Soil Degradation and Rehabilitation in Humid Tropical Forests (Sabah, Malaysia)

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Doctoral thesis
Swedish University of Agricultural Sciences
Umeå 2002

Acta Universitatis Agriculturae Sueciae
Silvestria 249

ISSN 1401-6230
ISBN 91-576-6333-5

Printed by: SLU, Grafiska Enheten, Umeå, Sweden, 2002

Abstract

Ilstedt, U. 2002. Soil Degradation and Rehabilitation in Humid Tropical Forests (Sabah, Malaysia). Doctor's dissertation. ISSN 1401-6230, ISBN 91-576-6333-5.

Physical degradation of soil, reductions in plant growth, and increases in the frequency of wild fires are common consequences of forest operations in humid tropical forests. However, there is little available information on the interaction of plant growth, soil nutrients and microbial properties, especially in connection with man made rehabilitation of these soils. Therefore, the objectives of the work described in this thesis were as follows. Firstly, to quantify the effect of skid tracks in a forest plantation in Sabah, Malaysia, on the soil's physical, chemical and biological properties. Secondly, to test methods to speed up the rehabilitation of these skid tracks with regard to the soil's physical, chemical and biological properties, as well as plant production. Thirdly, to test and develop assays based on measurements of microbial respiration kinetics for assessing soil degradation and rehabilitation. Fourthly, to assess the effects of fire in a humid tropical Dipterocarp forest on the soil's chemical and microbial properties.

In the study area, where rehabilitation were tested, the growth, soil nutrient content, and soil pore distribution were severely affected by crawler tractors. About 10 days with little rain resulted in water potentials close to the permanent wilting point (-1500 kPa) irrespective of the type of amendments applied, while outside skid tracks the soil dried at a slower rate. Fertilization and tilling of the tracks increased basal area growth of *Acacia mangium* from 1 to 7 m^2 ha^{-1} yr^{-1}, despite high soil bulk densities. Two years after the treatments many soil microbial properties had improved, although they had not returned to the levels observed outside the tracks. Microbial growth kinetics were shown to be promising tools for assessing the effect of soil disturbance and rehabilitation. The recommended water content for measurements of microbial respiration kinetics in Acrisols was -15 to -50 kPa. The effect of fire was either minor or positive on soil nutrient pools (partly due to the extensive leaf shedding that followed it), as measured by chemical methods. In contrast, microbially available N decreased by about 50%.

Key words: Acrisol, Nutrient availability, Pore structure, Rainforest, Reclamation, Restoration, Ultisol

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Appendix

Papers I-IV

This thesis is based on the following papers, which will be referred to in the text by their respective roman numerals:

I. Ilstedt, U., A. Nordgren and A. Malmer. 2000. Optimum soil water for soil respiration before and after amendment with glucose in humid tropical acrisols and a boreal mor layer. *Soil Biology and Biochemistry 32,* 1591-1599. *

II. Ilstedt, U., R. Giesler, A. Nordgren and A. Malmer. 2002. Changes in soil chemical and microbial properties after a wildfire in a tropical rainforest in Sabah, Malaysia. (Submitted Manuscript.)

III. Ilstedt, U., P. Liau, A. Nordgren and A. Malmer. 2002. Tractor Disturbance and Rehabilitation after Logging: Tree Production and Soil Physical Properties in a Tropical Plantation (Sabah, Malaysia) (Manuscript.)

IV. Ilstedt, U., A. Nordgren and A. Malmer. 2002. Tractor Disturbance and Rehabilitation after Logging: Soil Chemical and Microbial Properties in a Tropical Plantation (Sabah, Malaysia). (Manuscript.)

Introduction

Significance of Global Soil Degradation

As long as ten years ago Oldeman (1992) estimated that globally a land area about the size of India (>300 million ha) was so severely degraded that it was unsuitable for local farming ("severely degraded land" being defined as land on which original levels of production could only be achieved through major investments and engineering works). In addition, he estimated that a land area about the size of the USA (>900 million ha) showed serious, human-induced declines in productivity (although according to his definition this land was still usable for local farming). Even if the accuracy of these estimates may be questionable, including the subjectivity of expert judgments (Oldeman, 1992), and the definition of some of the terms, the sheer magnitude of the estimates should be enough to draw attention to the need for soil rehabilitation. For the South and South East Asian regions, soil degradation (including relatively light degradation) affected an estimated 1393 million ha of land. A later report for this region supports these large figures (Van Lynden and Oldeman, 1997). However, methodological differences make more detailed comparison between these studies impossible (Van Lynden and Oldeman, 1997).

Detailed knowledge of the total extent of soil degradation inside 'forest covered' areas is not available. However, in accordance with, for example, the 'Forest Resources Assessment' by the FAO (2001b; 2001c; 2001a) it can be reasonably assumed that there is a connection between degradation of vegetation and soil. Fragmented forest, vegetation promoted by shifting cultivation with short fallows and shrub land all represent vegetation types where there has been soil degradation (see below, in *'Changes in soil after forest operations and fire'*). The "Pan-tropical survey of forest cover changes", which is currently the only consistent, statistically sound survey of forest change processes at pan-tropical and regional levels (FAO, 2001b) (Fig. 1), estimated the total area of fragmented forest, short fallow, and shrub land to comprise 520 million ha. Another estimate of the area of degraded forests and woodland in 'tropical' continents by Grainger (1988) was about 600 million ha. Even though these two estimates use different definitions, they further emphasize the vast extent of degraded areas, and indicate that forested land accounts for a large part of the total affected by degradation. One example showing that successful rehabilitation can be possible, even on severely degraded soil, is the relative success of some reforestation experiments on *Imperata* grasslands in Indonesia, where growth rates up to 20-30 m^3 ha^{-1} yr^{-1} have been recorded (e.g. Otsamo et al., 1995) depending on species, site preparation and fertilization.

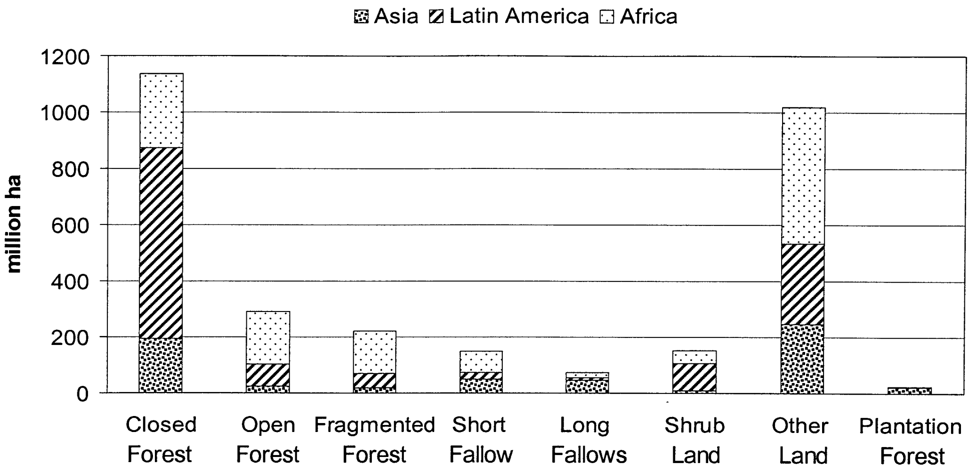


Fig. 1. *The distribution of land classes according to the Pan-tropical survey of changes in forest cover (adapted from FAO, 2001b). "Other land" refers to agricultural and urban land.*

Justification and Framework of the Project

Forests and Forest Research in Sabah

The Malaysian state of Sabah covers a land area of about 7.4 million ha, and according to Sabah Forestry Department (2002) about 4.4 million ha of this is under forest cover. Undisturbed high forest (lowland and highland Dipterocarp forest) presently covers 0.27 million ha (Sabah-Forestry-Department, 2002), which can be compared with the 1975 coverage of 2.8 million ha (Mannan and Awang, 1997). In contrast, the area covered by "immature, disturbed and regenerating forest" increased from 1.4 to 3.0 million ha during this period. In addition, it has been estimated that the area of 'idle land' in Sabah comprises somewhere around 300 000 to 500 000 ha (Kollert and Trockenbrodt, 1997; Abod and Siddiqui, 1999).

Since Sabah has relatively good infrastructure and low levels of bureaucracy compared to most of South East Asia, it hosts several important forest ecosystem studies. Even though it has significant differences from other states in the region, much of the research at these sites is applicable to other parts of the region. The longest standing is the 'Forest Research Centre' in Sepilok, where studies of its forest reserve started more than 40 years ago. Today, the Forest Research Centre studies, amongst other things, aspects of both natural forest and forest plantation management. Another research area, Danum Valley, has been the site of extensive research on the natural forest ecosystem and its management (e.g. Nussbaum et al., 1995; Douglas et al., 1999; Newbery et al., 1999; Walsh and Newbery, 1999; Sterck et al., 2001). Danum was established 1986, and consists of 43 800 ha of uninhabited, mostly lowland forest. Another important project is the 'Malaysian-German sustainable forest management project' in the 55 083 ha Deramakot Forest Reserve, which is researching methods to attain sustainable yield by natural forest management in formerly logged-over forest, as described by (e.g. Kleine and Heuveldop, 1993; Glauner, 2000; Huth and Ditzer, 2001). The Swedish University of Agricultural Sciences is participating in collaborative projects with Sabah Forest Industries Sdn.

Bhd. (SFI) (see *Project Background*, below) and Innoprise Corporation (Cedergren, 1996; Cedergren et al., 1996; Falck and Udarbe, 2001). The cooperation with Innoprise Corporation has involved silvicultural evaluations of stand characteristics after pre-felling climber cutting and directional felling in primary dipterocarp forest. Recently, a project concerning enrichment planting of forest degraded by logging and fire has also been initiated.

The Project Background

The project described in this thesis was carried out in the Sabah Forest Industries Sdn. Bhd. (SFI) plantation concession. The concession consists of 289 000 ha of forest, including 17 990 ha of protected water catchment (SFI, 2002). SFI currently operates a pulp and paper mill as well as an integrated timber complex including a plywood mill and sawmill. The main objectives of forest management here are to provide the SFI mills with 750 000 m^3 yr^{-1} of pulp wood and 339 000 m^3 yr^{-1} of commercial wood. Today, most extracted pulpwood comes from the natural forests, but in the future, the raw materials should come entirely from the SFI plantations. The company started planting in 1985 and the present plantation comprises about 37 000 ha (SFI, 2002) dominated mainly by Acacia (mostly *Acacia mangium*) and Eucalypts (above 800 m.a.s.l). However, on deep fine textured soils in the lowland, *Gmelina arborea* is planted. In 1998, large parts of the plantations were burned, and since then intensive efforts have been made to replant the affected areas. In addition to wood from the concession, villagers close to the concession area have been encouraged to establish smallholder plantations through agroforestry projects (Nykvist, 1993) in which an area of about 1 699 ha has been established (SFI, 2002). These villagers have been selling the wood to SFI since 1992.

Mendolong research area and laboratory, about 35 km east of the pulp and paper mill in Sipitang, have been run under a joint program between SFI and the Department of Forest Ecology at the Swedish University of Agriculture Sciences (1984-2001). The project was started as a paired catchment research project in 1985, and, when the trees were felled at the end of 1997, the whole first rotation of the plantation forest had been continuously monitored in terms of water and nutrient balances. In terms of longevity, accumulated data and results, this study is unique in the tropics (Whitmore, 1996) and provides a good example of fruitful cooperation between industry and the academic world. The sub-project covered by this thesis started in 1997 as a consequence of the external program evaluation by Whitmore (1996), which indicated the need to rehabilitate large areas of skid tracks in Sabah and elsewhere.

Soil Changes after Forest Operations

It is well documented that poor adaptation of logging systems like heavily-mechanised timber extraction on humid tropical soils causes long-term physical soil degradation (e.g., Kararuzaman, 1996; Malmer et al., 1998) and is detrimental to plant growth (e.g., Johansson and Kluge, 1995; Nussbaum et al., 1995; Woodward, 1996; Pinard et al., 2000). For example, in different Dipterocarp forests in Sabah, plant density on skid tracks had still not recovered significantly, three, nine and 18 years after logging operations (Pinard et al., 2000). When these logging systems are unplanned, skid tracks may cover up to 40% of the operation area, both in logged Dipterocarp forest and forest plantations (42%, Fox, 1969; 24%, Malmer and Grip, 1990; 30%, Nussbaum et al., 1995; 17%, Pinard et al., 2000). Planning can substantially reduce the area covered by tracks (Pinard et al., 2000). However, planning, including the use of designated skid tracks, is still not commonly performed.

