class were recorded.
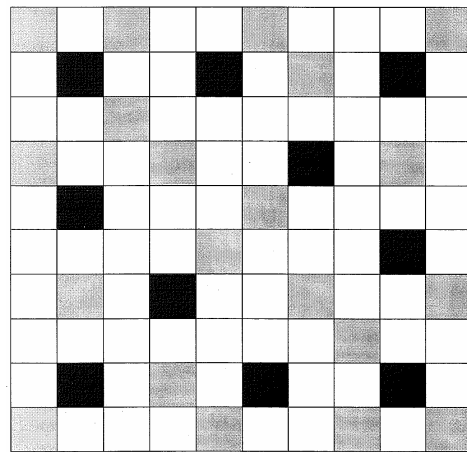

Figure 4. Sampled sub-plots within the 100x100 m net plot. Black sub-plots were used to analyse the growth dynamics of 10.0-44.9 cm dbh trees and ≥ 45.0 cm dbh trees. Grey sub-plots were used for ≥ 45.0 cm trees.

19

In Study I the trees were divided into three diameter classes and in Study III into five classes. If the species identification differed between the years, for an individual tree, its species was judged to be the one that had been most frequently recorded in the different inventories. Missing and extremely outlying dbh-values were replaced with the mean of the surrounding inventory values.

In the experiment, two logging methods were used. One was Conventional Logging (CL), which was the selective method that the contractor routinely used when logging. In CL no guidance whatsoever was given to fellers and tractor operators regarding how to conduct the harvesting operation. The trees were felled before the tractor was called in for skidding. In CL the fellers were the contractor's personnel and they did not have any formal education in directional felling techniques. The other method was Supervised logging (SL), in which directional felling was combined with the use of systematically pre-aligned skid trails parallel to one another as far as the topography allowed (Figure 5). Both uphill and downhill skidding was allowed, but sharp curves were avoided. The trails were aligned at a distance of about 62 m from one another, starting 30 m from a natural border.

Both methods strictly followed the forestry laws and regulations that applied in Sabah at that time. Most importantly, in this context, the diameter cutting limit was 60 cm dbh, *i.e.* all commercial trees larger than this should have been harvested, except for fruit trees and rare species.
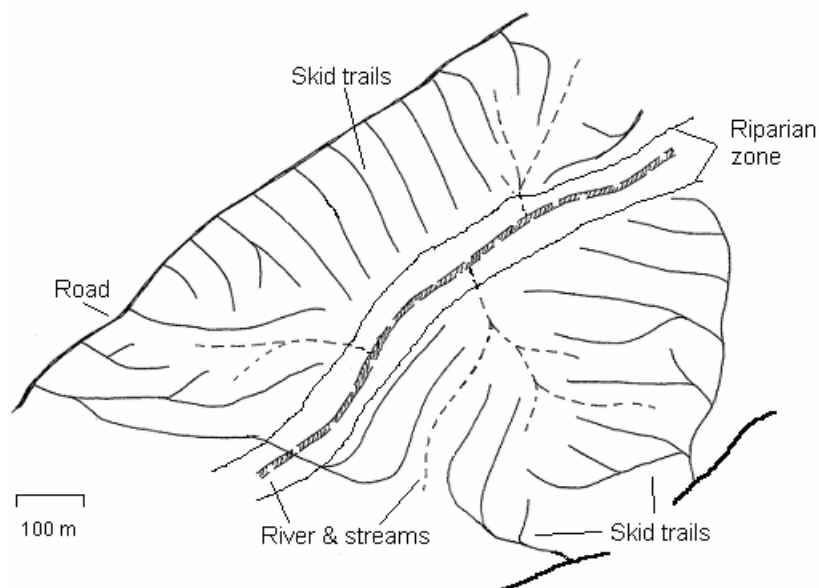

Figure 5. Schematic sketch of the pre-marked skid trail network, with skid trails systematically aligned parallel to one another with approximately uniform spacing. Both up- and down-hill skidding was accepted.

The skid-trail alignment was based on the assumptions that logs with an average length of 20 m will be extracted with a winching distance of no more than 15 m, and a tractor backing-up distance of 7 m to winch out logs (Figure 6). A cable wire was used for winching. Skid-trails were opened up before felling and medium-sized trees or PCTs along the skid-trails were marked with paint, so that tractor operators could easily spot, and try to avoid damaging them.. During the SL operation, tractors were not allowed to open up new tracks or to deviate from the trails (which had been laid out in advance) while skidding out logs.

Trees were felled towards skid-trails, sometimes even at the expense of medium-sized PCTs. Attempts were made to fell them so that the felled trees lay at an angle of about 45 degrees to the skid trails, except for trees close to skid trails. Tree crowns were directed to fall into skid trails to minimise gap creation. Trees that could not be felled towards skid-trails were felled in a direction that caused least problems when winching out the logs to the tractor. Teamwork was an important component of the logging, with frequent communication between the skilled fellers, tractor operators and hook men. For further details of the skidding and skid trail alignment see Cedergren *et al.* (1996a, 1996b).
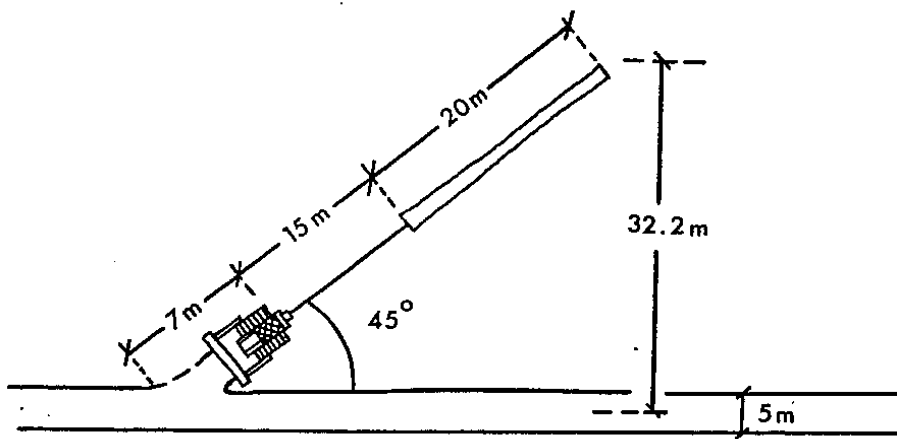

Figure 6. Estimation of log drainage distance. The log length (20 m), winching distance (15 m), reversing distance (7 m) at an angle of 45° was assumed. (From Cedergren *et al.* 1996a).

