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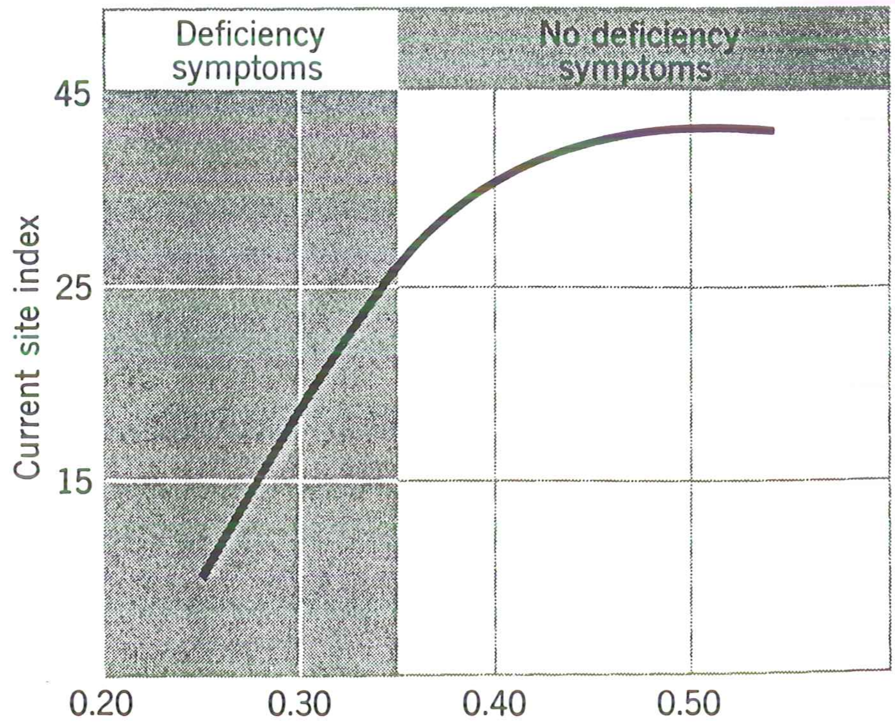

Percent Potassium in First Year Needles of Pinus resinosa (STONE et al., 1958)

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Content

Volume 5

FOREST SOIL FERTILITY AND FERTILIZATION

DEGRADATION AND AMELIORATION OF SOIL AND TREE NUTRIENT STATUS WITHOUT AND WITH MINERAL FERTILIZER

Wolfgang Zech and Pay Drechsel[1]

ABSTRACT

Natural tropical forests are more and more destroyed and transfered into farm- and rangeland. But, only relatively small areas are reforested usually with fast growing tree species in short rotation. This contributes to the degradation of the soil and tree nutrient status. The intensity of degradation may be assessed by different approaches, including detailed observation of deficiency symptoms and yield development, foliar and soil analyses, as well as diagnostic fertilizer experiments. Input/output analyses, taking into consideration water and nutrient fluxes between the different plant and soil compartments are means to evaluate the sustainability of tropical tree plantations. Only few data are available up to now, indicating poor sustainability. Soil and tree nutrient status can be improved by the application of mineral fertilizer, which is usually rapidly effective. In contrast, amelioration by management practices is only slowly effective, nevertheless important in view of sustainability, environmental protection and biodiversity. A big gap exists in reliable data on water and element dynamics in forest plantations with different tree species under different ecological conditions, and under different management practices.

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1. INTRODUCTION

Soils of tropical forest ecosystems generally are poor in nutrients. Despite this fact, undisturbed natural forests seldom reveal symptoms of mineral deficiencies which are typical indicators of degradation. It seems that nutrient balances in undisturbed systems are in a "steady state", and losses - if they occur - are more or less "neutralized" by input rates (PROCTOR, 1987). Disturbances of these balances e.g. by slash and burn or logging only may cause degradation of soil and tree nutrient status and initiate „savannization" (BRUIJNZEEL, 1992; DEZZEO, 1990; FÖLSTER AND RUHIYAT, 1991). In contrast to undisturbed natural forests, unfertilized tropical tree plantations often show signs of degradation, like foliar chlorosis or necrosis, leaf cast, growth deformancies, and even large scale decline, thus indicating that plantation systems are highly susceptible to nutrient imbalances, perhaps due to the following reasons:

- Accelerated soil nutrient leaching and physical degradation, like structural deterioration, after clearing natural forests, site preparation and after establishment of the plantation.
- Discrepancy between site requirements of the planted species and site conditions encountered.
- Impoverishment of the available soil nutrient pools after multiple rotation with high nutrient export by (un)controlled fire, thinnings and logging.
- Phytopatological disturbances due to the fact that forest plantations are mainly established as monocultures which are highly susceptible to diseases.