Although logged-over Dipterocarp forests and forest plantations are different systems, with different management problems, the underlying soil issues on tractor disturbed soil seem to be similar (Kararuzaman, 1996; Malmer et al., 1998). Natural rehabilitation of physical prop-erties is slow, both in secondary forests and forest plantations. Both in plantations and 'logged-over' forest it takes about 20 years for soil organic content and bulk density to reach original values, while macro porosity and soil permeability take about 50 years to recover (Kararuzaman, 1996; Malmer et al., 1998).

Despite the importance and extent of this type of disturbance there have been few reported attempts to accelerate rehabilitation. In Sabah, Malaysia, there was a study, by Nussbaum et al. (1995), which found fertilization significantly improved tree performance on timber landing sites, in contrast to mulching and loosening of soil, which had no effect. In Amazonian Ecuador, Woodward (1996) noted that fertilization, but not topsoil addition, increased plant growth. However, the results of the treatments in these two studies were evaluated after six and nine months respectively, which might have been too short a time to detect the full effects of the treatments (Malmer et al., 1998). Landings are soils of more extreme traffic when it comes to number of machine passes. However, even during the first passes tractors remove the topsoil of Acrisols, and thus expose the subsoil, which tends to already have high bulk-densities (1.2 to 1.5 g cm^{-3}) and lower nutrient contents. Additional passages therefore have little further effect on the soil properties and vegetation (Johansson and Kluge, 1995).

Development of Microbial Respiration Kinetics Assays to Measure Soil Degradation

Our understanding of disturbed systems and their recovery is hampered by our lack of predictive ability when it comes to the interaction between plants, soil biota and soil quality (Syers, 1997). This is especially true regarding our methods to measure phosphorus (Tiessen, 1998), which has been shown by various authors (c.f. Lal, 1997; Tiessen, 1998; Lal, 2000) to be a major limiting nutrient for plant production in the tropics. It is therefore also important that at the same time as we restore plant productivity, we also develop our understanding of the underlying soil properties (Lamb, 1994a). However, in contrast to tree growth and soil physical properties, the effect of skid-tracks on the interaction between soil chemical and biological properties has received little attention, although nutrients could be equally responsible for the poor performance of plant growth as the soil's physical properties (Nussbaum et al., 1995; Woodward, 1996).

Measurements of microbial respiration kinetics after addition of easily available substrate (Nordgren et al., 1988; Marstorp and Witter, 1999) can be used to investigate microbial-nutrient interactions (Nordgren, 1992; Demetz and Insam, 1999). In temperate, N-limited top soils, initial microbial growth after glucose additions is generally exponential, while the peak of microbial growth has been related to different indices of nitrogen availability (Nordgren, 1992). The Acrisols in the project area of this thesis provided an interesting comparison for these temperate systems, since the P-fixation assumed to occur in them could limit the rate of phosphorous uptake, and therefore also the growth kinetics of microorganisms during P-limitation. The underlying assumption was that the microbial measurements and chemical analyses would together provide information on changes in soil quality. This is because microbial respiration analyses give an indication of nutrient resources that are available to the microbes, whereas chemical analyses tend to measure elemental pools without clear relation to their extractability by organisms (Attiwill and Adams, 1993). Furthermore, soil structure (which might be important for P sorption and uptake by plants; (Wang et al., 2001) is much less disturbed by these microbial measurements than by chemical extractions, which destroy soil structure.

It is widely recognized that any study on soil microbial activity must consider the water relations of the microorganisms (e.g., Harris, 1981). Usually, the response of the researcher (e.g. Luizao et al., 1992; Feigel et al., 1995; Johnson et al., 1996) has been to adjust the water content to a specific value, and measure the microbial activity at that water content. However, there has been little attempt to optimize methods or to determine the most suitable water content for studying microbial respiration kinetics. The only available information of this kind relates to Swedish boreal mor layers, for which a gravimetric water content of about 250% gave optimum growth rates after substrate addition in a study by Nordgren et al. (1988). Therefore, preliminary tests were required to determine optimal water adjustment protocols for respiration studies both before and after substrate addition for the tropical Acrisols used in this study.

Effect of Wild Fire on the Soil in a Humid Tropical Forest

It is now recognized that fire has played an important role in shaping natural humid tropical forests (Goldammer, 1997; Whitmore and Burslem, 1998). However, increased population pressures and logging activities have increased the frequency and severity of wildfires (Goldammer, 1997; Nepstad et al., 1999; Siegert et al., 2001), and studies in South-East Asia have shown that changes in vegetation following each consecutive fire increase the likelihood of new fires (Woods, 1989; Siegert *et al.*, 2001). Studies that have considered the effects of fire on soils in the humid tropics have mainly dealt with fire as a tool in shifting cultivation (e.g., Corbet, 1934; Varghese, 1979; Kauffman et al., 1995; Sommer et al., 2000) or forest operation (e.g., Ellis et al., 1982; Sanchez et al., 1983; Romanya et al., 1994; Saharjo, 1999). The characteristics and effects of fire on soil and water differ greatly according to the type of vegetation present (Malmer, in press). However, reports on the effects of the increasing frequency of wild fires in mature or secondary forests are very scarce (Malmer et al., in press).

In 1997 and 1998, extensive wildfires swept over Borneo in connection with the drought caused by the El Niño/Southern Oscillations (ENSO) event of the time (Siegert et al., 2001). Areas affected included most of the Mendolong project areas in Sabah, Malaysia. In a Dipterocarp forest inside this research area, soil was sampled in December 1997 to test the validity of assaying microbial respiration kinetics to determine P and N availability. After the fire burnt the area, it was decided that a repeated sampling would provide a unique possibility to assess changes in the soil caused by drought and wildfire in a dipterocarp forest (lightly logged in 1981) with no previously known fires. Furthermore, this would provide an additional comparison for the development of assays based on microbial respiration kinetics.

Objectives

The studies this thesis are based upon were designed:

1) To determine optimal water contents for assays based on microbial growth kinetics (**Paper I**), and the suitability of such assays for assessing soil degradation and rehabilitation (**Papers II** and **IV**).
2) To assess the effects of wild fire in a humid tropical Dipterocarp forest on soil chemical and microbial properties (**Paper II**).
3) To quantify the effects of skid tracks in a forest plantation in Sabah, Malaysia, on soil physical, chemical and biological properties (**Papers III** and **IV**).
4) To test methods to speed up rehabilitation of these skid tracks with regard to soil physical, chemical and biological properties as well as plant production (**Papers III** and **IV**).

Material and Methods

Conceptual Framework

Concepts like soil degradation, rehabilitation and quality are central to the subject of this thesis. In order to maintain the usefulness of the science, the inherently subjective nature of these terms must be recognized (cf. Sayer et al., 1997). Therefore, the conceptual framework must encompass flexibility towards changing and conflicting values, while maintaining the ability to test hypotheses and to develop relevant theories or models. In this thesis, it is recognized that the value of soil is based upon ecosystem structure (e.g. diversity) and function (biomass and nutrients) (Bradshaw, 1990; Lamb, 1994b) as well as other social goods and services provided by the soil (Sayer et al., 1997). Soil quality is here defined as the potential of a soil to produce goods and services at a certain management input. In this conceptual framework, degradation can be defined as a reduction in soil quality. Consequently, a sustainable system is stable, or has increasing potential. Rehabilitation is here defined as a complete or partial reversal of degradation, while restoration is the re-creation of a defined system, which is assumed, in most cases, to be primary forest. (cf. Bradshaw, 1990; Lamb, 1994b).

Study Areas

Overview

The Mendolong research area (Fig. 2) is situated at an altitude of 650-750 m.a.s.l. in the foothills of Mt. Lumako (1967 m.a.s.l.), 35 km southeast of the coastal city Sipitang (5.0°N, 115.5°E), Sabah, Malaysia (Northern Borneo). The area includes 11 catchments that have been extensively studied with regard to climate, hydrology, nutrient budgets and soil types (e.g., Malmer and Grip, 1990; Nykvist et al., 1994; Malmer, 1996a). In addition to the catchment studies, where soil types have been mapped on a 10 m grid, SFI (2001) has surveyed and mapped large parts of the concession on a 200 m grid (Wong, 1989). These surveys used major soil groupings and units described by (FAO, 1988) and soil families according to Bower (1975). The study site for **Papers I** and **II** is situated within the Mendolong research area, while the study site for **Papers III** and **IV** is situated about 5 km east of the catchments, still in the foothills of Mt. Lumako, but at an altitude of 580-620 m.a.s.l. A general description of the climate, vegetation and soil in the catchment area is given below.

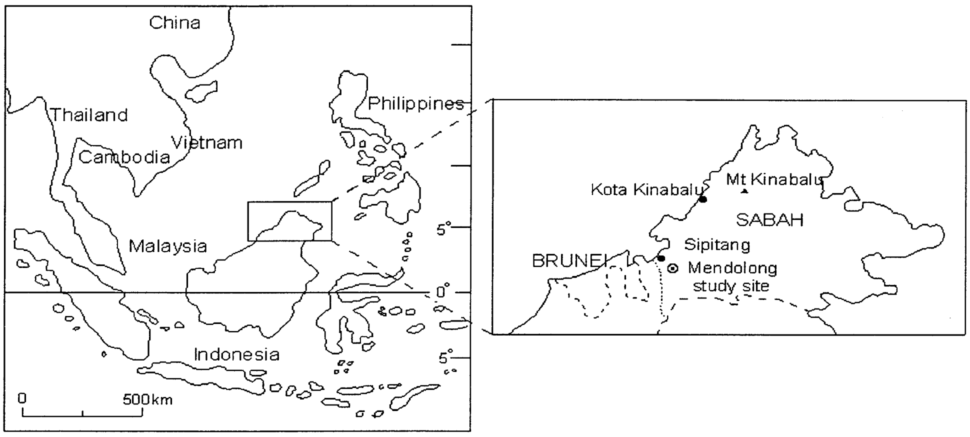


Fig. 2. *Location of the Mendolong research area in Sabah, Malaysia. From Björck (2002), adapted after Malmer (1993).*

Climate

The research area has a humid tropical climate with little seasonal variation in temperature and rainfall (Malmer, 1993). Towards the south-western coast there are maritime and monsoonal influences from the north-east monsoon (December to February) and the south-west monsoon (June to August), but the strength of their influence decreases rapidly with distance from the coast (Wong, 1989). During the transition period between the two monsoons, rain can occur at almost any time of the day, in contrast to the monsoonal periods when rain generally falls only in the afternoon.

There are no government weather stations in or around the concession, except at the coast and far inland. However, in young plantations at 500 m.a.s.l. the monthly minimum temperatures vary only between 20 and 22°C, and maximum temperatures between 27 and 31°C (Malmer, 1993). Before and during the study period the annual precipitation for the research catchments was 3250, 3920, 1840 and 3290 mm in 1995, 1996, 1997 and 1998, respectively (Anders Malmer, pers. com.). The end of 1997 and the beginning of 1998 were unusual in that there were prolonged dry periods, lasting several months, associated with the strong ENSO-event of 1997/98 (Walsh and Newbery, 1999). El niño Southern Oscillations form a multi-year quasi-periodic oscillation in the patterns of atmospheric pressure in the Pacific Ocean (Kellman and Tackaberry, 1997).

Vegetation

The original vegetation in the research catchments was a hill dipterocarp forest (Whitmore, 1984 after Symington, 1943), which was lightly logged in 1981. Sim and Nykvist (1991) published biomass and nutrient inventories of different compartments of the vegetation in two of the research catchments before clear-felling and 18 months after planting of *Acacia mangium*. A brief description of vegetation and biomass follows, for more details see Nykvist (1991).

In the dipterocarp forest the number of trees with a diameter at breast height (dbh) greater than 20 cm was about 145 per ha, and the total above ground biomass was 261 t ha^{-1}. Vegetation other than trees accounted for 4.2 t ha^{-1} of this total above ground biomass. The number of trees with a dbh greater than 60 cm was about 11 per ha. The five most common types of trees were *Koompassia malaccensis* and representatives of the Rubroshorea, Lauraceae, *Richetia* and *Parashorea*, which comprised about 50% of the tree biomass with a dbh greater than 20 cm. Sim and Nykvist (1991) found that the total biomass was in the lower range of studied natural humid tropical forest, and attributed this to the earlier logging operations in the Mendolong area. However, the other forests he used for this comparison were mostly lowland forests. In contrast, the leaf area index (6.7) in Mendolong was comparable to forest with higher biomass.

The biomass of *Acacia mangium* in the planted catchments was lower in the area with a higher degree of disturbance due to harvesting and extraction. Eighteen months after planting, the yearly biomass production was 3.8 t ha^{-1} in the area where slash burning and tractor logging had been performed (W5), compared with 7.4 t ha^{-1} in the area where there had been no slash burning or tractor disturbance (W4). However, ground vegetation biomass was higher in W5 (3.3 t ha^{-1}) compared to W4 (1.8 t ha^{-1}). Furthermore, in an area that had been burned during the great fires in 1983, and later reburned and planted with *Acacia mangium*, tree biomass production amounted to only 2.3 t ha^{-1}, while ground vegetation biomass came to 6.2 t ha^{-1}. The most common species in the ground vegetation were grasses (*Imperata cylindrical* and *Paspalum conjugatum*), *Eupatorium odoratum*, *Melastoma malabathricum* and *Nephrolepis bisenata*.