Data analysis

The main method used to analyse the treatment effects in all of the studies was analysis of variance, based on the model:

$$Y_{ijk} = \mu + b_i + t_j + c_k + (bt)_{ij} + (bc)_{ik} + (tc)_{jk} + \varepsilon_{ijk} \qquad (1)$$

21

where Y_{ijk} is the response variable, μ is the grand mean, b_i is the random effect of the block, t_j is the fixed effect of logging treatment (SL or CL), c_k the fixed effect of climber cutting or not, and ε_{ijk} is the random error. The model also includes three interaction effects; $(bt)_{ij}$ and $(bc)_{ik}$ were both regarded as random effects, while $(tc)_{jk}$ was regarded as a fixed interaction effect.

In addition, since differences in variables such as stand density between plots could affect the results, variables that seemed likely to be important for each response were included and tested in the model (1), *e.g.* numbers of dipterocarps ($\geq$ 60 cm) per plot before logging as a covariate for numbers of logged dipterocarps. If a covariate decreased the error term and/or had a P-value ≤ 0.2, it was included in the final model.

$$Y_{ijk} = \mu + b_i + t_j + c_k + (bt)_{ij} + (bc)_{ik} + (tc)_{jk} + \lambda x_{ijk} + \varepsilon_{ijk} \quad (2)$$

where λ is the coefficient for the regression of the covariate and x_{ijk} is the covariate. When a covariate was included in the final model, least square means were calculated for the response variable.

Differences between treatments and controls were evaluated by analysis of variance using the model:

$$Y_{ij} = \mu + b_i + t_j + \varepsilon_{ij} \quad (3)$$

where Y_{ij} is the response variable, μ is the grand mean, b_i is the random effect of the block and t_j is the fixed effect of the four treatment combinations (CL+CC, CL+NCC, SL+CC, SL+NCC) and the control (Virgin forest), and ε_{ij} is the random error.

The Anderson-Darling test showed no deviation from normal distribution, and plotting the residuals against fitted values showed that the assumption of homogenous variances was fulfilled. A general linear model (GLM) was used for analysing the models. All statistical analyses were done with MINITAB 13.1 and 14 (Minitab Ltd). Results of the statistical analyses were considered significant if $P \leq 0.050$ and to show a tendency if $0.050 < P \leq 0.100$. To determine the significance of differences between treatments, Tukey's studentised range test was used and Dunnett's test was used to determine the significance of differences from the controls.

Results and discussion

Pre-logging conditions

The experimental forest in the hilly Gunung Rara Mile 41 area before logging had an overall mean of ca. 500 stems per ha >10 cm dbh, amongst which dipterocarps accounted for 50% of the basal area (Table 1). Similar figures have been found *inter alia* by Sist & Saridan (1999) and Verburg & van Eijk-Bos (2003) in lowland dipterocarp forests in East Kalimantan. In contrast, this forest slightly differed from a nearby forest examined by Cedergren *et al.* (2002a), where both the basal area and number of stems were lower; ca. 28 m^2 and 400 stems ha^{-1}, respectively. However, this is consistent with the known variability of dipterocarp forests, especially hilly ones (*cf.* Burgess 1970, Lee 1982). Variability was also found within the experimental blocks in terms of both the number of stems and the basal area.

The highest mean number of stems was found in the steepest area (Block 1), where there were around 80 – 100 more stems per ha than in the other blocks. Block 1 also had the highest basal area, but the differences between the blocks were not statistically significant in this respect. In contrast the flattest area, Block 4, held the highest mean of dipterocarp basal area (statistically significant); almost twice as high as in Block 1 (Study I). Further considerable variability was also found between the individual plots, as demonstrated by the high standard errors and deviations. The numbers of seedlings in the stand were relatively low, on average 13880, (Table 1) compared to previous studies in Sabah (Nicolson 1958b, Burgess 1961, Fox 1967), where numbers of up to 30000 and 40000 seedlings per acre were found. However, the cited studies were carried out in lowland areas, and included small seedlings such as germlings, which were excluded in this study. The seedlings and saplings were also irregularly spread over the experimental plots and blocks (Study II). The number of dipterocarp seedlings per ha could differ more than two-fold between blocks. The lowest mean number of dipterocarp seedlings was found in Block 1 and the highest in Block 3. However, the saplings were found to be more equally distributed over the plots, at a density of ca. 2000 per ha.

Logged trees and extraction rates

For both logging methods, the number of logged trees was within the "normal cut" range for the region (5-15 trees per ha in conventional logging, according to figures presented by Bertault & Sist 1997, Pinard *et al.* 2000b, Mattson-Mårn & Jonkers 1981). Figures for the individual plots in this experiment also spanned this range, probably due to the irregular distribution of large harvestable crop trees. However, the CL method tended to be more productive, yielding 13 logged trees per ha compared with 9.4 logged trees per ha in SL. In addition about 50% more dipterocarps were cut in the CL plots than in the SL plots (Table 1). However, this difference was not statistically significant, and is difficult to explain, since it was believed by the loggers and during the logging operation that all trees that met the

cutting criteria were reached and cut with the SL-system (although, whether this perception was true or not cannot be judged from the results).