In the following overview we will not focus on diseases but on decline phenomena caused by degradation of the soil and tree nutrient status with special emphasis on the identificaton of nutrient imbalances, and on the sustainability of tropical tree plantations taking into consideration changes in nutrient cycles in connection with forest clearing and tree harvesting. In a final section aspects of ameliorating soil and tree nutrient status without and with mineral fertilizer will be discussed.

2. IDENTIFICATION OF NUTRIENT IMBALANCES IN TROPICAL FOREST PLANTATIONS

For the reliable diagnosis of nutrient disorders in plants several approaches are available, including detailed observation of symptoms, laboratory analyses, and diagnostic fertilizer experiments (MEAD, 1984; DRECHSEL and ZECH, 1993).

2.1 Detailed observation of degradation symptoms

Generally, plants with adequate nutrient supply look healthy, develop green leaves and grow vigorous. Latent deficiencies primarily reduce growth, but do not induce deficiency symptoms. Only severe disturbances of the tree nutrient status due to deficiency or toxicity induce symptoms like leaf discoloration, die back and growth deformances or decline of the stand. If only one nutrient is lacking (or toxic) an identification often is possible just by detailed observation of the symptoms, taking into consideration site conditions, age of foliage, symptom development during the season, etc.. In Table 1 some typical symptoms of mono-causal deficiencies are summarized on the example of tropical conifers. Special guidelines for identifying deficiency symptoms of, e.g., eucalypts and teak are reported by IPI (1962), DRECHSEL and ZECH (1993) and EVANS (1992).

Table 1

However, several deficiency symptoms are very similar. In addition, frequently not only one nutrient is lacking but multiple deficiencies may occur under field conditions. The reason could be a general low soil fertility or a synergism between a mono-deficient nutrient and physiologically related elements. Then it is difficult or impossible to identify nutrient disorders just by detailed observations. In these cases analytical or experimental approaches are necessary, like foliar and soil analyses in combination with diagnostic fertilizer trials.

2.2 Foliar analysis

This technique is widely used for the assessment of the fodder quality of browsed trees and shrubs (ZECH, 1981; ZECH, 1984), and has been found to be very suitable in the identification of nutritional stress, using reference data of healthy trees or comparing vigorously and poorly growing trees or trees with and without yellowing (BOWEN and NAMBIAR, 1984; WESTERMAN, 1990; DRECHSEL and ZECH, 1993). Most (reference) foliar data are available for pines and eucalyps especially from Australia and South Africa (e.g. LAMBERT, 1984; GRANT, 1991; HERBERT AND SCHÖNAU, 1991), but there are only few studies on tropical broad-leaved trees, especially tropical hard woods (EVANS, 1992). Recently, DRECHSEL and ZECH (1991) published a tabular review on foliar nutrient levels of broad-leaved tropical and subtropical trees in order to support the identification of ranges in concentrations indicating deficient, marginal (low), adequate (intermediate), high and toxic foliar mineral-nutrient levels. This work has to be considered as a first approximation since our knowledge on mineral nutrition of these tree species, which are more and more used in reforestation, is still fragmentary. Also nutrient contents corresponding to deficiency or optimum supply are not clearly delineated up to now or may even vary from case to case, e.g. due to differences in water supply (BRUNCK, 1987; NAMBIAR et al., 1984).

Despite these limitations foliar analyses can be a valuable tool in characterizing the nutrient status of trees if the principal factors that influence foliar nutrient contents like age and position of the foliage, sampling time, number of trees to sample etc. are taken into consideration. As example, foliage of at least 10 dominant or codominant trees per plot should be sampled for the detection of concentration differences of 20% (or more) between two plots or stands. 20 trees are considered as sufficient for most problems (VAN DEN DRIESSCHE, 1974; BOWEN and NAMBIAR, 1984; WEETMANN and WELLS, 1990; DRECHSEL and ZECH, 1993).

To analyse multiple nutrient disorders in more detail besides

- the direct comparison of healthy and declining trees, and
- the comparison of analysed data with already published reference values ("critical levels"), in addition
- DRIS (Diagnosis and Recommendation Integrated System, see BEAUFILS, 1973) could be a valuable instrument of data interpretation.