Soils and Topography
In the SFI concession the most common soil types are Haplic and Gleyic Acrisols, Gleyic Podsols and Dystric Cambisols (Wong, 1989). The bedrock mainly consists of sandstones and siltstones, but interbedded dark shales also occur. The slopes in the study areas are convexo-concave ranging between 15 and 60% (Malmer, 1996b), however most slopes are intermediate in this range.

On the basis of the surveys of the area, Haplic Acrisols (FAO, 1988) (Typic Hapludults; (Soil-Survey-Staff, 1996)) developed on sandstones and shales were chosen for all studies described in this thesis because this soil type dominates in the SFI concession area, as well as large parts of South East Asia. In the topsoil (0-5 cm), textures in the Acrisols ranged from sandy loam to clay loam, porosity was high (up to 70%) and bulk density was 0.83 (standard deviation, SD, 0.09) g cm^{-3} (Malmer and Grip, 1990). The loss-on-ignition (LOI, %w/w) in the topsoil was in the range 5-15% (Malmer et al., 1998). Below this topsoil a 5 to 20 cm deep A/E horizon is generally found with lower organic matter content and bulk densities between 1.0 and 1.2 g cm^{-3} (Malmer and Grip, 1990; Ohta and Syarif, 1996). Below the A/E horizon there is a massive argillic Bt horizon with a lower boundary at about 1 to 2 meters depth. Bulk densities in the Bt horizon are in the range 1.2 to 1.5 g cm^{-3}. These profile characteristics are accompanied by increases in exchangeable aluminum, and reductions in nitrogen and phosphorous availability with depth (Ohta and Syarif, 1996). The crawler tractors used for skidding in the concession area expose the Bt horizon by moving the A/E horizon and parts of the B horizon to the side of the tracks.

Experimental Designs

*Optimizing Water Content for Measuring Microbial Respiration Kinetics **(Paper I)***
Three different samples of Malaysian Acrisol soil were chosen, as well as one Swedish mor layer. The Swedish mor layer was included because this was the only type of soil for which any relevant information was available (Nordgren et al., 1988). The soils spanned a range of organic matter content from 4 to 96% and the soil texture ranged from sandy loam to clay loam (**Paper I**). The soils were first tested for water holding capacity (WHC) and gravimetric water content (Wg). Water filled porosity (%WFP) was subsequently calculated (calculations described in **Paper I**), while water potential (Wp) was measured independently for all replicates of the adjusted soils by the filter paper method (Deka et al., 1995). The range of water filled porosity tested was 10 to 70%, corresponding to a range of 10 to 80% for water holding capacity, 0.2 to 7 g for gravimetric water content, and -2700 to -1 kPa for water potential.

*Effect of Wild Fire on Soil in a Humid Tropical Forest **(Paper II)***
The soil samples were collected from six soil pits, distributed with 15 m between each pit along two 70 m catenas, sloping 5-30° towards a small stream. The first catena was selected randomly within a watershed, close to (but separate from)

catchments used in other studies located in this research area (Malmer, 1996a). The second catena was located at a fixed, predetermined distance of 60 m from the first. The uppermost pits were situated 30 m from the water divide and the lowest pits were about 10 m from the stream. The same randomization of catenas was performed both before and after the fire. For further details about sampling and sample handling see **Paper II**.

*Track Rehabilitation Study (**Papers III** and **IV**)*

In 1988 the original hill dipterocarp forest had been harvested and planted with *Acacia mangium*. This plantation was logged in early 1998 (Fig. 3), and residues were burned as a routine pre-planting practice. In October 1998, 90 experimental plots (10x4m) were laid out on the tracks resulting from skidding in the plantation with crawler tractors (class D6). Furthermore, 10 plots of the same size as those on the tracks were laid out at random positions outside the tracks in order to test if untreated tracks were different from areas outside tracks. Seventy plots on tracks were tilled and amended (singly and in combination) with fertilizer, ash and green organic material (Table 1; for more detailed information about the amendments see **Paper III**). In addition, 10 plots on tracks were tilled, but not otherwise treated (used for evaluation of growth in **Paper III**). All treatments were stratified for two slope positions (convex and concave plot-surface along the track) to account for effects of topography. Out of the total of 100 plots this resulted in five replicates per treatment combination and slope position. The effect of amendments was tested by a four-way fully factorial design (**Papers III** and **IV**), while the effect of tilling was tested by a two-way fully factorial design (**Paper III**). The effect of tracks in comparison to areas outside tracks was tested by a two-way fully factorial design (**Papers III** and **IV**).

For the studied physical soil parameters (**Paper III**) a subset of treatment combinations were used. This was because a full use of all plots would have been impossible within the budgetary and technological constraints of the project. These treatments were untreated tracks, tracks with all combinations of amendments and plots outside tracks. In addition, plots in a nearby area on newly exposed tracks were included.

Table 1. *The amount of nutrients in amendments*

	C	N	P	K	Ca
			(kg ha^{-1})		
Fertilizer[a]	0.0	100	50	450	450
Ash[b]	n.d.	1	5	450	450
Organic[c]	940	26	1.0	24	4.0

a. 0.4, 0.2, 1.8 and 1.8 kg per plot of Urea, Christmas island rock phosphate, K_2O and $CaCO_3$ respectively.
b. 11 kg per plot
c. 25 kg fresh weight per plot

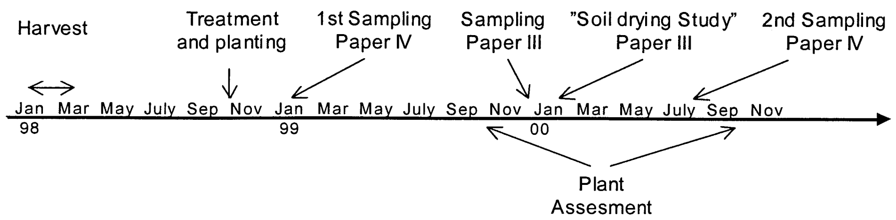


Fig. 3. *Timing of the different treatments and assessments in the skid track study (**Papers III and IV**).*

Assessment Methods

Microbial Respiration Kinetics

In **Papers II** and **IV** microbial respiration kinetics were assessed in the laboratory by hourly measurements of soil respiration over two to three weeks. Both basal respiration (BR) and respiratory rates after addition of glucose plus either nitrogen (N) or phosphorus (P) in excess were measured. The resulting respiration curves (Fig. 4) were assumed to reflect activity of the microbial community under P or N limitation, respectively (Nordgren, 1992). The substrate addition induces an immediate increase in microbial respiration (substrate induced respiration; SIR) related to microbial biomass (Anderson and Domsch, 1978), accompanied with an increase in respiration rate that has been related to microbial growth (Marstorp & Witter, 1999). The respiration rates 12 hours after substrate addition (N_{lim12} and P_{lim12}) were used as measures of the maximum possible rate of respiration, given the N and P in the soil available to the microbial community, respectively. I assume N_{lim12} and P_{lim12} to be limited by the rate of N and P supply (microbial nutrient extraction rate) to the microbial community, respectively (**Papers II** and **IV**). After some time the respiration rate peaks, presumably when either N (glucose and P added) or P (glucose and N added) in the soil sample begins to limit further microbial respiration, thus providing an index of the amount of microbially available N and P (Nordgren, 1992; Demetz and Insam, 1999), hereafter abbreviated as N_{lim} and P_{lim}, respectively. For further details, see **Papers II** and **IV**.

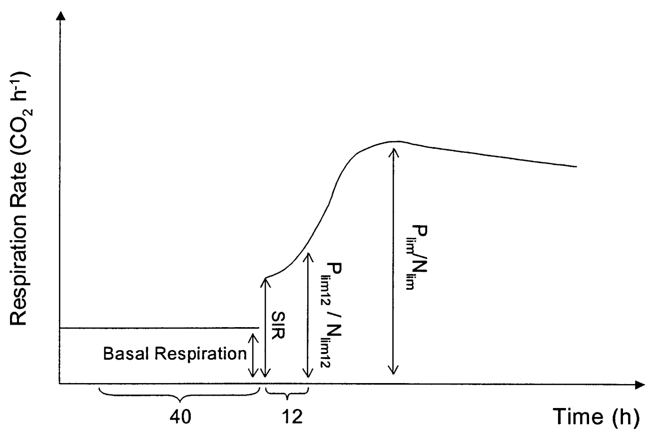


Fig. 4. *Hypothetical example of respiration kinetics with and without calibration. The definitions of basal respiration, substrate induced respiration (SIR), nutrient limited respiration after 12 hours (N_{lim12}/P_{lim12}) and maximum nutrient limited respiration (N_{lim}/P_{lim}) are indicated in the figure (from **Paper II**).*

Soil Nutrients

In **Paper II** traditional chemical methods of measuring soil nutrient levels were compared with microbial growth kinetics assays, before and after a wildfire. For phosphorus, a modified (Binkley et al., 2000) sequential Hedley fractionation procedure (Hedley et al., 1982) was used. In addition, KCl (2.0 M) extractable ammonium and nitrate, as well as total acid digestible carbon and nitrogen were analyzed (for further details, see **Paper II**). In the track rehabilitation study phosphorus was extracted by an anion resin (P-sibbesen) using the Sibbesen method (Sibbesen, 1978). Total acid-digestible phosphorous (P), potassium (K), magnesium (Mg), calcium (Ca) and Kjeldahl N were also analyzed in the track rehabilitation study (for further details, see **Paper IV**).

Soil Physical Properties

Soil water potential was measured at 5 and 15 cm depth with the gypsum block method (Campbell and Gee, 1986) during periods with little rainfall. In this thesis I report on a time sequence of 17 days in January 2000 with little rain. On days 4, 5, 6, 10, 12 and 13 of this 'dry period' 7, 4, 5, 5, 3, and 2 mm of rain was recorded in a rain gauge placed in the center of the skid track research area. The dry period ended when 36 mm of rain fell on the 18^{th} day, which was enough to bring the water potential back to values observed at the start of the dry period. In December 1999, pore-size distribution was assessed by sampling undisturbed soil using soil sampling rings (d=5 cm; h=5 cm) from a depth of 0-5 cm and 10-15 cm. Pore-size distribution was estimated from water retention curves measured by pressure and suction plates (Klute, 1986).

Plant Growth

In the track rehabilitation study (**Papers III** and **IV**), rehabilitation success was assessed by measuring the average height and total basal area (at 1.3 m above the ground) per plot of five *Acacia mangium* seedlings, planted in October-November 1998. *Acacia mangium* was chosen because it of its excellent reputation for good growth and survival on poor and degraded soils (Awang and Taylor, 1993; Otsamo et al., 1997; Eldoma and Awang, 1999; Otsamo and Kurniati, 1999). Furthermore, it is the most commonly used species in the SFI concession (SFI, 2002), and is being planted increasingly often throughout South East Asia (FAO, 2001b).

Height was measured 12 and 24 months after planting while basal area was measured at 24 months. According to routine nursery practices, the seedlings had been raised in seedling trays and were planted three months later (when 25-30 cm tall). In the nursery, 5 g Agroblen (NPK; 10:26:10) per seedling was mixed into the mineral soil used as a potting medium. Agroblen is a fertilizer that is slowly released over about seven months. In the field, planting was carried out only during consecutive rainy days. On untilled tracks a spade was used to dig the planting holes (8 cm in diameter and 10 cm deep). Planted seedlings were inventoried two weeks after planting and dead seedlings were replaced. On each plot, five trees were planted with a spacing of 2 m. Plots were manually weeded using 'parangs' (machetes) at 3-month intervals throughout the full study period. All plots were fenced to avoid human disturbance. Plots outside tracks were planted one month after the plots on the tracks.

Statistics

In **Paper I** regression analysis was used to find the optimum soil water content for microbial respiration and growth. In **Paper II** multiple linear regression was used to test the effect of fire on the different soil variables, and in **Paper III** general linear models were used. Partial least squares projections to latent structures (PLS) were used in **Paper IV** to test the effect of treatments on skid-track rehabilitation. For further details, see the respective papers.