Table 1. *Absolute mean values per ha (including new Least Square Means created by the inclusion of significant covariates) of stand data prior to logging and logging data. DMC=diameter class*

Stand data prior to logging	All species	Dipterocarps
Seedlings (No.)	*13880*	*4512*
Saplings (No.)	*1998*	*277*
Trees (DMC 10-29 cm) (No./Basal area)	*389/8.3*	*83/2.0*
Trees (DMC 30-59 cm) (No./Basal area)	*81/11.1*	*31/4.5*
Trees (DMC > 60 cm) (No./Basal area)	*26/13.5*	*19/10.2*
Trees > 10 cm (No./Basal area)	***498/32.9***	***133/16.6***

Logging data		
	All species	Dipterocarps
Logged trees:		
CL: (No./Basal area)	*13.0/8.5*	*11.3/7.5*
SL: (No./Basal area)	*9.4/6.1*	*7.8/5.1*
Lost no. of seedlings:		
CL: (No.)	*-3904*	*-125*
SL: (No.)	*-4737*	*-825*
Lost no. of saplings:		
CL: (No.)	*-720*	*-114*
SL: (No.)	*-491*	*-74*
Trees lost and severely damaged:		
CL: (DMC 10-29 cm) (No./Basal area)	*-165/-3.0*	*-39/-0.9*
SL: (DMC 10-29 cm) (No./Basal area)	*-137.6/-2.4*	*-38/-0.7*
CL: (DMC 30-59 cm) (No./Basal area)	*-22.5/-2.9*	*-8.8/-1.0*
SL: (DMC 30-59 cm) (No./Basal area)	*-22.0/-2.9*	*-8.3/-1.1*
CL: (DMC > 60 cm) (No./Basal area)	*-2.4/-1.1*	*-1.9/-0.9*
SL: (DMC > 60 cm) (No./Basal area)	*0/+0.6*	*-0.5/+0.3*
CL: (> 10 cm) (No./Basal area)	***189.9/7.0***	***49.6/2.9***
SL: (>10 cm) (No./Basal area)	***159.6/4.7***	***46.8/1.6***

The results from Study I showed that very similar numbers of $\geq$ 60 cm dbh trees were left in the residual stands following logging by both methods. However, in the study of subsequent developments (Study III), one finding was that more trees within the 60 – 89 cm diameter interval were retained in the SL plots (although the difference was not statistically significant). It is also possible that more trees that did not meet the cutting criteria were "accidentally" cut and left in the forest during the CL-operation than during the SL operation. The trees in the CL plots that perhaps should not have been cut, for instance because of injuries or disease (*e.g.* root rot or hollow interiors *etc*.) may have been inspected less thoroughly before felling than those in SL plots, and therefore accidentally cut. Thus, SL

probably led to less trees being harvested than CL, but crucial issues to consider are how many of the trees actually reached the sawmill and how many were left in the forest. Other studies have also found that fewer trees are harvested when some kind of RIL approach is applied (Bertault & Sist 1995, Pinard & Putz 1996, Pinard *et al.* 2000b). As mentioned in the introduction (and discussed by Marsh *et al.* 1996), this belief has been prevalent for a long time, and it is probably one of the main reasons why there is resistance to implementing RIL methods in routine logging practices.

Skid trail disturbance

The systematically aligned skid trail network used in this experiment seemed to work quite well. Theoretically, the systematically aligned trails should cover at most 10% of the surface and this percentage was not exceeded in any of the SL plots, where 9.2% was the maximum level of soil disturbance by tractor skid trails and the mean level was 7% (Study I). However, there seemed to be quite a small difference in this respect between the planned SL system and the unplanned CL skidding network, for which the mean level of disturbed soil was 10%. However, this is relatively low for conventional logging, since figures of up to ca. 30 % have been found in other studies (Bertault & Sist 1995, Okimoro & Matius 2000). There was also great variation within the CL plots, since the disturbance exceeded 10 % in several plots, and the highest percentage was 22.5 %. No statistically significant differences were found either between the treatments or between the blocks in this respect. However, graphs of the data for the individual plots suggest that the disturbed area percentage in the CL plots was affected by the inclination (Figure 7), while the disturbed area in SL was less dependent on the inclination, which was one element of the rationale underlying the method.
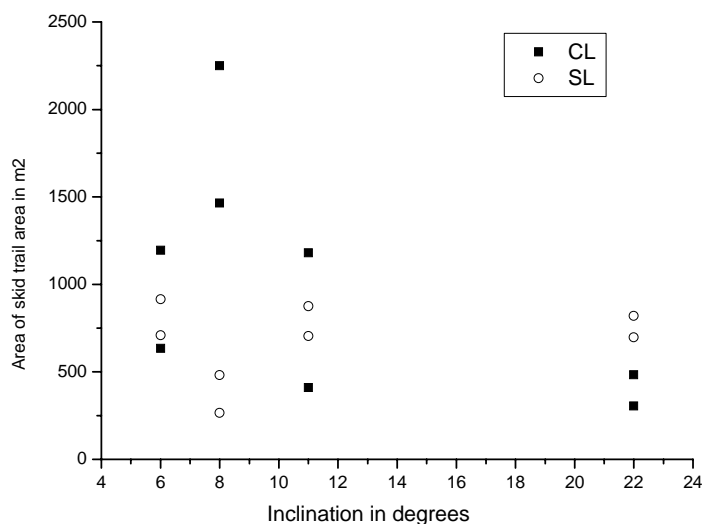

Figure 7. Area of skid trails (m^2 ha^{-1}) plotted against the mean inclination per block in degrees. Conventional logging (CL) and Supervised logging (SL).

When the steepest areas (Block 1, which was much steeper than the other three blocks) were excluded, there was a tendency ($P=0.052$) for the skid trail area to differ between logging methods, since mean disturbance levels were almost twice as high in CL as in SL areas (CL=12 %, SL=6.5 %). This finding indicates that the use of systematically pre-aligned skid trails efficiently reduced soil skidding disturbance when the area was flat. However, the opposite could probably be said for steep areas, in which SL areas seemed to be disturbed more than CL areas (Figure 7).

Whether this approach for aligning skid trails is better or more efficient in terms of soil disturbance than alignment using stocking maps cannot be evaluated without further studies. Intuitively, however, a stocking map alignment may result in a lower disturbed area if the area is lightly stocked. In more densely stocked areas the two methods could give more similar results, or the systematically alignment may even cause less disturbance. Comparing the data obtained in study I with corresponding figures obtained in other studies, the absolute skidding disturbance caused by the SL-system was intermediate. For instance, it fell between the 10% and 20% levels found by Bertault & Sist (1997) and Pinard *et al.* (2000b), respectively, following logging by RIL. However, it may be inappropriate to compare results like this, since initial conditions, *e.g.* stand structure, could differ markedly between sites.