DRIS describes and analyses nutrient balances/imbalances in multiple deficient plants by comparing all nutrient interactions (like N/P, N/K etc) of healthy, fast growing plants (= norm population) with those of the collective under study (= e.g. declining subpopulation). Under multiple deficiency DRIS allows to rank deficient nutrients (i.e., to identify the most deficient nutrient) and to detect over-supply, like Mn-toxicity (WALWORTH and SUMNER, 1987, 1989; DRECHSEL, 1994).
Up to now only few DRIS-related studies have been carried out with tropical trees for instance with Anacardium occidentale, Eucalyptus grandis, E. saligna, E. viminalis, Pinus taeda, P. patula, and P. radiata (for sources see SCHUTZ und DE VILLIERS, 1987; DRECHSEL, 1994). Recent DRIS studies deal with Cunninghamia lanceolata (ZHONG and HSIUNG, 1993) and Tectona grandis (DRECHSEL und ZECH, 1994).

Table 2 describes a typical example from young teak plantations studied in a Vertisol landscape in southern Togo and Benin (DRECHSEL, unpubl.). The 2 years old trees showed in some stands interveinal chloroses (of middle age foliage) and especially in shallow basins a very low growth rate. The symptoms indicated according to the symptom key several different possibilities of mono-nutrient deficiency, but also multiple deficiency was possible. The comparison of foliar data with reference values showed that indeed a broad range of nutrient concentrations (N, S, P, K, Mn, Zn, Cu,..) should be classified as deficient (Tab. 2). To get additional information we analysed the nutrient balance using DRIS. Fig. 1 shows that DRIS allows to identify the order of deficient nutrients: Mn > Fe > N > Cu etc.

Nevertheless, a reliable interpretation of nutrient disorders should always base on the combination of foliar and soil analyses.

Table 2, Figure 1

2.3 Soil analysis and site evaluation

Without doubt the majority of growth disttrbances and decline phenomena is closely related to soil and site properties. Though, a thorough evaluation of these properties will contribute significantly to the identification and prevention of growth and health disorders. In contrast to foliar analysis soil and site studies can be carried out before the establishment of a plantation. They should refer to the evaluation of soil fertility and soil water supply considering first of all parameters like root available soil depth, slope position, occurence of stagnating water, texture (soil water capacity), acidity (pH), organic matter content and salinity.

These parameters are without big efforts to study and usually show quite good correlations with tree growth. In the case study mentioned above Mn- and Fe-deficiency were enhanced by pH-values between 6.5 and 8.1 and traces of lime, which are known to reduce Mn and Fe availability. The generally bad nutrient status and tree growth were significantly correlated with water stagnation (Fig. 2). Decline phenomena were most pronounced in basins where the clay was covered by a nutrient poor sand sheet of about 30 cm, inducing typical pseudogley conditions.

Figure 2

In a second step and especially in industrial plantations soil nutrient analyses could be a very useful supplement in site evaluation for forestry. However, soil analysis only gives limited information on tree availability of soil nutrients because most chemical extraction methods were developed for agricultural crops. In addition, there are no data about the influence of mycorrhiza and very seldom an idea about the lower boundary of the forest root network. In fact, there exist nearly no verified guidelines for the interpretation of distinct soil nutrient levels with respect to tropical trees. Nevertheless, linear and multiple regression analyses between tree growth and foliar or soil/site data can give valuable information, especially if a distinct nutrient is lacking or if complex parameters, like "topsoil depth", "amount of organic matter" or "pH" are used (SCHÖNAU and HERBERT, 1983; LAMB, 1977, SRIVASTAVA and YUE MUN 1978; LAMBERT, 1984; DRECHSEL and ZECH, 1994; DE HOOGH, 1981; BELLOTE, 1990; and ZECH and CEPEL, 1970). Multiple regression analysis allows the quantification of the influence of more than one factor on tree growth. However, it should be tried to concentrate the calculations on simple morphological, chemical or physical soil parameters, which allow a transfer of the results to soil mapping and site classification (e.g ZECH and CEPEL, 1970). An other example was given by KAUPENJOHANN (1991) from Eucalyptus camaldulensis under water stress in Burkina Faso:

$$\text{tree growth} = 0.25\ A/B - 2.44\ C + 5.04$$

A: thickness of the Ah-horizon (cm), B: bulk density of the Ah (g/cm^3), C: slope (%)