Results and Discussion

Soil Disturbance on Tracks and Effects of Rehabilitation

Soil Drying and Porosity

Outside tracks the soil dried at a slow rate, and remained above -300 kPa during a 17-day period of dry weather that occurred fourteen months after the amendments (**Paper III**). However, even after 8 to 10 days with little rain the water potentials were close to the permanent wilting point (-1500 kPa) on tracks, regardless of whether or not amendments had been applied. At 15 cm depth, drying was delayed, compared to the surface layers, for all treatments. Plots outside tracks had the longest delay and did not start to dry until day 12 (at 15 cm depth). New tracks started to show measurable drying at 15 cm soil depth after five days, while old and treated tracks were intermediate in their drying behaviour. This contradicts the assumption that dry soil does not occur, even on disturbed soil, in humid tropical climates (Basri and Nik Muhamad, 1987). In fact, short dry periods are common (Brunig, 1969; Bailie, 1976; Walsh, 1996; Walsh and Newbery, 1999) and can have a profound effect on soil water content, according to models derived from precipitation and pan-evaporation data (Bailie, 1976). Periods of 30 days with less than 60 and 100 mm of rain occur approximately one and 3-4 times a year, respectively, in Sarawak (Brunig, 1969) which is considered to lie within the most per-humid part of Borneo (Walsh, 1996). In Danum, which is considered to have intermediate drought frequency, compared to both local and global humid tropical forests generally, there were 16 periods with at least 10 consecutive days in which less than 1 mm rain fell between 1986 and 1998 (Walsh and Newbery, 1999). In addition, in the Mendolong research area, 10-day periods without rain occur regularly around July and December (Malmer, 1992). However, in the 17-day period described in **Paper III**, a total of 26 mm of rain fell, but the soil still dried to the wilting point in less than 10 days. Thus, 1 mm or less of rain for a 10-day period appears to be too low for defining the frequency of important dry periods, at least for the growth and survival of seeds and seedlings on skid tracks. Furthermore, 30-day periods as used by Brunig (1969) might be too long, because without the rain, the permanent wilting point would probably have been reached in only 6-8 days at 5 cm soil depth (**Paper III**).

Because it is very difficult to anticipate the onset of these short dry periods, extra caution might be warranted when replanting on degraded soil such as these skid tracks. For example, since the rate of drying was lower at 15 cm soil depth, it could be argued that good contact between the root ball and sufficiently deep soil layers should decrease the probability of desiccation. In practice, this might involve producing plants with large root volumes and taking extra care during planting. However, more thorough studies are needed on seedling performance and planting techniques on this type of heavily disturbed soil before firm conclusions can be made.

The differences in drying behaviour can probably be explained, in large part, by differences in the conductive properties of the soil (**Paper III**), which is governed by the soil pore distribution. However, changes in pore distribution also affect soil as a habitat for soil biota. The main differences between the treatments in total porosity were in the 38 to 1000 μm pore range and in the pores smaller than 3.8 μm. The pores between 38 and 1000 μm are important for fine roots, mites, nematodes and protozoa (**Paper III**) as well as for aeration at field capacity. The percentage of pores larger than 38 μm in the 0-5 cm soil was 16, 14, 10 and 10% for the no track, amended track, old track and new track plots, respectively. These findings indicate that the roots may be in danger of oxygen limitation even in the surface soil. Even small changes in the frequency of air filled pores might be important, and 10% is often considered a threshold, above which air diffusion is significant in the soil (Glinski and Stepniewski, 1985). For pores smaller than 3.8 μm the differences between treatments can probably be explained by the higher amounts of organic material found in the plots outside tracks and in the amended treatments. This pore range is important for bacteria and actinomycetes because they are protected from larger predators in such pores (Brussaard, 1994).

In this context it is also of interest to consider the implications of soil drying for microbial growth and nutrient cycling, by combining information from **Papers I** and **III**. When water content was measured as water holding capacity or gravimetric water content, the more organic-rich soils appeared to sustain a wider range of favourable water potentials, thus allowing high microbial growth over a wider range of water contents. This implies that when soil moisture was fluctuating outside the optimum range of -50 to -15 kPa (**Paper I**), as seen after one or two days on tracks (**Paper III**), microbial growth was limited more often in the organic-poor soils (e.g. skid tracks) than in the organic-rich soils (**Papers I** and **III**). In the field, the times that microbes can work effectively may therefore be more limited on the tracks than outside tracks.

Soil Microbiology and Nutrients

In **Paper IV** it was confirmed that the disturbance (including removal of topsoil) on skid tracks not only affected soil physical and chemical properties, but also severely affected the soil as a habitat for the microbial population. As was initially assumed, the decrease in soil organic content (Malmer et al., 1998) was also reflected in changes in the activity and biomass of the microbial community (affecting

BR and SIR, as well as P- and N-limited growth kinetics; Fig. 5). However, while basal respiration decreased in proportion to the observed 25% decrease in organic content, the other microbial parameters decreased by 44 to 56%. Furthermore, while organic content between the first and the second year, both on tracks and outside tracks, increased by approximately 11 and 14% respectively, changes in the different microbial parameters were more complex (**Paper IV**). Clearly, in this study, the observed changes in total organic content (which is commonly used as a soil quality index), did not give the full picture of changes in soil microbial indices after disturbance.

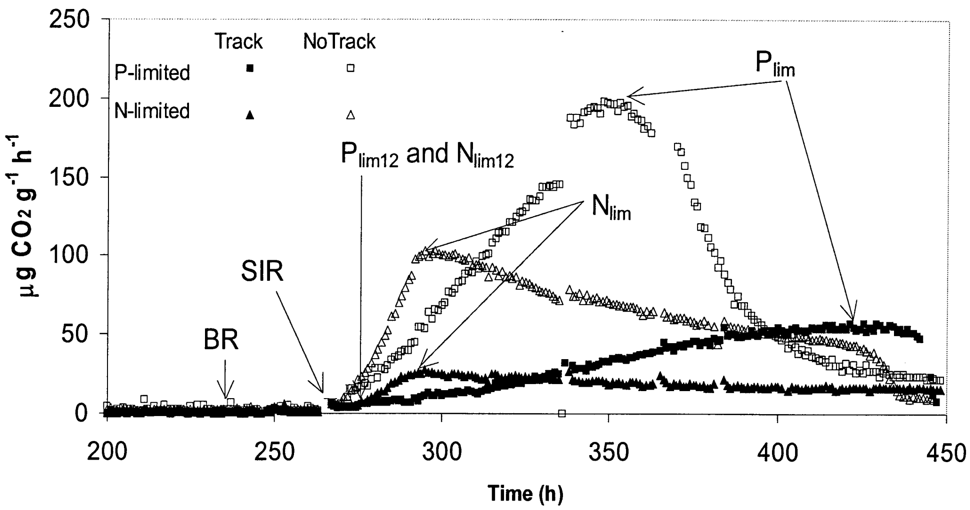
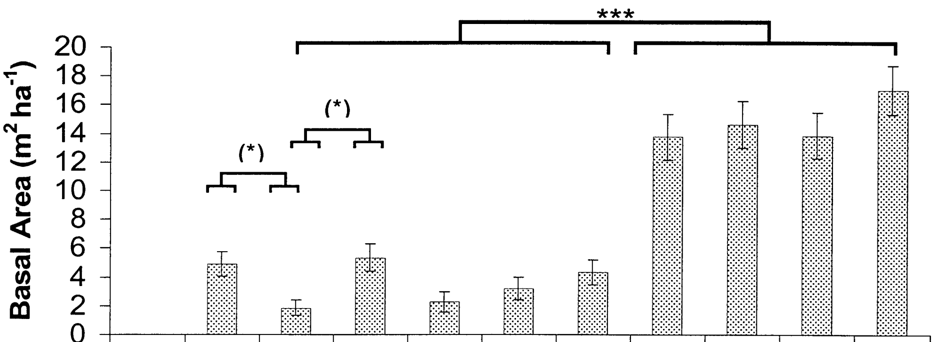


Fig. 5. *Example of microbial growth kinetics with induced N- and P-limitation for two soils sampled on tracks and outside tracks. In the N-limited curve (N_{lim}) glucose and P were added and in the P-limited curve (P_{lim}) glucose and N were added (adapted from* ***Paper IV****).*

The simultaneous decrease in Sibbesen-P concentration and P_{lim12} on the tracks gave an indication that the amount of readily available P and the nature of the bound P were changed. Fertilizer addition increased the microbial biomass (SIR) and the microbial P-extraction rate (P_{lim12}) at the first sampling. In contrast to plant growth, the microbial measures were also influenced by organic matter amendments as well as the topography (concave or convex) of the plot surface. Effects of organic addition were only detected on concave plot surfaces. One possible explanation for this is that the decomposition on the presumably more aerated convex plots may have been so fast that the effect of the added organic material had already diminished by the time of the first sampling (after about three months). In accordance with this reasoning, the effect of organic addition was also diminished on concave plots at the second sampling. As a comparison, in the Mendolong catchments the peak of dissolved nutrients due to decomposing slash and logging debris after clear felling the dipterocarp forest was diminished within a few months (Malmer, 1996a).

Tree Growth

The basal area of *Acacia mangium* 24 months after planting was 62% higher outside tracks compared to on unimproved tracks, while on NPK-fertilized tracks it was 700% higher than on unimproved tracks (Fig. 6). Corresponding changes in average height were 40% and 80% (**Paper III**). In contrast, application of organic material and ash to tracks did not significantly affect tree growth.



Org.	0	0	0	0	1	1	0	1	0	1
Fertil.	0	0	0	0	0	0	1	1	1	1
Ash	0	0	0	1	0	1	0	0	1	1
Tilled	0	0	1	1	1	1	1	1	1	1
Track	0	1	1	1	1	1	1	1	1	1

Fig. 6. *Average basal area and standard error of trees on treated skid-tracks 24 months after planting. Significant differences at the 0.1, 0.05, 0.01 and 0.001 probability levels are indicated by (*), *, **, *** respectively (from **Paper III**).*

There have been few published studies of rehabilitation of tractor-disturbed soil in the humid tropics. However, Nussbaum at al. (1995) and Basri (1987) both studied rehabilitation of landings in Malaysia, and Woodward (1996) studied tracks with less than 5% slopes in Ecuador. Woodward (1996) and Nussbaum et al. (1995) concluded that nutrients were the most limiting factors for tree growth (nine and six months after planting, respectively). The present study shows that this finding also applies to skid-tracks, and over two years, possibly with the reservation that the establishment phase, at least for the present study, occurred outside dry-periods. If there had been a dry period before the seedlings had established sufficiently large root systems, they would probably have wilted (see section on soil drying above). However, there is probably an interaction between the degree of compaction and nutrient uptake by the plants (cf. Greacen and Sands, 1980; Kozlowski, 1999), although this possibility was not addressed experimentally in these studies. Therefore, one should not come to the conclusion that high bulk density is unimportant, but rather that nutrient additions can ameliorate some adverse effects of high bulk density. Notably, tilling without additional treatments made growth levels on tracks similar to those observed on areas outside tracks (Fig. 6).

There have been more studies on the rehabilitation of skid tracks in areas outside the humid tropics. However, the effects of compaction and rehabilitation seem to vary with site factors, e.g. soil texture and climate. For example, on coarse textured glacial till in Ontario, Canada, seedlings performed better on disturbed and compacted soil than on undisturbed soil: a finding that was attributed to improved microclimatic conditions in the former (Fleming et al., 1998). In British Columbia, Canada, a green legume fallow improved Douglas fir height growth by 300% on coastal eroded soil, while growth on landings in the interior was not improved (Carr, 1987). In another study in British Columbia, new methods of skid road decompaction and replacement of topsoil resulted in better growth than older methods, even though site conditions were only partly restored (Dykstra and Curran, 2000). In New Zealand, studies by Berg (1975) and Hall (1999) found that ripping and sub-soiling, combined with fertilization, generally resulted in increased plant performance, but not at all sites.

It should be noted that the soil and climate might not be the only important factors affecting disturbance and rehabilitation: the choice of species and genetic sources may also influence these processes. For example, Woodward (1996) found no consistent response to compaction or treatments among three studied species, while Nussbaum et al. (1995) noted a more consistent performance in two dipterocarp and three pioneer species. For rehabilitation, as for any forest plantation, the choice of planting techniques and the quality of the plant material will also influence the success of seedling performance (Appanah and Weinland, 1996; Nussbaum and Hoe, 1996; Weinland, 1998). Maintenance, in particular weeding, might be one of the most important measures to prevent failures of planting operations (Appanah and Weinland, 1996; Nussbaum and Hoe, 1996; Weinland, 1998), and in SFI plantations weeding and maintenance after planting account for about 50% of the total pre-harvesting costs (Paul Liau, pers. com.). In general, the slower the growth of plants, the longer it takes for the canopy to close, and consequently the longer the period that weeding is needed. However, it was noted in this study that the growth of weeds was also faster outside tracks than on tracks, which was probably the main reason for the lower survival of seedlings outside tracks (68%) than on tracks (93%) during the first year (**Paper III**). The timing of planting and maintenance is also an important factor for the success or failure of forest plantations. In humid tropical climates, failure to plant during the first few weeks after clearing increases the risk of severe loss of nutrients for the crop due to leaching, erosion or uptake by other vegetation (e.g. weeds) (Malmer, 1996a; c).