A possible advantage of the systematic alignment is that it should be relatively easy to implement. The logging teams seemed to understand the concept quickly and it was also easily communicated within the team. There was no requirement for stocking maps, which are (as mentioned above), time consuming and costly to prepare (Pinard *et al.* 2000b). In practice, high costs could be an obstacle in implementing new techniques. A systematically aligned skid trail network could also be used several times, *e.g.* at the next harvesting. In such cases no new tracks with added extra soil disturbance would be required. In a system requiring stocking maps, a more or less completely new skid trail network has to be established for every harvesting cycle, probably leading to more soil disturbance in the long term. The greatest disadvantage with the systematic network compared with a stocking map network is probably that erosion-sensitive areas such as small streams and slopes will be disturbed to a greater extent since the system takes such features less into consideration than a stocking map system.

Tree damage and the residual stand

Both logging methods had substantial effects on the forest due, firstly of course, to the absence of felled and extracted trees and, secondly, to damage caused by the felling and extraction. In this study (I) the trees that were dead, seriously damaged (presumably leading to a quick death) or missing (crushed beyond recognition by tractor-crawlers or smashed by felled trees) were all counted as "lost and damaged trees". Trees with minor damage (considered likely to live and grow) were all counted as "healthy and alive trees". In CL plots ca. 38% of the original stems were lost and damaged, representing 21% of the basal area. In SL plots the corresponding figures were 32% and 14%, respectively. On closer examination of the data it was found that the differences were mainly within the smallest and

largest diameter classes (10-29 and > 60 cm dbh, respectively) (Study I). Medium-sized trees had very similar damage levels. The damage level following SL found here is consistent with levels reported in other RIL studies (*cf.* Bertault & Sist 1997, Pinard *et al.* 2000b, Sist *et al.* 2003b).

Evaluating the damage levels among the seedlings and saplings was complicated by difficulties in determining the numbers of seedlings that were damaged and destroyed after logging, since a sporadic or mass fruiting probably occurred close to the logging date. This possible fruiting may explain why increasing numbers of seedlings were found in some plots and blocks, even within the control plots (Study II). However, the fact that 44 % more dipterocarp seedlings were found after CL than after SL (Study II) could be due to the larger skid trail area and larger numbers of logged trees (which presumably led to the formation of more gaps) in CL plots than in SL plots (Study I). The higher rate of recruitment of dipterocarp seedlings in the CL-plots than in the SL-plots is consistent with the results of other studies (*e.g.* Bebber *et al.* 2002, Leakey *et al.* 2003) that have shown dipterocarp seedling growth and survival to be favoured by large gaps and increases in available light. The saplings, which were not affected by any putative fruiting, showed relatively large absolute differences; 50% more saplings (of both all species, and just dipterocarps) being destroyed in CL plots than in SL plots (Study II), however this difference was not statistically significant.

The causes of damage to each tree, seedling and sapling were not analysed in these tudies. Most of the damage probably occurred during either the felling or the extraction, but the relative proportions are not known. It would also have been difficult to identify the causes of damage after the operation. For example, trees were sometimes felled into skid trails during SL and thus caused no felling damage since the tractor had already destroyed all seedlings, saplings and trees along the trails, while the opposite applied in CL, where the trees were felled before the skid trail was constructed. Therefore, the cause of damage sometimes depends on the definition. However, damage such as broken branches or crowns in large and medium-sized residual trees was probably exclusively caused by the actual felling or by surrounding trees being dragged down together with the felled tree.

In a directional felling study, Cedergren (1996) found that eight trees (> 10 cm dbh) were destroyed and 13 were damaged per felled tree. If these figures are relevant, and those destroyed are regarded as being equivalent to trees that were "lost and severely damaged" in our studies, extraction damage could account for ca. 50% of the overall damage, since between 14 and 20 trees were damaged per felled tree (Study I). However, these assumptions must be treated carefully since there were also probably interactive advantages between skid trails and directional felling. The skid trails and the extraction of logs by skidding and winching were probably the main damage factors for the small trees, which also suffered the largest losses in terms of both numbers of trees and basal area (Study I). This conclusion is supported by Sist *et al.* (1998), who found that the main cause of injured trees could be traced to the skidding process. Seedlings and saplings probably also suffered great losses through skidding. However, felled trees and the

falling debris also probably accounted for a substantial part of the damage and mortality observed amongst the small trees as well as the seedlings and saplings.

The lower damage levels associated with SL, in comparison with CL, led to SL-residual stands containing significantly more small (10-29 cm dbh) dipterocarp stems; 16.5 or 44% more stems per ha (Study I). However, this correlation was not found in the subsequent study (Study III), where a different sample was used. In Study III, it was found that the standing dipterocarp basal area of 10-29 cm dbh trees directly after logging was more or less the same, irrespective of the logging method. There was also an indication (not statistically significantly) in Study III that the healthy basal area in the 60-89 cm diameter class was larger after SL than after CL, corresponding with the finding in Study (I) that fewer trees were cut using that logging method.

The residual stands seemed to be fairly similar after logging by these two methods. However, there were several indications that SL may have advantages over CL, such as the lower skid trail disturbance in flat areas and denser dipterocarp populations, from saplings all the way up to the largest canopy trees. In contrast, the higher disturbance level in flat CL areas seemed to create environments that were better suited for dipterocarp regeneration.

Stand development and basal area growth

Mortality

The overall annual basal area mortality rate for both logging methods was ca. 2.8%, equivalent to around 0.7 m^2 $ha^{-1}yr^{-1}$, or 5.5 m^2 $ha^{-1}yr^{-1}$ for the whole eight-year period. The mortality was distributed across the whole range of diameter classes (Study III, Figure 4) and no statistically significant differences were found between treatments in this respect. However, substantial absolute differences were found. The absolute annual dipterocarp basal area mortality rates were 2.8 % for CL and 2.3 % for SL. Dipterocarps with the largest diameters were the most affected by mortality; the largest diameter classes accounting for a third to half of the total dipterocap basal area lost through mortality (Study III, Figure 4). No significant differences were found, but the main difference observed, concerning dipterocarps, was the lack of dead trees in the SL plots within the 60-89 cm dbh range. Dipterocarp mortality after SL was mainly due to the death of a number of large trees (> 90 cm dbh), which were probably not logged because of injuries or diseases such as rot. Excluding trees in this large diameter class, the dipterocarp mortality rate in CL plots was about double the corresponding rate in SL plots.