About 70% of the variations in growth could be explained and predicted in this way (KAUPENJOHANN, 1991). In Gmelina plantations of Costa Rica STUHRMANN et al. (1994) found a negative correlation between monthly tree height increment and surface soil compaction, as well. In view of soil fertility, the storage capacity for nutrient cations in kaolinitic soils highly depends on soil organic matter contents. This fact explains, why a soil parameter like the thickness of the Ah-horizon, often used in site evaluation, frequently is well correlated with tree growth, soil nutrient reserves (especially N and P) and foliar nutrient contents (e.g. STUHRMANN et al., 1994; BERGMANN et al., 1994).

These results demonstrate that the combination of detailed field observations plus foliar and soil analyses can significantly contribute to the identification of nutrient disorders. Despite this knowledge mapping of soil and site conditions before the establishment of tree plantations in tropical countries is up to now less practiced. This is an avoidable risk which contributes in many cases to unsatisfying results of tropical reforestation programmes (ZECH et al., 1989).

2.4 Diagnostic fertilizer trials

The diagnostic approaches mentioned up to now in the previous sections (symptom observations, leaf analysis and soil analysis and site evaluation) can be realized within relatively short time. This is not the case for the 4th approach, including diagnostic fertilizer experiments. Only the establishment of such experiments by applying the identified deficient elements in different quantities and mixtures allows a definitive verification of the diagnosis. In addition, only fertilizer trials are able to give information on growth response. The application of a nutrient in deficit may cure the symptoms within 1 or 2 seasons depending on the age of the plantation. Growth responses sometimes need more time. Before large scale fertilization is carried out, preliminary diagnostic experiments should be performed on representative, homogeneous sites and with replicates (CELLIER and CORRELL, 1984). Evaluating the results should include foliar, soil and growth analyses. If in addition nutrient stores and nutrient dynamics in the different compartments of the biomass and soils are taken into consideration, sustainability of forest plantations can be evaluated. This will be discussed in the following section 3. Then, in section 4 the potential of ameliorating soil and tree nutrient status without and with fertilizer will be looked at.

3. NUTRIENT STORAGES AND CYCLES IN TROPICAL TREE PLANTATIONS

Tropical tree plantations often are established on marginal soils with fast growing species like Eucalyptus (38 %), Pines (34 %), Tectona grandis (14 %) and Acacia species (5 %). The figures in parantheses inform about the percentage each tree species contributes to reforestation activities in tropical countries (EVANS, 1992; PANDEY et al., 1983/84). Rotation time in these monocultures usually is very short, and each harvest is accomponied by nutrient exports. If these exports are higher than the nutrient stores and nutrient availability in the soil, soils and plantations will degrade due to nutrient disorders (SANCHEZ et al., 1985; HASE and FÖLSTER, 1983; BRUIJNZEEL, 1992). For this reason nutrient balances for different sites with different tree species have to be carried out in order to evaluate sustainability.

It is interesting to note, that EVANS outstanding book on "Plantation Forestry in the Tropics" (1992) mainly refers on silviculture and yield related research activities. Aspects of mineral nutrition are handled in about 14 pages, but the fundamental question whether plantations can be considered as sustainable in view of high nutrient exports by generally low nutrient stores is discussed only marginally. There is really a big deficit in our knowledge on nutrient balance development in tropical plantations under different management and fertilizer practices, considering

- internal cycles, like nutrient retranslocation before leafshed, root necro-mass decomposition and below-ground biomass turnover
- inputs due to precipitation, dry deposition, chemical weathering of the parent material, fertilizer, N-fixation, interflow, and
- outputs/losses due to harvest, thinnings, soil erosion, nutrient leaching and e.g. volatilization.

It is clear that in short term rotations these losses are higher than in long term ones because each harvest is accompagnied by accelerated soil erosion, nutrient leaching and volatilization due to the destruction of the protecting canopy, burning of residues and higher microbial activity. These losses may reduce soil and biomass nutrient stores and thus sustainability.