Even if rehabilitation was shown to be possible, planning the routes and use of skid tracks must still be made a high management priority. This includes measures such as avoiding steep areas, optimising track spacing, minimizing stream crossings and clearly designating the tracks (i.e. mapping and marking them, so the same tracks are used in other operations and in the next rotation). If possible, systems that totally suspend the harvested logs above the ground should be used. For further details the reader can consult various texts, including Sessions and Heinrich (1993), Dykstra and Heinrich (1996) and Sist et al. (1998).

Effect of Wildfire on the Soil in a Dipterocarp Forest

The wildfires involved in this study of a humid tropical dipterocarp forest had mostly positive effects on soil nutrient fertility (**Paper II**). The main reasons for this were the low intensity of the fires, due to the low amount of fuel on the ground, and the shedding of green leaves shortly after them, which contributed to the high amounts of nutrients in the upper layers of the soil. Exceptions to this pattern were the changes in microbially available N contents, which decreased by 50% in the uppermost 10 cm of the mineral soil and KCl-extractable NO_3-N, which increased by 700 to 1000% (representing about 6 kg ha^{-1} down to 10 cm). Wildfires have affected large areas in the humid tropics (Goldammer, 1997; Nepstad et al., 1999; Siegert et al., 2001), and I investigated only one of the many ecosystems affected by them in **Paper II**. Malmer (in press) showed that nutrient leaching after wild fires was minor in lightly disturbed dipterocarp forests compared to plantations and more severely disturbed secondary forests, where there are generally higher loads of fuel on the ground. However, too detailed generalizations should be avoided at this stage because the number of previous fires in the original ecosystem, fuel load and topography (steepness and hydrology) modify the intensity of fires and their effect on the soil. Furthermore, predicting the effects of fires is complicated by variations in factors that can fluctuate markedly at a single site, for example, wind speed and wind direction, the length of drought events and the intensity of the rains after the fires.

Microbial Growth Kinetics as Measures of Soil Quality

Water relations

For the Malaysian Acrisols in **Paper I**, a water potential of approximately -50 to -15 kPa resulted in maximum microbial growth after substrate addition. A similar response was also observed for a Swedish mor-layer, indicating a possibly general relationship. The other water measures were not as successful, because there were different optima for the different soils when water-filled porosity and gravimetric content were used. Water holding capacity had similar optima for the different soils, but the spread of the optima seemed to depend on the organic content (or the maximum water holding capacity) of the soil. Water holding capacity is also very method dependent and should therefore ideally be calibrated with water potential, if used. In **Paper I** it was also suggested that the filter paper method (Al Khafaf and Hanks, 1974; Hamblin, 1981; Deka et al., 1995) for measuring water potential could be used more than at present, especially in countries where expensive equipment is difficult to obtain. It can be used both in the field and the laboratory, while good estimates can be obtained if many replications are used, and the only extra equipment needed is an accurate balance and plastic (zipper) bags.

Nutrient availability

Are microbial growth kinetics directly related to common N- and P-extraction methods, or are there differences in the nutrient status of soils as 'experienced' by the microorganisms? In **Paper II** the absence of correlations between the KCl-extractable inorganic-N pool and microbially available N (N_{lim}) indicated that microorganisms in the study may have utilized sources of N that would not normally be considered readily available to plants. Similarly, the strongest relationship between microbially available P and the different soil P pools was that between microbially available P and NaOH-extractable P. The latter is assumed to consist mainly of surface-bound inorganic P and organically bound P, and has usually been considered to be available to plants only on a long-term scale (Cross and Schlesinger, 1995). The observation that microorganisms can access these nutrients in a matter of days suggests that bacteria and non-symbiotic fungi, at least, do not necessarily use the same nutrient sources as plants.

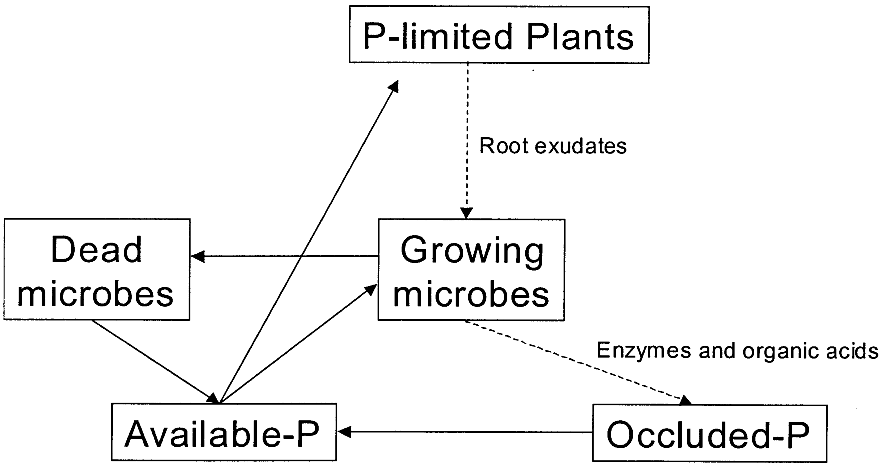


Fig. 7. *A conceptual model of the suggested influence of plant root exudation on microbial community and plant-available phosphorus. Some possible flows of phosphorus (solid lines) and biological controls of phosphorous flows (hatched lines) are indicated.*

The slow and non-exponential increase in respiration seen under P limitation compared to the fast and exponential increase under N limitation indicates that the extraction of P was more restricted and required a higher use of C than did the uptake of N. However, higher growth rates were eventually attained under P limitation than under N limitation. It could therefore be concluded that in the Acrisol bioassays there was more available P than N in total, relative to the needs of the microorganisms, but they required more time and energy to extract the phosphorous. The latter hypothesis seems reasonable if one assumes that most of the P utilized by the microorganisms was either surface-bound or organically bound. Utilization of these sources by the microbes will most likely involve either exudation of organic acids to release surface-bound P or production of phosphatases to hydrolyse organic P compounds. Either process would substantially decrease the C use efficiency with regard to microbial growth.

Plant-derived root exudates collectively comprise one of the largest sources of readily available C for microbes (e.g., Högberg et al., 2001). The microbial growth kinetics observed after additions of easily available carbon in these P-fixing soils (**Papers II** and **IV**) suggest that it may be possible for plants to obtain access to P by releasing carbon exudates into the rhizosphere to stimulate microbial growth. Assuming that only one nutrient can be limiting at any particular time, we can get an idea of the nutrient limitations for microbes that would apply if external energy was added to the soil, but no N or P, by combining the P- and N-limitation curves (Fig. 4). Then, the microbial activity, at each particular time, would follow the lower of the two curves for each soil in Fig. 4. Since the P-limitation curve for these soils was always lower than the N-limitation curve initially, the microbes should first grow at a rate limited by phosphorus. Nitrogen should be limiting only at about the stage when the P- and N-limitation curves cross. Given the pattern of the growth kinetics, one could ask if enough energy (i.e. C) is ever available from litter or exudates for N limitation to occur in natural conditions (other than in extreme microhabitats). If so, it should be possible for plants to obtain access to P by releasing carbon exudates into the rhizosphere to stimulate microbial growth (Fig. 7). For growth, the microbial community would then need to extract P, most of which is unavailable to the plants. If we assume that the P extracted by the microbes becomes directly or indirectly available to the plants, the P availability to plants in P-fixing soils may actually be energy-limited and plant productivity could involve a trade-off in carbon utilization between plant metabolism and increasing P availability. If it is possible for plants to exude so much carbon that N limitation occurs, there may be a further possibility for the plants to access more P by exuding N-rich compounds. From the above discussion, it could be speculated that this may be the reason why the microbial N-extraction rate (N_{lim12}) increased on the severely degraded tracks (**Paper IV**). In such cases, the P-starved plants in highly weathered tropical soils may invest exceptionally large proportions of their photosynthesised C, and symbiotically fixed N, into below-ground root production and exudation.

Future Research Needs

Skid Tracks

The conclusions made about skid track rehabilitation in this thesis were based on measurements taken two years after treatment and planting. These two years represent 'only' 20-25% of a normal rotation period. Therefore, it should be asked whether the noted reductions (both on tracks and outside tracks) in soil bulk density (**Paper III**) and nutrient availability (**Paper IV**) are restored under the production phase of the plantation, or if the rotation length is too short. Other questions related to time are whether the growth rates induced by fertilization will be maintained during the full length of the rotation and if the growth on untreated tracks will be comparable to areas outside tracks in the following generation. These issues could be addressed by sequential sampling in this experiment, or for the last question possibly by comparing growth and soil properties on tracks made in first generation plantations at the beginning of the second generation.

Some of the underlying hypotheses about the effects on soil and plants of the amendments applied to the skid tracks are outlined in Fig. 8. The figure illustrates some important areas that have not yet been considered in our studies or this thesis. For example, the effects of degradation and amendments on the nitrogen fixation of *A. mangium*, and the possibility that inoculation by *Bradyrizobia* (a nitrogen-fixing symbiotic microorganism) could decrease the need for fertilizer, and thus potentially make rehabilitation more profitable. Also, the effects of disturbance and amendments on root structure and mycorrhizae are likely to be important, especially with respect to their distribution with depth, since half of the fine root mass has been found below 50 cm in undisturbed plantation soil (Zetterberg, 2000; Boström, 2001). This might also have implications for carbon sequestration in tropical plantations, since carbon allocation patterns will be affected. The interaction of the soil faunal community with treatments, as well as with soil structure and quality, are other aspects that deserve further attention. It was suggested in **Paper III** that rehabilitation of pore-structure might need the addition of organic matter differing in quality from the material used in the study. This question could potentially be incorporated in a factorial nutrient optimisation experiment. If ash could be included in an optimised nutrient approach, it might also solve a recycling problem.

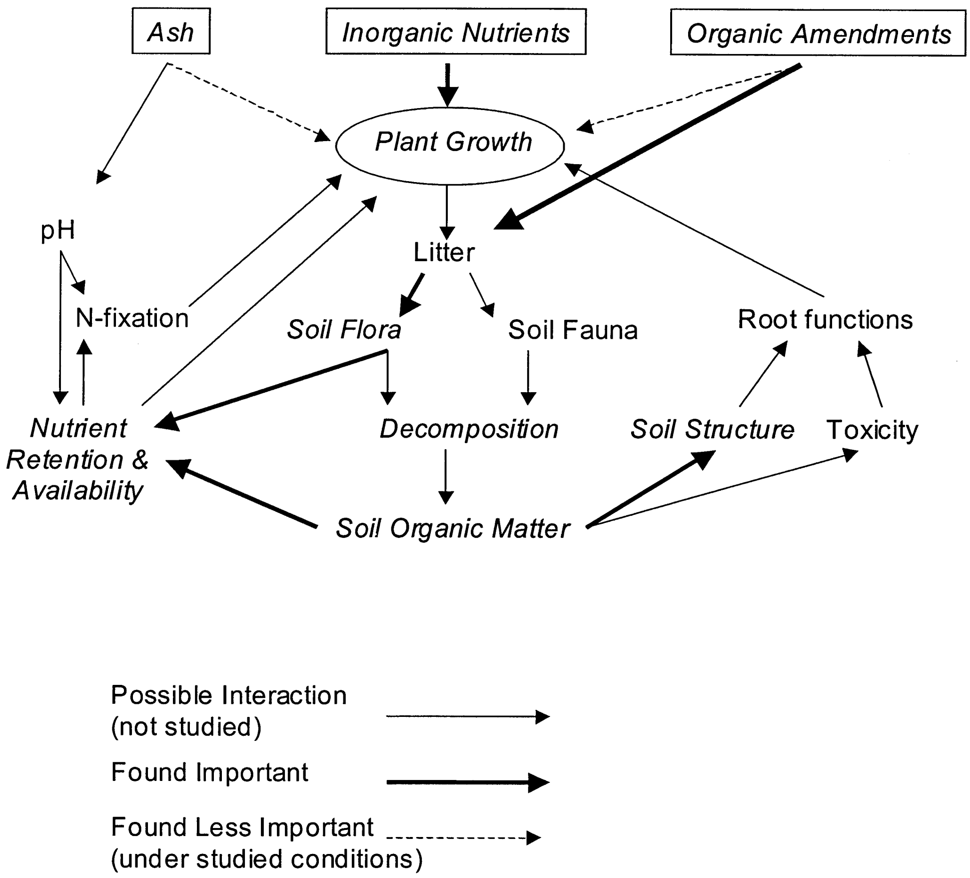


Fig. 8. *Underlying effects and interactions of treatments on soil properties and plant growth in **Papers III** and **IV**. Treatments and soil properties in italics were studied in this thesis.*

Another aspect that was initially intended to be included in this study was the use of indigenous plants in the rehabilitation. Unfortunately, the fire that was a central element of **Paper II** also destroyed the first layout of this experiment, which included identical treatments in logged dipterocarp forest. However, when the first layout burned a year after the treatments, we decided to concentrate our efforts solely on the present layout. Nevertheless, indigenous species deserve more attention, and a possible continuation of the skid track study presented here would be to plant indigenous species underneath the *Acacia*, both on and outside tracks, to test if the combination of species plus the treatments used in the original study would allow soil quality and tree diversity to be fully rehabilitated. Several authors have suggested this approach, but it has rarely been tested (Appanah and Weinland, 1996; Weinland, 1998), and studies on degraded land have been limited to *Imperata* grasslands (Otsamo, 1998b; a; Otsamo and Kurniati, 1999; Otsamo, 2000).