These findings are in accordance with results reported by Sist & Nguyen-Thé (2002), who found a basal area mortality rate of 2.9 % in the two years following logging in stands that had a high level of damage after a combination of RIL and conventional logging. However, the dipterocarp mortality rate in SL was lower than the 3.0 % found in the same forest (Sist & Nguyen-Thé 2002), although not as low as the rate they found in a forest classified as moderately damaged (1.2%).

Recruitment

The recruitment rates during the eight-year period of new >10 cm dbh trees of all species into the stands showed no statistically significant treatment effects. This finding was also consistent with expectations, since the sapling densities after logging were fairly similar (CL=1195 and SL=1445) and not significantly different (Study II). During the subsequent eight-year period, the basal areas of newly recruited saplings were also similar; approximately 3.4 m^2 ha^{-1} (around 54 new trees $ha^{-1}yr^{-1}$) in CL and 3.1 m^2 ha^{-1} (around 50 new trees $ha^{-1}yr^{-1}$) in SL plots. New dipterocarp basal area was also similar between treatments: 0.25 (CL) and 0.26 (SL) m^2 ha^{-1}, equivalent to ca. 4 – 4.1 new dipterocarps $ha^{-1}yr^{-1}$, respectively.

The recruitment rates were higher than the 130.8 new recruited trees (> 10 cm dbh) per ha found by Sist & Nguyen-Thé (2002) in forests that were highly damaged four years after logging. The overall recruitment rates also seemed to be much higher than in old secondary forests (55 years), where annual recruitment rates of 0.74% have been found (Brearley *et al.* 2004). These differences could be due to the recruitment of pioneer trees ceasing at an earlier phase (Kuusipalo *et al.* 1996). The main non-dipterocarp trees recruited consisted mainly of pioneer trees belonging to the family *Euphorbiaceae* (*Macaranga spp.*). Euphorbiaceous seedlings were probably established directly after logging and then grew to ≥10 cm dbh over the following four years (Study III). During the 4-8 years following logging the basal area of > 10 cm dbh pioneer trees increased at an annual rate of ca. 0.5 m^2 ha^{-1}, equivalent to ca. 60-65 stems $ha^{-1}yr^{-1}$.

Net basal area

Net basal area changes were determined by combining the mortality, recruitment and basal area increment figures. For all species, in the first eight years > 10 cm dbh trees showed fairly similar net basal area increases in the CL plots (4.7 m^2 ha^{-1}) and SL plots (5.0 m^2 ha^{-1}) (Table 2), equivalent to annual net basal area growth rates of 0.59 m^2 $ha^{-1}yr^{-1}$ and 0.63 m^2 $ha^{-1}yr^{-1}$, respectively.

Table 2. *Net basal area growth (m^2 ha^{-1}) after conventional logging (CL) and supervised logging (SL) in each diameter class (DMC) for all species (all sp.) and dipterocarps alone (dip.) over the eight-year study period. DMC 1=10-29 cm DMC 2= 30-44 cm, DMC 3=45-59 cm, DMC 4=60-89 cm, DMC 5 > 90 cm. P-values for logging methods (LM). Bold figures indicate tendencies (0.050>P≥0.100). Figures with an asterisk were influenced by a significant covariate and have a new Least Square Mean value*

DMC	1	2	3	4	5	Σ1-5
CL (all sp.)	3.3	-0.2	0.6*	-0.6*	-0.1*	4.7
SL (all sp.)	4.0	0.2	-0.5*	1.6*	1.2*	5.0
CL (dip.)	-0.5	-0.1	0.5*	-0.3	0.3	-0.1
SL (dip.)	-0.2	0.4	-0.6*	1.4	0.1	1.0
P-values:						
LM all sp.	*0.625*	*0.938*	***0.077***	***0.078***	*0.378**	*0.498*
LM dip.	*0.389*	*0.226*	*0.244**	***0.053***	*0.871*	*0.382*

Considering all species, most of these increases, for both logging methods, appeared within the 10-29 cm dbh class and were due to the abovementioned recruitment of *Euphorbiaceae* trees (mainly *Macaranga spp.*). Amongst the smallest dipterocarp trees (10-29 cm dbh), it was found that the net basal area actually decreased during the period for both logging methods. However, recruitment of new dipterocarp trees occurred after logging by both methods, but the mortality among the small dipterocarps was higher and very few grew into another diameter class. This suggests that small (10-29 cm dbh) dipterocarp trees may struggle in the post-logging environment, while saplings and seedlings more easily adapt to this new environment with, *inter alia*, increased light availability.

Excluding the smallest trees (10-29 cm dbh) and focusing on larger diameter trees, those thicker than 30 cm, the main diameter increases in CL and SL plots occurred within the 45-59 cm and 60-89 cm diameter classes. An interesting observation here was that most of the basal area, in both treatments, was non-dipterocarp in the 45-59 cm class, while dipterocarps accounted for most of the basal area increases in the 60-89 cm diameter class. For the dipterocarps, net basal area growth across the whole diameter range over the eight-year period amounted to ca. 1 m^2 ha^{-1} (0.13 m^2 $ha^{-1}yr^{-1}$) where SL had been practiced and to - 0.1 m^2 ha^{-1} (-0.01 m^2 $ha^{-1}yr^{-1}$) in CL plots. However, although the absolute means differed, no statistically significant differences or tendencies were found between them, due to the high variance.

The declining net basal area of dipterocarps in CL-areas was due to mortality rates being higher than combined growth and recruitment rates, especially within the 30-45 cm, dbh and 60-89 cm dbh classes. Such mortality was not found following SL, where the death of a few large trees (>90 cm dbh) accounted for most of the basal area mortality (Study III). The positive net dipterocarp basal area growth following SL was found to be mainly due to high growth rates of 60-89 cm dbh trees. In addition, several dipterocarp trees changed their diameter class from 45-59 cm dbh to 60-89 cm dbh. The greater growth of 60-89 cm dbh of trees in SL areas was probably due to the lower logging intensity in them, and consequently denser residual stand in that diameter range.