Whether nutrient reserves are exhausted after two or ten rotations depends on tree species planted, site conditions and management. But reliable data which allow modelling of nutrient dynamics and yields in tropical plantations are scarce (SANCHEZ et al., 1985). Figures on nutrient losses due to tree harvesting mainly refer to stands in the northern hemisphere or Australia and New Zealand (e.g. TURNER and LAMBERT, 1983; MADGWICK et al., 1977; STEWART et al., 1981). One of the first outstanding investigation with respect to the tropics was realized by LUNDGREN (1978, 1980). He pointed out that in Tanzania highlands clearing of the natural forests runs parallel with SOM decrease and availability of soil nutrients only increases immediately after burning. During the life span of the first rotation SOM tended to increase somewhat but nutrients were continuously leached or lost by erosion. At the beginning of the second rotation SOM and soil nutrient levels were reduced significantly in comparison to the initial phase at the beginning of the first rotation. The magnitude of these changes mainly depends on the intensity of clearing and kind of harvest (SANCHEZ et al., 1985; NYKVIST et al., 1994).

Basic studies on nutrient balances and cycling with respect to sustainability of tropical tree plantations were conducted in Nigeria (e.g. KADEBA and ADUAYI, 1986; EGUNJOBI and BADA, 1979; NWOBOSHI, 1983, 1984), India (e.g. SINGH, 1982), and Indonesia e.g. by BRUIJNZEEL (1983, 1992) and by FÖLSTER and his coworkers from the Forest Faculty at the University of Göttingen. They found for instance that clearing of a Dipterocarpacee forest growing on Ultisols in East-Kalimantan by logging and burning was accompanied by significant nutrient losses (Tab. 3).

Table 3

To evaluate sustainability of the plantations (Eucalyptus deglupta, Acacia mangium, Albizzia falcataria) established after clearing the natural forests FÖLSTER and RUHIYAT (1991) calculated nutrient losses after harvesting the first generation (20 years). The figures for potassium in Eucalyptus deglupta plantations are summarized in Tab. 4, as example. They indicate a drastic decrease of the "available" K pool in the soil of about 34% within the first rotations. It is assumed that during the second rotation the same amount will be lost again.

Although some sources of nutrient inputs like precipitation and by weathering of parent materials are not taken into consideration, the results indicate that in contrast to the majority of natural tropical forests which reveal "closed" nutrient cycles (input = output), frequently disturbed systems like short term tree plantations are highly susceptible to degradation of at least one nutrient pool. Similar results were published from Nigeria by EGUNJOBI and BADA (1979) or KADEBA and ADUAYI (1986) for Pinus caribaea. HASE and FÖLSTER (1983) compared nutrient stores and cycles in the different compartments of natural forests, teak plantations and secondary forests growing on Fluvisols in Venezuela. Like in Indonesia, it was mainly K besides Ca and Mg being primarely lost in the plantation due to hardwood exploitation (Ca) and leaching (K), especially on sandy soils. N and P were less affected. Modelling the nutrient balances indicates that the establishment of several teak generations seems less promising.

Table 4

For Eucalyptus grandis plantations in Eastern Amazonia SPANGENBERG (1994) analysed average nutrient losses due to exportation of wood and bark to amount 65% N, 54% P, 76% Ca, 57% K, and 61% Mg of the corresponding stores in the whole tree biomass. Assuming the same nutrient removal during the second rotation, losses would correspond to about 100% K, more than 100% Ca, about 30% Mg of the actual "available" soil stores in these elements. Especially the bark of Eucalyptus grandis is very rich in Ca (TURNER and LAMBERT, 1983). Figures like these explain why with rising numbers of rotations base saturation and e.g. Ca soil stores sharply decrease. For compensation an application of up to 250 kg Ca ha-1 appeared to be necessary in the case of the Amazonia study.

In contrast to these findings BRUIJNZEEL (1983, 1992) and BRUIJNZEEL and WIERSUM (1985), who studied nutrient and water balances in small water catchments reforested with Agathis dammara in Central Java demonstrated that proper land management systems excluding whole tree harvesting may avoid soil degradation. However, this study was carried out on moderately fertile Andosols. If besides boles also bark, twigs and leaves were exported, P, Ca and again K stores were rapidly exhausted. This is a very frequently reported conclusion (DRECHSEL and ZECH, 1993).