Rehabilitation research often fails to address whether the benefits from the increased production compensates for the investments needed, with the result that the research is not applied in practice. Therefore, a study of the net present value before and after the rehabilitation of skid tracks outlined in **Paper III** was initiated (Ilstedt, manuscript). Results from this study indicate that, for conditions applicable to SFI, the benefits following rehabilitation more than compensated for the increased costs of tilling and fertilization, if tracks covered more than 10% of the area (based on data from **Paper III** and SFI (1991)). Furthermore, without rehabilitation the growth rates in the study area were below zero at all studied interest rates (0-25%). These indications should be followed up, and extended with inventory results from larger areas in the SFI concession and other parts of the region.

Effects of Fire on the Soil

Wildfires have affected large areas in the humid tropics, and **Paper II** investigated only one of the many affected ecosystems (Richards, 1996; Whitmore and Burslem, 1998; Nepstad et al., 1999). Our findings indicate that the effects of wildfire in a 'natural' dipterocarp forest soil are minor, which supports a conclusion reached by many authors (e.g., Woods, 1989; Goldammer, 2000; Malmer et al., in press), namely that not all fires are responsible for increased erosion, oxidation and leaching of soil nutrients. Instead, repeated fires successively lead to these effects through the successive fragmentation of vegetation and the accumulation of fuel. Indeed, the results presented in **Paper II** and recent reviews on vegetation and fire (Goldammer, 1992; Whitmore and Burslem, 1998), suggest that a regime of natural wildfires with long intervals is unlikely to be detrimental to forest regeneration through adverse effects on soil quality. However, in tropical plantations the effect of fire is often more detrimental, (Nykvist et al., 1994; Malmer, 1996a) owing to the generally high loads of fuel on the ground (Malmer, in press). It is therefore often argued for political and social (Dennis, 1999; Eaton and Radojevic, 2001), as well as ecological reasons (Mackensen et al., 1996; Goldammer, 1997; Nepstad et al., 1999), that alternatives to burning are urgently needed for site preparation in tropical plantations. However, as stated by Malmer (in press), the large numbers of people and companies who routinely use fire as part of their land use practices, make a total ban impossible. Instead, the emphasis should be on avoiding repeated burns at short intervals, and on identifying the most sensitive sites. One step towards such a goal could be to initiate research into the management of harvest residues after the first rotation of plantations, with two main aims. Firstly, to identify feasible planting strategies that do not involve fire (the main objective of fire in industrial plantations is often to remove harvest residues), and secondly to ensure that nutrients released from residues are taken up by crop plants, instead of being taken up by weeds or leached away.

Plant-Microbial Interactions

An interesting extension to the 'nutrient limited growth kinetics' studies would be to assess whether the extraction rate of the microorganisms, or the amount of microbially available nutrients, could be related to nutrient uptake by plants and, thus, to plant growth. Correlating microbial growth kinetics to plant uptake or defined P-pools could also be a valuable field of research. More detailed studies of the relation of different parts of the growth kinetics curve to the organic and inorganic Hedley fractions could give insights into the sources microbes use to extract phosphorous. Another interesting field would be to determine the groups of microbes that are responsible for extraction of low solubility P, and what organic compounds and enzymes are used for this purpose. If these microbial groups are highly specialized there might be prospects to use them as indicators of soil quality and possibly also to improve soil quality.

Site Indicators for Economic Plantation Management

The large variation in productivity in tropical plantations, which is coupled both to management and inherent soil fertility (cf. Binkley et al., 1997; Fölster and Khanna, 1997) has also been highlighted in this study. The variation demonstrates a need for accurate and easily determined site indices for predicting wood production as well as responses of the soil to management practices. Management procedures that could be improved by good indicators include site selection, choice of soil preparation technique, fertilizer optimisation and site-species matching. Microbial growth kinetics together with other site variables (e.g. soil depth, rainfall and elevation) might provide such a framework. In the tropics, another under-utilized possibility is to use plant indicators for this purpose. In this regard, a pilot-study in Sabah that successfully predicted site factors from plant species cover and foliar nutrients showed promise (Comstedt, 2001; Björck, 2002). Again, the perfect format for such a study would be a factorial fertilizer trial stratified for important site factors.

Application of the Research to Society

In this thesis, and the studies it was based on, issues connected with soil degradation had to be simplified, as suggested in the proposed conceptual framework. Here, reductions in the value of goods and services (i.e. degradation) were indicated by changes in plant production and in various physical, chemical and microbial soil properties. In reality, the value of goods and services from a management system will be influenced by many more factors, for example; diversity, risk reduction, recreational value, and watershed protection. In turn, each of these factors can be affected by several more or less useful indicator variables. However, many of these variables are likely to be inter-related and can therefore be reduced to fewer components by available multivariate methods such as principal component analysis (PCA). One of the future challenges of soil science and forestry will be, in my opinion, to develop quantitative assessment methods that can be used by social scientists and policymakers to apply multi-dimensional value systems at regional and national scales. The only way to achieve this is by close collaboration between different groups of scientists and the stakeholders to which the model is applied.

Major Conclusions

1) The tree growth, soil pore distribution, soil nutrient content, and microbial properties in the study area were adversely affected by skidding operations with crawler tractors

2) Nutrients were the most limiting factor for growth of *Acacia mangium* on the skid tracks, and despite high bulk densities after rehabilitation, basal area growth was increased 700% by fertilization. Soil physical properties (e.g. bulk density and pore-size distribution) had not improved substantially two years after treatment and planting. However, there were improvements in many soil microbial properties on tracks after two years, even if their values had not returned to levels seen outside the tracks at the time of planting.

3) Microbial growth kinetics were shown to be promising tools for assessing the effects of soil disturbance and soil fertility. Water potentials of -50 to -15 kPa are suitable for laboratory measurements. More effort should be made to make the method quantitative with respect to microbial and plant nutrient uptake.

4) The effect of fire on soil nutrient pools as measured by chemical methods was minor or positive, partly due to extensive leaf shedding after the fire. In contrast, microbially available N decreased by about 50%.

References

Abod, S.A. and M.T. Siddiqui. 1999. Current issues in tropical plantation forestry - A Malaysian perspective. *Indian Forester 125*, 1228-1238.

Al Khafaf, S. and R.J. Hanks. 1974. Evaluation of the filter paper method for estimating soil water potential. *Soil Sci. 117*, 194-199.

Anderson, J.P.E. and K.H. Domsch. 1978. A physiological method for the quantitative measurement of microbial biomass in soils. *Soil Biol. Biochem. 10,* 215-221.

Appanah, S. and G. Weinland. 1996. Experience with planting dipterocarps in Peninsular Malaysia. In *Dipterocarp forest ecosystems: Towards sustainable management* (ed. A. Schulte and D. Schöne), pages 411-445. World Scientific Publishing, Singapore.

Attiwill, P.M. and M.A. Adams. 1993. Tansley Review No. 50: Nutrient cycling in forests. *New Phytol. 124*, 561-582.

Awang, K. and D. Taylor. 1993. Acacia mangium: growing and utilization. In *MPTS monograph series*, pages 280. Winrock International and FAO, Bangkok.

Bailie, I.C. 1976. Further study of drought in Sarawak, East Malaysia. *J. Trop. Geography 43*, 20-29.

Basri, H. and M. Nik Muhamad. 1987. Effects of soil compaction on growth of three-year old Acacia mangium willd. stand in Setul, Negeri Sembilan, Malaysia. *The Malaysian Forester 50*, 250-257.

Berg, P.J. 1975. Development in the establishment of second rotation radiata pine. *New Zealand J. For. Sci. 20*, 272-282.

Binkley, D., A.M. O'Connell and K.V. Sankaran. 1997. Stand development and productivity. In *Management of Soil, Nutrients and Water in Tropical Plantation Forests* (ed. E.K.S. Nambiar and A.G. Brown), pages 219-442. ACIAR, Canberra.

Binkley, D., C. Giardina and M.A. Bashkin. 2000. Soil phosphorus pools and supply under the influence of Eucalyptus saligna and nitrogen-fixing Albizia facaltaria. *For. Ecol. Manag. 128*, 141-147.

Björck, M. 2002. Analysis of foliar nutrients in predicting productivity of Acacia mangium forest plantations in Sabah, Malaysia. MSc Thesis in Soil Science. *Swedish University of Agricultural Sciences, Department of Forest Ecology, Stencilserie No. 81*. Umeå. 41 pages.

Boström, B. 2001. Abundance of roots and mycorrhiza in deep soil horizons under a humid tropical forest plantation. *Swedish University of Agricultural Sciences, International Office, Minor Field Studies No. 136*. Uppsala. 23 pages; MSc Thesis in Soil Science. *Swedish University of Agricultural Sciences, Department of Forest Ecology, Stencilserie No. 61*. Umeå. 23 pages.

Bower, R.P., P.A. Burrough, M.S. Kalsi and P. Thomas. 1975. *The soils of Sabah Volume 4 - South-western districts*. Tolworth Tower, Surbiton, Surrey. Land Resources Division, Ministry of Overseas Development. 96 pages.

Bradshaw, A.D. 1990. The reclamation of derelict land and the ecology of ecosystems. In *Restoration ecology: A synthetic approach to ecological research* (ed. W.R. Jordan, E. Gilpin and J.D. Aber), pages 53-74. Cambridge University Press, Cambridge.

Brunig, E.F. 1969. On the seasonality of droughts in the lowlands of Sarawak (Borneo). *Erdkunde 23*, 127-133.

Brussaard, L. 1994. Interrelationships between biological activities, soil properties and soil management. In *Soil resilience and sustainable land use* (ed. D.J. Greenland and I. Szabolcs), pages 309-329. CAB International, Wallingford.

Campbell, G.S. and G.W. Gee. 1986. Water potential: miscellaneous methods. In *Methods of soil analysis: part 1-physical and mineralogical methods* (ed. A. Klute), pages 619-633. SSSA, Wisconsin.

Carr, W.W. 1987. *Restoring productivity on degraded forest soils: two case studies*. Canadian Forest Service and the British Columbia Ministry of Forests and Lands. 21 pages.

Cedergren, J. 1996. *A silvicultural evaluation of stand characteristics, pre-felling climber cutting and directional felling in a primary dipterocarp forest in Sabah, Malaysia*. PhD Thesis. Swedish University of Agricultural Sciences, Department of Silviculture. 37 pages.

Cedergren, J., J. Falck, A. Garcia, F. Goh, M. Hagner and D.P. Dykstra. 1996. Impact of selective logging on silvicultural values in a mixed dipterocarp forest in Sabah, Malaysia. In *Forest operations for sustainable forestry in the tropics. Proceedings of a Symposium organised by IUFRO Subject Group S3.05 00, "Forest Operations in the Tropics" at the XX IUFRO World Congress, 6-12 August 1995, Tampere, Finland. 1996, 39 45*. IUFRO (International Union of Forestry Research Organizations) Secretariat, Wien, Austria.

Comstedt, D. 2001. The use of foliar analysis in Acacia mangium as a complementary tool for evaluation of productivity trails. MSc Thesis in Soil Science. *Swedish University of Agricultural Sciences, Department of Forest Ecology, Stencilserie No. 69*. Umeå. 30 pages.

Corbet, A.S. 1934. Studies on tropical soil microbiology II. The bacterial numbers in soil of the Malay Peninsula. *Soil Sci. 38*, 407-416.

Cross, A.F. and W.H. Schlesinger. 1995. A literature review and evaluation of the Hedley fractionation: Applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. *Geoderma 64*, 197-214.

Deka, R.N., M. Wairiu, P.W. Mtakwas, C.E. Mullins, E.M. Veenendaal and J. Townend. 1995. Use and accuracy of the filter-paper technique for measurement of soil matric potential. *Europ. J. Soil Sci. 46*, 233-238.

Demetz, M. and H. Insam. 1999. Phosphorus availability in a forest soil determined with respiratory assay compared to chemical methods. *Geoderma 89*, 259-271.