Focusing on the recruitment of trees of the larger diameters (> 45 cm), the absolute values showed that stems of both all species and solely dipterocarps were more numerous following CL than SL during the studied period (Study III). The recruitment rate, in terms of stem numbers (all species), was around 50% higher per ha in CL plots (14.3) than in SL plots (9.4) (not statistically significant). For the recruitment of > 60 cm dbh trees the relation between the logging methods was different, since almost 60% more stems (all species) grew into the ≥ 60 cm dbh class following SL (6.7) compared with CL (4.2). The same pattern was found solely for dipterocarps.

Summarising the data for the eight-year period, SL seemed to favour the growth primarily of ≥ 45 cm dbh dipterocarps. The mortality rates also seemed to differ between the methods, being much higher following CL than after SL, if ≥ 90 cm dbh trees were excluded. Otherwise, no great differences were observed between the methods; both led to reductions in net dipterocarp basal areas within the 10-29

cm dbh class, which could cause problems for the long-term recruitment of dipterocarps into larger classes.

Climber cutting

Cutting climbers a year prior to logging resulted in three more stems being logged per ha (a statistically significant difference), or almost 50% more dipterocarp basal area being harvested, than if no climber cutting was carried out (Study I). The reasons for this might be stochastic, and no other studies have been found that either support or conflict with this finding. However, it might be easier to find, identify and decide what trees you want to cut when climbers have been cut, since the visibility may be better without vines, climbers and leaves covering the tree trunks. Furthermore, no other specific difference in initial impact, such as differences in damage levels or soil disturbance, were found between areas where climbers had and had not been cut in terms of seedling, sapling or tree densities (Studies I and II).

However, during the first eight years following logging some notable differences appeared, primarily that tree growth seemed to be stimulated by climber-cutting. The net basal area growth for all species showed significantly different levels over the studied period, since total net growth per ha amounted to ca. 6.4 m^2 (0.80 m^2 ha$^-$yr^{-1}) in areas where climbers had been cut and to about half of this value (ca. 3.3 m^2, 0.41 m^2 ha^{-1}yr^{-1}) in areas where they had not been cut (Table 3).

Table 3. *Net basal area growth (m^2 ha^{-1}) after logging with pre-felling of climbers (CC) and logging without climber cutting (NCC) for each diameter class (DMC) for all species (all sp.) and dipterocarps alone (dip.) over the eight-year study period. DMC 1=10-29 cm DMC 2= 30-44 cm, DMC 3=45-59 cm, DMC 4=60-89 cm, DMC 5 > 90 cm. P-values for climber cutting methods (CM). Bold figures indicate values with significant differences (P$\leq$0.050) and tendencies (0.050>P$\geq$0.100). Figures with an asterisk were influenced by a significant covariate and have a new Least Square Mean value. ---- indicates interaction effects*

DMC	1	2	3	4	5	Σ1-5
CC (all sp.)	4.8	-0.05	1.2*	0.2*	0.2*	6.4
NCC (all sp.)	2.5	0.1	-0.9*	0.8*	0.8*	3.3
CC (dip.)	-0.1	-0.6	0.5*	0.3	-0.03	-0.01
NCC (dip.)	-0.6	0.9	-0.6*	0.8	0.4	0.9
P-values:						
CM all sp.	*0.237*	*0.832*	***0.005****	***0.075****	*0.820**	***0.011***
CM dip	*0.343*	*----*	*0.170**	*0.624*	*0.750*	*0.428*

For dipterocarps the net basal area increased by 0.91 m^2 ha^{-1} during the eight-year period if no climber cutting was carried out, while the corresponding figures for climber cutting were close to zero (-0.01 m^2 ha^{-1}). However, this difference was not statistically significant.

The main growth (of all species) for both climber cutting methods occurred in 10-29 cm dbh trees and was mainly due to the in-growth of pioneers (*Euphorbiacae*). Net basal growth in the 10-29 cm dbh class was almost twice as high in areas where climbers had been cut than in areas where they had not been cut (although this was not a statistically significant difference). Vines and climbers can have a significant impact on tree growth (Putz 1991) and several authors have reported that removing them can stimulate increases in tree growth (*e.g.* Grauel & Putz 2004 and Schnitzer *et al.* 2004), however the cited studies were not carried out on dipterocarps.

In the present study it was probably more difficult for climbers and vines to take over gaps and skid trails if climbers were removed before logging, as observed in a Bolivian rainforest after climber cutting (Alvira *et al.* 2004). This lack of climber and vine competition probably led to faster regeneration and growth of small trees, especially pioneer species. The lack of climber competition also apparently led to a higher recruitment of dipterocarps, since basal area recruitment of > 10 cm dbh dipterocarp stems was 60% higher in areas where climbers were cut during the eight-year period than in areas where they were not cut. This finding was supported at the tendency level (Study III).

Net basal area growth in the bigger diameter classes was also affected by climber cutting. The net basal area growth of 45-59 cm dbh trees, which included large numbers of non-dipterocarps, was significantly higher if pre-felling of climbers had been carried out (Table 3). In addition, there was a large absolute difference in the numbers of stems recruited into the > 45 cm dbh class between the treatments (CC=17.0; NCC=6.8), supported at the tendency level (Study III). However, net basal area growth within the 60-89 cm dbh diameter class tended to be negatively affected by climber cutting.

Net basal area growth of dipterocarp trees within the 60-89 cm diameter class was almost three times higher in areas where climbers were not cut than in areas where they were cut (Table 3). However, the numbers of dipterocarp stems growing into this class were more or less the same (Study III). This difference is difficult to explain, since mortality rates were higher in this diameter class in plots where climbers were not cut and the in-growth of trees seemed to be similar, irrespective of logging method, suggesting that this difference must have been due to the basal area growth of the trees within this diameter class being higher if climbers were not cut before logging. The finding that more dipterocarp stems were logged if climber cutting was carried out (Table 1) could also have affected these results, since more trees were probably left to grow in areas where climbers were not cut.

32

Long-term effects and rotation cycles

Since the study was relatively short, just eight years, it is of course difficult to predict how the stand will develop in the future. Some tentative predictions can be made, but longer-term time studies are needed and it must be recognised that tropical forests vary widely. The time needed for the forest to develop a structure that is similar to that of the pre-logged primary forest, or suitable for logging again, depends on how such a state is defined, *e.g.* the species composition and tree diameter (cutting limits) criteria that are applied.