In summary, the following statements can be given:

a) To evaluate sustainability of forest plantations water and nutrient balances have to be studied using an ecosystemary approach. Up to now only few results are available with respect to tropical plantations, indicating poor sustainability. No successful stable crop production system can be based on "mining" the soil without returning a proportionate amount of what was removed by harvesting (SANCHEZ et al., 1985). However, a modelling is till now not possible.

b) Data on bole, bark, branche and twig nutrient contents and on nutrient exports due to harvesting are available only for about 10-13 tropical plantation species, mostly conifers and eucalypts, as well as Gmelina arborea and Tectona grandis (BRUIJNZEEL, 1992; DRECHSEL and ZECH, 1993). These data are highly correlated with the local soil fertility status and difficult to extrapolate.

c) Even less information is known on nutrient losses due to accelerated mineralization, leaching and volatilization (fire) during and immediately after plantation harvest.

d) Further deficits in our knowledge concern e.g. nutrient contents and turnover of the below ground biomass.

Due to these gaps it is difficult to evaluate future development of nutrient dynamics in tropical tree plantations and thus their sustainability. Optimizing plantation management offers some possibilities to keep nutrient cycles in a better equilibrium or even to ameliorate soil and tree nutrient status. This subject will be discussed in the last section.

4. AMELIORATION OF SOIL AND TREE NUTRIENT STATUS WITHOUT AND WITH MINERAL FERTILIZER

Improving and maintaining fertility of tropical soils are big challenges in view of increasing population and increasing demands of people, especially in developing countries. Degradation and amelioration of the soil nutrient status both relates to forestry and agriculture. Since mineral fertilizers usually are expensive, alternatives for improving and maintaining soils fertility and reducing the risk of nutrient disturbances are of high relevance.

4.1 Amelioration of soil and tree nutrient status without mineral fertilizers

These methods comprise:

a) Site evaluation before planting (YOUNG, 1993)
- contributes to proper tree species selection
- informs about hazards due to erosion, inondation, water logging, and mass movement
- on sites too poor and not suited for reforestation, natural forests should be protected or their regeneration supported
- may help to estimate yields
- allows to discriminate areas where similar or different management practices have to be carried out.

b) Site adapted clearfelling and proper site preparation (PANCEL, 1993b)
- conserve SOM and nutrients which are mainly accumulated in the soil surfacelayer reduce soil compaction
- prevent nutrient and water losses and support root growth by terracing and preparation of planting holes
- reduce salinity hazards in semiarid regions by using rain water harvesting systems.

c) Tree species selection (PANCEL, 1993a)
- according to site quality, using e.g. less demanding or even pioneer species on infertile sites
- use of tree legumes for restoring soil fertility as "improved fallow" before introducing demanding species, or interplanted as in agroforestry
- besides fast growing exotic species also local probably better adapted ones should be taken into consideration
- site adapted mixed plantations have tc be studied in more detail.

d) Proper plantation management (DRECHSEL and ZECH, 1993; PANCEL, 1993b)
- promotes sufficient inoculation (already in the nursery)
- selective weeding around the trees to reduce competition
- protection against livestock
- proper spacing and thinning
- optimal rotation period (nutrient removal per unit of biomass is higher in short term rotations in comparison with longer rotations)
- no whole-tree harvest; foliage, branches and bark should remain on the soil
- no lopping, no regular litter harvest, no regular burning of the litter layer if possible
- promotion of N-fixing undergrowth
- low intensity fire to stimulate decomposition of (pine)litter
- avoid slash burning between rotations because it may accelerate decline in second-rotation plantations (WOOD, 1990).

To obtain high yields within short time, mineral fertilizer usually seem to be most promising (BRUIJNZEEL, 1992). In contrast, the alternative methods for the amelioration of the soil and tree nutrient status are slowly effective (SMITH et al., 1994). However, as there exist only a few data on their contribution to nutrient balance, future research should be focused on these methods. In view of fertilizer prices and long-term sustainability *nutrient management* will become more and more important not only in cropping systems but also in plantation forestry (VAN DER HEIDE, 1989; NYKVIST et al., 1994).

4.2 Application of mineral fertilizers

Proper fertilizer application improves mineral disorders, supports the establishment of plantations on infertile sites, stimulates growth and may increase resistance against diseases, frost and drought (EVANS, 1992).

Many different methods of applying fertilizers especially to eucalypts and pines have been studied all over the world. The results were variable and partly confusing. They depend mostly on the specific site conditions (e.g. soil texture, clay type, water regime, pH), weed competition, weather conditions, test species, time and kind of application as well as type and quantity of fertilizer. General conclusions certainly valid for different regions, soils and species are not possible. Recommendations have always to base on local fertilizer trials and experiences.