Dennis, R. 1999. *A Review of fire projects in Indonesia (1982-1998)*. CIFOR, Bogor. 105 pages.

Douglas, I., K. Bidin, G. Balamurugan, N.A. Chappell, R.P.D. Walsh, T. Greer and W. Sinun. 1999. The role of extreme events in the impacts of selective tropical forestry on erosion during harvesting and recovery phases at Danum Valley, Sabah. *Phil. Trans. R. Soc. Lond B 354*, 1749-1761.

Dykstra, D. and R. Heinrich. 1996. FAO model code of forest harvesting practice. FAO, Rome. 85 pages.

Dykstra, P.R. and M.P. Curran. 2000. Tree growth on rehabilitated skid roads in southeast British Columbia. *For. Ecol. Manag. 133*, 145-156.

Eaton, P. and M. Radojevic. 2001. *Forest fires and regional haze in South-east Asia*. Nova Science Publishers Inc., New York.

Eldoma, A. and K. Awang. 1999. Site adaptability of *Acacia mangium*, *Acacia auriculiformis*, *Acacia crassicarpa* and *Acacia aulacocarpa*. *APAFRI publication series no. 3*. APAFRI, Kuala Lumpur, Malaysia. 72 pages.

Ellis, R.C., R.K. Lowry and S.K. Davies. 1982. The effect of regeneration burning upon the nutrient status of soil in two forest types in southern Tasmania. *Plant Soil 65*, 171-186.

Falck, J. and T.S. Udarbe. 2001. Selective logging in the tropical rain forest of Sabah, Malaysia. *Currents 25/26*, 41-46. Uppsala.

FAO. 1988. *FAO-Unesco soil map of the world. Revised legend.* FAO, Rome. 119 pages.

FAO. 2001a. *Global forest fire assessment 1990-2000.* FAO, Rome. 495 pages.

FAO. 2001b. *Global forest resources assessment 2000 - Main report.* FAO, Rome. 119 pages.

FAO. 2001c. *State of the world's forests 2001.* FAO, Rome. 181 pages.

Feigel, B.J., G.P. Sparling, D.J. Ross and C.C. Cerri. 1995. Soil microbial biomass in Amazonian soils: evaluation of methods and estimates of pool sizes. *Soil Biol. Biochem. 27*, 1467-1472.

Fleming, R., N. Foster, J. Jeglum and P. Hazlet. 1998. Soil compaction and sustainable productivity on coarse-textured jack pine sites. In *Developing Systems for Integrating Bioenergy into Environmentally Sustainable Forestry. Proc. of the International Energy Agency Bioenergy Agreement Task 18 "Conventional Forestry Systems for Bioenergy"* (ed. A.T. Lowe and C.T. Smith), pages 72-81. Nokia, Finland. New Zealand For. Res. Instit.

Fölster, H. and P.K. Khanna. 1997. Dynamics of nutrient supply in Plantation soils. In *Management of Soil, Nutrients and Water in Tropical Plantation Forests* (ed. E.K.S. Nambiar and A.G. Brown), pages 339-378. ACIAR, Canberra.

Fox, J. 1969. Soil damage factor in present day logging in Sabah. *Sabah Soc. J. 5*, 43-52.

Glauner, R. 2000. The role of soil-and-site science in management planning in managed natural forests: an example from Sabah, Malaysia. PhD Thesis. *Mitteilungen der Bundes-forschungsanstalt für Forst und Holzwirtschaft.* Hamburg. 313 pages.

Glinski, J. and W. Stepniewski. 1985. Soil airation and its role for plants. CRC Press, Boca Raton. 229 pages.

Goldammer, J.G. 1992. Tropical forests in transition: Ecology of natural and anthropogenic disturbance processes - An introduction. In *Tropical forests in transition: Ecology of natural and anthropogenic disturbance processes* (ed. J.G. Goldammer), pages 1-16. Birkhäuser Verlag, Basel.

Goldammer, J.G. 1997. Overview of fire and smoke management issues and options in tropical vegetation. In *Transboundary Pollution and Sustainability of Tropical Forests: Towards Wise Forest Fire Management* (ed. H.A. Hassan, D. Taha, M.P. Dahalan and A. Mahmud), pages 189-217. ASEAN Institute for Forest Management, Ampang Press. Kuala Lumpur.

Goldammer, J.G. 2000. The fire and smoke episodes of 1983 to 1998 in Southeast Asia: Ecological background, socio-economic and environmental implications and challenges for regional and global fire research programes. In *Forest and Society, the Role of Research, Sub-plenary Sessions, Volume 1, XXI IUFRO World Congress* (ed. B. Krishnapillay, E. Soepadmo, N.L. Arshad, A.H.H. Wong, S. Appanah, S.W. Chik, N. Manokaran, H.L. Tong, and K.K. Choon), pages 15-24. IUFRO, Kuala Lumpur, Malaysia.

Grainger, A. 1988. Estimating areas of degraded tropical lands requiring replenishment of forest cover. *Int. Tree Crops J. 5*, 31-61.

Greacen, E.L. and R. Sands. 1980. Compaction of forest soils. A review. *Australian J. Soil Res. 18*, 163-89.

Hall, P. 1999. *Rehabilitation of logging extraction tracks.* New Zealand Logging Industry Research Organisation. 8 pages.

Hamblin, A.P. 1981. Filter-paper method for routine measurement of field water potential. *J. Hydrol. 53*, 355-360. Amsterdam.

Harris, R.F. 1981. Effect of water potential on microbial growth and activity. In *Water Potential Relations in Soil Microbiology* (ed. J.F. Parr, W.R. Gardner and L.F. Elliot), pages 23-95. Soil Sci. Soc. Am., Spec. Publ. No. 9, Madison.

Hedley, M.J., J.W.B. Stewart and B.S. Chauhan. 1982. Changes in inorganic and organic phosphorus fractions induced by cultivation practices and laboratory incubations. *Soil Sci. Soc. Am. J. 46*, 970-976.

Högberg, P., A. Nordgren, N. Buchmann, A.F.S. Taylor, A. Ekblad, M.N. Högberg, G. Nyberg, M. Ottosson Löfvenius and D.J. Read. 2001. Large-scale forest girdling shows that current photosynthesis drives soil respiration. *Nature 411*, 789-792.

Huth, A. and T. Ditzer. 2001. Long-term impacts of logging in a tropical rain forest - a simulation study. *For. Ecol. Manag. 142*, 33-51.

Ilstedt, U. Economic value of skid-track rehabilitation in Sabah, Malaysia. Manuscript for the conference: Bringing Back the Forests - Policies and Practices for Degraded Lands and Forests. Kuala Lumpur. 2002. (Manuscript.)

Johansson, E. and M. Kluge. 1995. Natural rehabilitation of tractor disturbed soils in tropical rain forest in Sabah, Malaysia. In *Working Paper Swedish University of Agricultural Sciences, International Rural Development Centre. 1995, No. 285, 36 pp.* Swedish University of Agricultural Sciences, International Rural Development Centre. Uppsala.

Johnson, C.K., M.F. Vigil, K.G. Doxtader and W.E. Beard. 1996. Measuring bacterial and fungal substrate-induced respiration in dry soils. *Soil Biol. Biochem. 28*, 427-432.

Kararuzaman, J. 1996. Estimation of rate of recovery of disturbed soils from ground-based logging in Peninsular Malaysia. *J. Trop. For. Sci. 9*, 88-100.

Kauffman, J.B., D.L. Cummings and D.E. Ward. 1995. Fire in the Brazilian Amazon 1. Biomass, nutrient pools and losses in slashed primary forests. *Oecologia 104*, 397-408.

Kellman, M. and R. Tackaberry. 1997. *Tropical environments: the functioning and management of tropical ecosystems.* Routledge, London. 380 pages.

Kleine, M. and J. Heuveldop. 1993. A management planning concept for sustained yield of tropical forests in Sabah, Malaysia. *For. Ecol. Manag. 61*, 277-297.

Klute, A. 1986. Water retention: Laboratory methods. In *Methods of soil analysis: part 1- physical and mineralogical methods* (ed. A. Klute), pages 635-662. SSSA, Wisconsin.

Kollert, W. and M. Trockenbrodt. 1997. Natural forests versus plantation: The conversion issue in Sabah. In *Trends and Challenges in Tropical Ecosystems: Forest Conversion* (ed. M. Trockenbrodt and M. Mohamad), pages 27-35. Forestry Department Sabah and University Malaysia Sabah, Sandakan, Sabah, Malaysia.

Kozlowski, T.T. 1999. Soil compaction and growth of woody plants. *Scand. J. For. Res. 14*, 596-619.

Lal, R. 1997. Soils of the Tropics and Their Management for Plantation Forestry. In *Management of Soil, Nutrients and Water in Tropical Plantation Forests* (ed. E.K.S. Nambiar and A.G. Brown), pages 571. ACIAR, Canberra.

Lal, R. 2000. Soil management in the developing countries. *Soil Sci. 165*, 57-72.

Lamb, D. 1994a. Forest rehabilitation in the Asia-Pacific region: Past lessons and present uncertainties. *J. Trop. For. Sci. 7*, 157-170.

Lamb, D. 1994b. Reforestation of degraded tropical forest lands in the Asia-Pacific region. *J. Trop. For. Sci. 7*, 1-7.

Luizao, R.C.C., T.A. Bonde and T. Rosswall. 1992. Seasonal variation of soil microbial biomass: The effects of clearfelling a tropical rainforest and establishment of pasture in the central Amazon. *Soil Biol. Biochem. 24*, 805-813.

Mackensen, J., D. Holscher, R. Klinge and H. Folster. 1996. Nutrient transfer to the atmosphere by burning of debris in eastern Amazonia. *For. Ecol. Manag. 86*, 121-128.

Malmer, A. and H. Grip. 1990. Soil disturbance and loss of infiltrability caused by mechanized and manual extraction of tropical rainforest in Sabah, Malaysia. *For. Ecol. Manag. 38*, 1-12.

Malmer, A. 1992. Water-yield changes after clear-felling tropical rainforest and establishment of forest plantation in Sabah, Malaysia. *J. Hydrol. 134*, 77-94.

Malmer, A. 1993. *Dynamics of hydrology and nutrient losses as response to establishment of forest plantation. A case study on tropical rainforest land in Sabah, Malaysia.* PhD Thesis. Swedish University of Agricultural Sciences, Department of Forest Ecology. Umeå. 54 pages.

Malmer, A. 1996a. Hydrological effects and nutrient losses of forest plantation establishment on tropical rainforest land in Sabah, Malaysia. *J. Hydrol. 174*, 129-148.

Malmer, A. 1996b. Observations on slope processes in a tropical rainforest environment before and after forest plantation establishment. In *Advances in Hillslope Processes* (ed. M.G. Anderson and S.M. Brooks), pages 961-973. John Wiley & Sons Ltd.

Malmer, A. 1996c. Phosphorus loading to tropical rain forest streams after clear-felling and burning in Sabah, Malaysia. *Water Resour. Res. 32*, 2213-2220.

Malmer, A., E. Johansson and M. Kluge. 1998. Natural rehabilitation of disturbed tropical rainforest soils in Sabah, Malaysia. In *Soils of tropical forest ecosystems: Characteristics, ecology and management* (ed. A. Schulte and D. Ruhiyat), pages 199-204. Springer-Verlag, New-York.

Malmer, A. 2002. Stream water quality as effected by wild fires in natural and man made vegetation in Malaysian Borneo. *Hydrol. Proc.* (In press.)

Malmer, A., M. Van Noordwijk and L.A. Bruijnzeel. 2003. Forest-water-people in the humid tropics: Effects of shifting cultivation and forest fire. In *Forest-water-people in the humid tropics: Past present and future hydrological research for integrated land and water management. Proceedings of an UNESCO-IHP symposium and workshop* (ed. M. Bonell, L.A. Bruijnzeel and C. Kirby). Cambrige University Press, Kuala Lumpur. (In press.)

Mannan, S. and Y. Awang. 1997. *Sustainable forest management in Sabah.* Sabah Forestry Department, Kota Kinabalu. 23 pages. (http://www.deramakot.com/English/PDFs/SFMinSabahSeminarPaper.pdf)

Marstorp, H. and E. Witter. 1999. Extractable dsDNA and product formation as measures of microbial growth in soil upon substrate addition. *Soil Biol. Biochem. 31*, 1443-1453.

Nepstad, D.C., A. Verissimo, A. Alencar, C. Nobre, E. Lima, P. Lefebvre, P. Schlesinger, C. Potter, P. Moutinho, E. Mendoza, M. Cochrane and V. Brooks. 1999. Large-scale impoverishment of Amazonian forests by logging and fire. *Nature 398*, 505-508.