Focusing solely on basal area, the forest "recovered" after CL and SL at annual rates of 0.59 m^2 ha^{-1} and 0.63 m^2 ha^{-1}, respectively, during the first eight years. If these basal area growth rates remained constant it would take approximately 20-25 years for the logged stands to reach the basal area they had before logging, depending on the residual stands' conditions. However, these forests would, of course, differ considerably from the pre-logged forests in terms of diameter and species distributions. Brearley *et al.* (2004) found in a secondary forest, logged 55 years before the inventory, that the stand still differed in species composition and that the basal area had only reached 82 % of the likely level in a primary forest. The forests in our experiments had reached 89 % and 92% of the original basal area after CL and SL, respectively, eight years after logging. However, the diameter distribution in relation to basal area had dramatically changed (Figure 8).
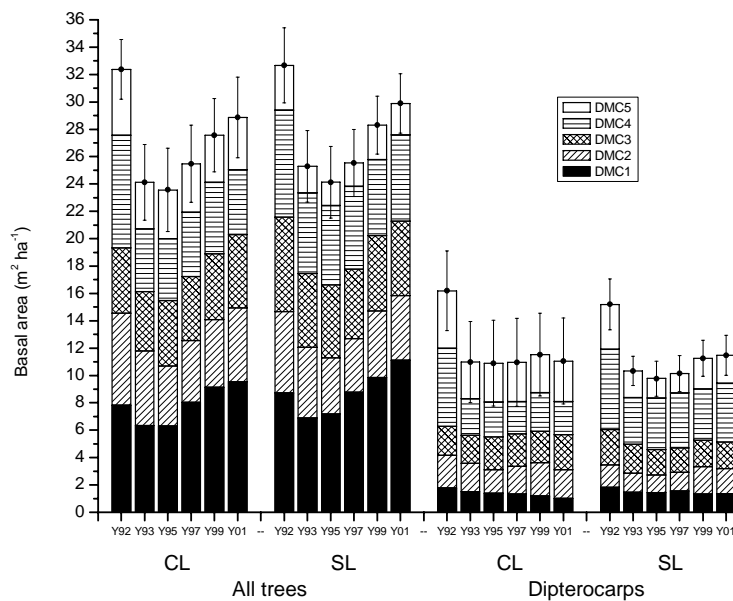
Figure 8. Standing basal area per ha prior to logging (Y92), standing basal area directly after conventional logging (CL) (Y93) and supervised logging (SL) (Y93) and the eight years subsequent development (Y95-Y01) for all trees (all species) and dipterocarps solely. Diameter at breast height class (DMC); DMC 1 = 10-29 cm, DMC 2 = 30-44 cm, DMC 3 = 45-59 cm, DMC 4 = 60-89 cm and DMC 5 $\geq$ 90 cm. Error bars = SE mean for the total standing basal area.

The time required for dipterocarps, to "recover", *i.e.* grow to a basal area equivalent to that of an un-logged or "ready to be logged" forest, would probably be longer after CL than after SL since the dipterocarp basal area seemed to decrease after CL. The standing dipterocarp basal area decreased from 67% immediately after logging to 65% of the original basal area after the first eight years (Figure 8). If the net basal area growth in SL-areas seen in the first eight years continued, the dipterocarp basal area would recover after ca. 40 years. During the first eight years after SL the standing dipterocarp basal area increased from 68% of the original dipterocarp basal area directly after logging to 75% (Figure 8).

Considering the number of tree stems that would grow to commercial dimensions (> 60 cm dbh), if the net in-growth rate of stems in the conventionally logged stand remained constant (0.16 trees per year), 10-15 dipterocarp stems with a dbh exceeding 60 cm would be recruited after ca. 60-95 years, which could be regarded as the normal number of stems cut in primary forests today (Pinard *et al.* 1995). These figures correspond to previously reported growth rates and recommendations for logging cycles for areas with similar quantities of logged trees (Wong 1973, Ong & Kleine 1995, Favrichon & Nguyen-Thé 2001, Huth & Ditzer 2001). For Supervised Logging the corresponding figures are 17-25 years (0.6 dipterocarp trees per year). These figures, which are markedly lower, could be explained (*inter alia*) by the fact that SL probably saved more potential dipterocarp crop stems in the 45-59 cm diameter class, and some crop stems in the 60-89 cm diameter class, which both survived and increased in diameter, similar to responses observed if fewer trees are cut (Sist *et al.* 1998).

However, this SL-recovery time is probably an underestimate and the recovery will probably take much longer. Sist *et al.* (2003c) and van Gardingen *et al.* (2003) recommend cutting cycles of 35-45 years in dipterocarp forests (East Kalimantan), in regimes where at most 8 trees ha^{-1} or around 50-60 m^3 ha^{-1} are cut. Such cycling intervals may be more realistic for this SL system. A 40-year cycle is also more consistent with the net basal area increment of the overall dipterocarp basal area mentioned above.

Data treatment and material weaknesses

There were around 12000 ≥ 10 cm dbh trees in total in the experimental plots, all of which were registered and measured six times. In addition, numerous seedlings and saplings were monitored. The huge dataset collected probably contains several errors, due partly to the involvement of different inventory rangers during the course of the project. We have noted, over the years, cases where the diameter of individual trees has both increased and decreased, the designated species of individual trees has changed, and some trees have "moved" around in the forest, *i.e.* their recorded positions have not been the same in all of the years. This has created a lot of extra work when linking data to individual trees. In order to handle the data within a reasonable timeframe, a sample of sub-plots was selected for calculating growth parameters (as described in *Material and Methods*) in Study III. The overall standing basal area of the stand prior to logging in Study I, which is based on the whole 1-ha plots, was similar to the standing basal area found prior

34

to logging in the sample in Study III (whole plot=32.9 m^2 ha^{-1}; sample=32.5 m^2 ha^{-1}). However, directly after logging the standing basal area based on the sampled sub-plots was higher, for all treatments, compared to the corresponding values for the whole plots. For example, the SL-plots had an overall standing basal area directly after logging based on the whole plot (Study I) of 20.2 m^2 ha^{-1} and of 25.3 m^2 ha^{-1} based on the sample (Study III). Using the sample of sub-plots instead of the whole net-plot has also led to higher confidence intervals, which could make it more difficult to find differences.