Most data are reported from South Africa (e.g. SCHÖNAU, 1984; SCHUTZ, 1976; SCHÖNAU and HERBERT, 1989), Australia (e.g. CRANE, 1984; GRANT, 1991; TURNER and LAMBERT, 1983, 1986) and New Zealand (e.g. WILL, 1985), and less intensive from Brazil (BELLOTE, 1990) and e.g. Malaysia, where fertilizer application in forest plantations can be considered as a routine. In contrast to the silviculture practices in these countries, little fertilizer is used in most developing countries due to high costs despite poverty of the soils. Since recently some reviews on fertilization of (sub)tropical tree plantations, especially with eucalypts and pines, have been published (e.g. HERBERT and SCHÖNAU, 1991; DRECHSEL and ZECH, 1993) we will focus in this paper on some examples from Western Africa (Nigeria). They cover typical problems and show the broad range of fertilizer studies. The tree species are Terminalia superba as hardwood, Gmelina arborea as pulp and paper source and Azadirachta indica for pole and firewood production (Tab. 5). The examples cover different causes (low soil fertility and high acidity) and purposes of fertilization (amelioration of tree growth and wood production as well as of wood quality).

In the first example from Southern Nigeria different amounts of lime were tested to enhance growth of Terminalia superba on acid Ultisols and to study changes in soil and foliar nutrient levels. Best growth was obtained using 6-9 g $Ca(OH)_2$ per seedling, increasing the soil pH-H_2O from 4.6 to about 6.0. At this pH highest foliar P levels were measured. However, soil tests for available P (Bray method) was not adapted to these conditions and shows no increase in soil P (Tab. 5a). The problem of non-sensitive soil tests for the analysis of tree available nutrients has already been mentioned above.

In the second example different kinds of fertilizer were used to increase yields of Neem on sandy Luvisols in Northern Nigeria. On the three stations under study, the application of farmyard manure usually gave the best results in comparison with comparable amounts of NPK (Tab. 5b). Similar results were found for Eucalyptus camaldulensis in the same region showing the importance of organic material under tropical conditions.

Nutritional disorders do not only decrease tree yield, but also wood quality. This is e.g. of interest in the production of pulp and paper with Gmelina. In this last example the effects of different kinds of N-fertilizer (NO_3-N, NH_4-N, NH_4NO_3-N, urea-N) on tree growth and wood properties were studied. Due to the central role of nitrogen in plant metabolism significant differences were found, e.g. in tree growth, specific gravity of the wood and size of fibre cells (Tab. 5b). The authors found that the application of NH_4-N fertilizer should not be recommended.

Table 5

Even these data make clear, that kind of fertilizer as well as application rates of nutrients depend on the objective of the plantation, the tree species selected, site and soil properties, stand age and density, and several other parameters including of course the financial possibilities. However, it is beyond the scope of this paper to summarize and evaluate all available data and technical experiences in fertilization.

CONCLUSIONS

In view of the global change phenomena it is believed that large scale reforestation activities in the tropics may contribute to the reduction of the CO_2-problem. But many tree plantations in the tropics suffer from nutrient disorders already during the first rotation, and the intensity of these disorders seems to increase with the number of rotations. This means that a significant carbon sequestration by increasing the area reforested on tropical sites is at least doubtful. Up to now our knowledge about the stability of these planted forests is too low. A big gap exists in reliable data on the development of the nutrient balance of plantations with different tree species on different sites with different management. Although, there exist several promising methods on the stabilization of plantations using fertilizers as well as management practices, the lack of data does not allow general conclusions. Therefore, local species- and site-adapted strategies have to be developed to prevent the risk of nutrient depletion and destruction of natural resources in tropical plantation forestry.

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Table 1: Typical symptoms of monocausal nutrient deficiencies in conifers (DRECHSEL and ZECH, 1993; WEETMANN and WELLS, 1990; modified).