Newbery, D.M., D.N. Kennedy, G.H. Petol, L. Madani and C.E. Ridsdale. 1999. Primary forest dynamics in lowland dipterocarp forest at Danum Valley, Sabah, Malaysia, and the role of the understorey. *Phil. Trans. R. Soc. Lond B 352*, 1763-1782.

Nordgren, A., E. Bååth and B. Söderström. 1988. Evaluation of soil respiration characteristics to assess heavy metal effects on soil microorganisms using glutamic acid as a substrate. *Soil Biol. Biochem. 20*, 949-954.

Nordgren, A. 1992. A method for determining microbially available N and P in an organic soil. *Biol. Fert. Soils 13*, 195-199.

Nussbaum, R., J. Anderson and T. Spencer. 1995. Factors limiting the growth of indigenous tree seedlings planted on degraded rain-forest soils in Sabah, Malaysia. *For. Ecol. Manag. 74*, 149-159.

Nussbaum, R. and A.L. Hoe. 1996. Rehabilitation of degraded sites in logged-over forest using dipterocarps. In *Dipterocarp forest ecosystems: Towards sustainable management* (ed. A. Schulte and D. Schöne), pages 446-463. World Scientific Publishing, Singapore.
Nykvist, N. 1993. An even better compromise! An interesting agroforestry system used by Sabah Forest Industries in Malaysia. In *Forest, Trees and People Newsletter No. 20.* 15 pages.
Nykvist, N., H. Grip, B.L. Sim, A. Malmer and F.K. Wong. 1994. Nutrient losses in forest plantations in Sabah, Malaysia. *Ambio 23*, 210-215.
Ohta, S. and E. Syarif. 1996. Soils under dipterocarp forests - characteristics and classification. In *Dipterocarp forest ecosystems: Towards sustainable management* (ed. A. Schulte and D. Schöne), pages 29-51. World Scientific Publishing, Singapore.
Oldeman, L.R. 1992. The global extent of soil degradation. In *Soil resilience and sustainable land use* (ed. D.J. Greenland and I. Szabolcs), pages 99-119. CAB international, Wallingford.
Otsamo, A., G. Adjers, T.S. Hadi, J. Kuusipalo, K. Tuomela and R. Vuokko. 1995. Effect of Site Preparation and Initial Fertilization on the Establishment and Growth of 4 Plantation Tree Species Used in Reforestation of Imperata-Cylindrica (L) Beauv Dominated Grasslands. *For. Ecol. Manag. 73*, 271-277.
Otsamo, A., G. Adjers, T.S. Hadi, J. Kuusipalo and R. Vuokko. 1997. Evaluation of reforestation potential of 83 tree species planted on Imperata cylindrica dominated grassland - A case study from South Kalimantan, Indonesia. *New For. 14*, 127-143.
Otsamo, R. 1998a. Effect of nurse tree species on early growth of Anisoptera marginata Korth. (Dipterocarpaceae) on an Imperata cylindrica (L.) Beauv. grassland site in South Kalimantan, Indonesia. *For. Ecol. Manag. 105*, 303-311.
Otsamo, R. 1998b. Removal of Acacia mangium overstorey increased growth of underplanted Anisoptera marginata (Dipterocarpaceae) on an Imperata cylindrica grassland site in South Kalimantan, Indonesia. *New For. 16*, 71-80.
Otsamo, R. and L. Kurniati. 1999. Early performance of ten timber species planted under Acacia mangium plantation on an Imperata cylindrica grassland site in South Kalimantan, Indonesia. *Int. Tree Crops J. 10*, 131-144.
Otsamo, R. 2000. Early development of three planted indigenous tree species and natural understorey vegetation in artificial gaps in an Acacia mangium stand on an Imperata cylindrica grassland site in South Kalimantan, Indonesia. *New For. 19*, 51-68.
Pinard, M.A., M.G. Barker and J. Tay. 2000. Soil disturbance and post-logging forest recovery on bulldozer paths in Sabah, Malaysia. *For. Ecol. Manag. 130*, 213-225.
Richards, P.W. 1996. *The tropical rain forest: an ecological study*. Cambridge University Press, Cambridge. 575 pages.
Romanya, J., P.K. Khanna and R.J. Raison. 1994. Effects of slash burning on soil phosphorus fractions and sorption and desorption of phosphorus. *For. Ecol. Manag. 65,* 89-103.
Sabah-Forestry-Department. 2002. Available at the Internet: http://www.sabah.gov.my/htan/data_1/a_toppage_main/frames.htm.
Saharjo, B.H. 1999. The effects of fire on the properties of soil in Acacia mangium plantations in South Sumatra, Indonesia. *J. Trop. For. Sci. 11*, 459-469.
Sanchez, P.A., J.H. Villachica and D.E. Bandy. 1983. Soil fertility dynamics after clearfelling a tropical rainforest in Peru. *Soil Sci. Soc. Am. J. 47*, 1171-1178.
Sayer, J.A., J.K. Vanclay and N. Byron. 1997. Technologies for sustainable forest management: Challenges for the 21st century. *CIFOR occasional paper*. Bogor.
Sessions, J. and R. Heinrich. 1993. Harvesting. In *Tropical forestry handbook* (ed. L. Pancel), pages 1325-1424. Springer, Heidelberg.
SFI. 1991. *Biannual Research Report (Soil & Hydrology) 1990/91, Vol. 3/8*. Sabah Forest Industries Sdn Bhd.
SFI. 2001. *Soil Science Section - Biannual report.* Sipitang. Sabah Forest Industries.
SFI. 2002. *Forest Management Plan 2001-2010.* Sabah Forest Industries Sdn Bhd.
Sibbesen, E. 1978. An investigation of the anion-exchange resin method for soil phosphate extraction. *Plant Soil 50*, 305-321.

Siegert, F., G. Ruecker, A. Hinrichs and A.A. Hoffmann. 2001. Increased damage from fires in logged forests during droughts caused by El Niño. *Nature 414*, 437-440.
Sim, B.L. and N. Nykvist. 1991. Impact of forest harvesting and replanting. *J. Trop. For. Sci. 3*, 251-284.
Sist, P., D. Dykstra and R. Fimbel. 1998. *Reduced-impact logging guidelines for lowland and hill dipterocarp forests in Indonesia.* CIFOR, Bogor. 19 pages.
Soil-Survey-Staff. 1996. *Keys to Soil Taxonomy*. USDA Natural Resources Conservation Service, Washington D.C.
Sommer, R., M. Denich and P.L.G. Vlek. 2000. Carbon storage and root penetration in deep soils under small-farmer land-use systems in the Eastern Amazon region, Brazil. *Plant Soil 219*, 231-241.
Sterck, F.J., F. Bongers and D.M. Newbery. 2001. Tree architecture in a Bornean lowland rain forest: intraspecific and interspecific patterns. *Plant Ecol. 153*, 279-292.
Syers, J.K. 1997. Managing soils for long-term productivity. *Phil. Trans. R. Soc. Lond B 352*, 1011-1021.
Tiessen, H. 1998. Resilience of phosphorus transformations in tropical forest and derived ecosystems. In *Soils of tropical forest ecosystems: characteristics, ecology and management* (ed. A. Schulte and D. Ruhiyat), pages 92-98. Springer, Berlin.
Van Lynden, G.W.J. and L.R. Oldeman. 1997. *The assessment of the status of human-induced soil degradation in South and Southeast Asia.* ISRIC, Wageningen. 35 pages.
Varghese, G. 1979. Effects of burning on soil microflora of the jungle. In *Soil microbiology and plant nutrition* (ed. W.J. Broughton, C.K. John, J.C. Rajarao and B. Lim), pages 102-110. Univ. of Malaya Press, Kuala Lumpur.
Walsh, R.P.D. 1996. Drought frequency changes in Sabah and adjacent parts of northern Borneo since the late nineteenth century and possible implications for tropical rain forest dynamics. *J. Trop. Ecol. 12*, 385-407.
Walsh, R.P.D. and D.M. Newbery. 1999. The ecoclimatology of Danum, Sabah, in the context of the world's rainforest regions, with particular reference to dry periods and their impact. *Phil. Trans. R. Soc. Lond B 354*, 1869-1883.
Wang, X., R.S. Yost and B.A. Linquist. 2001. Soil aggregate size affects phosphorus desorption from highly weathered soils and plant growth. *Soil Sci. Soc. Am. J. 65*, 139-146.
Weinland, G. 1998. Plantations. In *A review of dipterocarps: Taxonomy, ecology and silviculture* (ed. S. Appanah and J.M. Turnbull), pages 151-185. CIFOR, Bogor.
Whitmore, T.C. 1984. *Tropical rainforests of the Far East*, 2nd edn. Clarendon Press, Oxford. 352 pages.
Whitmore, T.C. 1996. *Swedish - Malaysian research cooperation on tropical rain forest management systems.* Sida, Department for research cooperation, SAREC. Stockholm. 51 pages.
Whitmore, T.C. and D.F.R.P. Burslem. 1998. Major disturbances in tropical rainforests. In *Dynamics of tropical Communities* (ed. D.M. Newbery, N. Brown and H.H.T Prins), pages 549-565. Blackwell Science Ltd., Oxford.
Wong, F.K. 1989. *Soil physical properties in relation to tropical forestry.* M.Sc. Thesis. University of Aberdeen, Aberdeen. 114 pages.
Woods, P. 1989. Effects of logging, drought, and fire on structure and composition of tropical forests in Sabah, Malaysia. *Biotropica 21*, 290-298.
Woodward, C.L. 1996. Soil compaction and topsoil removal effects on soil properties and seedling growth in Amazonian Ecuador. *For. Ecol. Manag. 82*, 197-209.
Zetterberg, T. 2000. Architecture and abundance of fine roots in deep soil horizons under a humid tropical forest plantation. *Swedish University of Agricultural Sciences, International Office, Minor Field Studies No. 95.* Uppsala. 24 pages.

Acknowledgments

The Swedish Agency for Research Cooperation with Developing Countries (SAREC) made this thesis possible by funding my salary and travels. Additional support, including housing, logistics and workers were provided by the joint project between SAREC and Sabah Forest Industries Sdn Bhd (SFI).

However, without the continuous support and input from large numbers of people this thesis would have looked very different (if it had been produced at all). Throughout the project my main supervisor, Anders Malmer, has provided invaluable experience and knowledge about the forests of Sabah. Thank you Anders, for your continuous support and your hospitality to me and other students at numerous visits at your house (I should not forget Beatrice here). My other supervisors, Anders Nordgren and Harald Grip, have each contributed in their own particular ways and with their expertise. Nordgren, with your never-ending ideas, you are truly a gold mine for anyone who knows how to mine your creativity. Harald, your experience, calm ways and sharp eyes have helped me many times. Reiner, even if not formally my supervisor, I owe you much for your support, encouragement, hospitality and hard words of wisdom (I still have a lot to learn, but without your help my article writing would not have improved to where it is today). Thank you Elisabeth for helping me with the final editing. I was indeed fortunate to get your assistance. I am also indebted to the evaluation committee for valuable comments and suggestions regarding the manuscripts, as well as to John Blackwell at 'Scientific English Editing Services', who made a wonderful job of amending my English.

My colleagues at SFI, Mr. Edmund Gan, Mr. Sim Boon Liang, Mr. Khamis Selamat and Mr. Paul Liau have provided much more than the usual warm hospitality that is so characteristic of the Malaysian people. For example, I could not count all the occasions I have stayed with Paul, Helena and the rest of the family. Paul, all the discussions we have had about everything from faith, politics, and family to forestry and science will always be a part of me. Furthermore, without the hospitality of all my other friends at the Mendolong Nursery my visits would not have been so memorable. Therefore, thank you everyone that worked together with me in the Mendolong forests (Francis, Pileh, Parimin, Daniel, Adirin, Andreas and all the others) and also everyone who invited me to play soccer, and 'sepak takraw' countless times in the afternoons.

I would also like to thank all the other students (Louise, Nils, Björn, Daniel, Jill, Adrienne and Maria) who shared my life and work in the Mendolong guesthouse and forests. I am also grateful to Nils Nykvist for sharing his enormous experience during our stays in Mendolong. To Ove and everyone else at the lab, without your supervision and help there would not have been much to write about. All other staff at the department have also contributed in their own ways to make the daily rounds of my work enjoyable, thank you all!

All friends, all the Sunday-school children, all customers at 'kafe Station', and everyone else who has helped to distract me from my scientific schooling also deserves a mention for keeping me reasonably sane. However, most important for me has been the support and concern from my dear family, and during the last years from Erika and the rest of the Elonsson family.

Finally, I would like to quote a dedication to tree planting, written about 2800 years ago, to acknowledge the One to whom I think all work should be devoted:

"I will put in the desert
the cedar and the acacia, the myrtle and the olive.
I will set pines in the wasteland,
the fir and the cypress together,
so that people may see and know,
may consider and understand,
that the hand of the LORD has done this..."
Isaiah 41:19-20