Tropical rainforests also vary greatly in terms of parameters such as basal area, and frequencies of both trees and species, both between and within stands. This is a well known problem for tropical rainforest research (*cf.* van Gardingen *et al.* 2003). It probably weakens the results when using statistical methods, like Analysis of Variance as used in the studies underlying this thesis. This problem is very difficult to overcome, and the very large experiments required to smooth out the heterogeneity can seldom be performed due to cost and other constraints.

In this study the net basal area growth, defined as the net result of mortality, recruitment, and diameter growth of living stems, was chosen as the main growth indicator. Including the height of the trees, which could have provided volume estimates, was deemed to be almost impossible since measuring the height of all of the trees would have entailed a huge amount of work. Use of predicted height assumptions was considered, but adding and linking numerous predicted heights to the heterogenic mass of trees would probably not generate better measurements, but instead add further uncertainties to the results.

In a few cases, statistically significant interaction effects between logging methods and blocks and between climber cutting methods and blocks were found, which made the interpretations of the main effect difficult to carry out. These interaction effects were caused by different rankings of the methods in the various blocks.

Conclusions and Recommendations

Use of the systematically aligned skid trail network in combination with directional felling reduced the immediate soil disturbance in flat areas in comparison with conventional logging using an unplanned skid trail network. The personnel involved in the operation believed that all the crop trees that met the cutting criteria were reached and felled, but fewer trees were felled when the Supervised system was applied than when the conventional system was applied, possibly because trees in SL plots were inspected for disease (*e.g.* rot) and damage more thoroughly than trees in CL plots, and more trees in the conventionally logged plots might have been "accidentally" cut in the latter.

In steep areas, the fixed systematically aligned skid trail network led to higher percentages of disturbed soil surface than the conventional network, probably because only the most valuable trees were picked when the conventional system was applied.

In terms of damage to trees and the productive residual stand after logging, supervised logging seemed not to differ substantially from the conventional logging method. However, there were some indications that the supervised logging may have advantages. For example, a greater number of small dipterocarp trees and saplings remained after the supervised logging, and the net basal area growth of dipterocarps was higher and positive following supervised logging, at least during the first eight years. The main explanation for this higher growth was probably that mortality rates were higher after conventional logging. However, more long-term follow studies on these issues must be carried out before definitive recommendations can be made.

Cutting climbers before felling did not reduce the initial damage in this study, indicating that the treatment is probably not necessary for that reason, when logging in forests containing relatively few vines, such as the stands examined here. However, cutting climbers created a better environment for saplings, and small light-demanding trees such as *Macaranga spp.* Recruitment of dipterocarp seedlings also seemed to be higher in areas where climbers were cut. However, mortality rates among large dipterocarps (>45 cm dbh) were probably higher after climber cutting, suggesting that cutting climbers probably stimulated the growth of non-dipterocarps over the whole diameter range while it only stimulated the recruitment of dipterocarps.

A recommendation would be to exclude climber cutting in forests that contain relatively few vines and lianas if the medium-sized trees are to be relied upon to create the next crop.

Further research priorities

Rainforest harvesting in the Malesian region today creates stands where the basal area is concentrated in large numbers of relatively small stems rather than in a few large stems, as these studies show. This creates secondary forests, which seem to be "non-productive" compared with primary forests, in terms of timber harvesting, at least in the short term. This phenomenon is a great disadvantage for logging techniques based on diameter cutting limits. The diameter cutting system and its effectiveness have also been questioned by several researchers (*cf.* Appanah & Weinland 1990, Sist *et al.* 2003a), particularly in terms of logging damage, leading *inter alia* to the development of RIL. However, current RIL-systems focus on large, harvestable stems above a certain diameter limit. Systems or techniques that treat the forest and its productivity more holistically are very rare.

In the early 20th century a selection system for uneven-aged forests was proposed, together with suggestions that it should be tested in the Malayan forests (Arnot & Landon 1937). However, it never seems to have been applied in practice during the whole century, not extensively at least, and proposals that it should be tested were raised again at the end of the century (Cedergren 1996). A selection system for uneven-aged forests, which in French is called "Jardinage" and "Plentersystem" in German, has been tried and implemented in both boreal and temperate areas with varying results (Schutz 1994, Matthews 1997). A dipterocarp rainforest with a well developed inverted J-shape curve, *i.e.* heterogeneous age

and diameter distributions with plenty of seedlings and small trees and only a few large individuals, would, at least theoretically, suit this system perfectly. The general concept underlying the system is that harvests should be based on a predicted volume taken from all diameters, with short intervals, leaving a residual stand with the same diameter distribution as before harvesting. A forest harvesting system like this would be very interesting to test since, if successful, it would create productive, diverse and heterogeneous forests, without long "unproductive" cutting cycles and could therefore be considered valuable for continuity. This perhaps could reduce the likelihood that the forests would be converted for other uses.

The experiment described in this thesis, which is still being inventoried every second year, could be of great help when developing such a harvesting system. The experimental forest holds valuable information about variables such as growth rates for specific species, diameters, recruitment and recovery rates. In addition, the systematically aligned skid trail network used here could be a valuable tool in such a system. Further, the experimental plots could be useful in research concerning the "traditional" diameter limit logging systems, which is of great importance since there are few long-term study plots in the whole region.

It would also be possible to extend the research in these experimental plots to study logging and silvicultural effects on features such as biodiversity. Much is known about overall logging effects, *e.g.* that it causes species richness to decline and fragmentation of the rainforest (*cf.* Putz *et al.* 2000, Meijard *et al.* 2005). However, relatively little is known about direct effects of silvicultural treatments, such as climber cutting practices (Meijard *et al.* 2005). Further research within this area could reduce the adverse effects of logging and improve our understanding of measures that could be applied when logging to reduce its destructive impact on wildlife and biodiversity.

In general, research on the management of rainforests should also be pragmatic in that any proposals it generates should be both effective and applicable in standard practice. New techniques and approaches that are not accepted and implemented at a broad level are useless, however potentially effective they may be. Therefore, tropical rainforestry research, to be successful, also needs to consider the social impact of proposed ideas; how people think, react, behave and feel when dealing with logging and other forestry-related issues.

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43

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