N:	Markedly reduced shoot growth and uniformly light-green to yellow needles, occuring first in the older foliage. Partly stunted needles.
S:	In general similar to those of N-deficiency, but more on younger foliage
P:	Untypical symptoms on older foliage: yellow (later dead) needle tips, or purple-brown tinged needles or thin and small needles
Mg:	Yellow needle tips on older foliage with distinct borderlines to the rest of the needle
K:	Firstly, older needles develop yellow tips which turn to brown-reddish, no distinct borderlines to the rest of the needle
B:	Terminal and leader die back often with orange-red discolouration. Resinous buds often fail to flush - main stem forks (multiple leader) and becomes deformed. Black or dark brown pith, shortened young needles. The higher the moisture stress, the higher the foliar levels at which the tree develops deficiency symptoms (LAMBERT, 1984).
Cu:	Often dark blue-green foliage; distorted (snake-tailed) shoots and branches, bushiness. Some needle tip burn. Prostrate growth in extreme cases. Application of N(PK)-fertilizer may accentuate the deficiency..
Fe:	Older needles green. Increasing chlorosis towards younger foliage. White colours in extreme cases (only common on calcareous soils).
Mn:	Yellow tipped young needles, sparse, light green foliage, stunting (especially on dry, alkaline soils; e.g. Vertisols, but also on highly weathered and acid Oxisols)
Zn:	Terminal needles very short. Premature needle fall and rosetting, tip dieback and yellowing. Partly multiple leadering.
Mo:	Blue-green needles, partly purple-brown tips with distinct borderlines to the rest of the needle, may occur on older or younger foliage.

Table 2: Foliar nutrient levels of 2 years old teak (site 21/Togo) in comparison with concentration ranges of adequate nutrient supply according to DRECHSEL (1992).

Element		Reference values	Site 21
N	%	3.16 ± 0.50	1.39 ± 0.22
S	$mg\ g^{-1}$	1.94 ± 0.34	1.19 ± 0.18
P	$mg\ g^{-1}$	2.65 ± 0.71	1.58 ± 0.21
K	%	2.00 ± 0.36	1.59 ± 0.11
Ca	%	0.96 ± 0.30	0.78 ± 0.23
Mg	%	0.33 ± 0.08	0.25 ± 0.04
Si	%	9.63 ± 3.42	16.1 ± 2.1
Fe	$mg\ kg^{-1}$	112 ± 50	55 ± 12
Mn	$mg\ kg^{-1}$	45 ± 14	19 ± 8
Zn	$mg\ kg^{-1}$	22 ± 4	13 ± 5
Cu	$mg\ kg^{-1}$	17 ± 3	9 ± 2

Table 3: Total nutrient stores in a Dipterocarpacee forest of East-Kalimantan, and average nutrient losses due to clearing (RUHIYAT, 1989; FÖLSTER and RUHIYAT, 1991)

	Total reserves in biomass, litter and soil (50 cm) before clearing the natural forest	Reserves in the biomass only (natural forest)	Mean losses during clearing the natural forest
	$kg \cdot ha^{-1}$	$kg \cdot ha^{-1}$	$kg \cdot ha^{-1}$
N	9000 (100%)	1180 (13%)	2000 (22%)
K	1150 (100%)	800 (70%)	400 (35%)
Ca	2000 (100%)	1400 (70%)	700 (35%)
Mg	900 (100%)	230 (25%)	90 (10%)

Table 4 : Decrease of K stores (kg ha^{-1}) in Eucalyptus deglupta plantations on clayey Ultisols in mid slope position due to wood exploitation and accelerated losses by erosion, mineralization and leaching in the context with harvesting (FÖLSTER and RUHIYAT 1991; RUHIYAT, 1989)

Total K stores at the beginning of the 1. generation	1013 (100%)
K loss due to wood exploitation at the end of the 1. generation (20 years)	231 (23%)
K loss due to accelerated mineralization, leaching and erosion during the 1. harvest	114 (-11%)
Total K stores at the beginning of the 2. generation	668 (66%)
K loss due to wood exploitation a the end of the 2. generation	231 (23%)
K loss due to accelerated mineralization, leaching and erosion during the 2. harvest	114 (11%)
Total K stores at the beginning of the 3. generation	323 (32%)

Table 5a: Methods and results of three fertilizer experiments carried out in Nigeria.

Example	Problem	Species	Kind of trial	Treatments	Results				
					Lime rate	Tree height (cm)	pH H_2O	Soil-P (ppm)	Foliar-P (%)
1 SW-Nigeria Ultisol (ALUKO, 1990)	soil acidity	Terminalia superba (seedlings)	greenhouse trials over 6 months	different lime quantities: 0/3/6/9/12/15 g $Ca(OH)_2$ per seedling	0	18	4.6	6.0	0.14
					3	21	5.7	5.8	0.17
					6-9	26	6.0	5.7	0.18
					12	18	6.5	5.6	0.15
					15	11	7.2	5.4	0.14

Table 5b: Methods and results of three fertilizer experiments carried out in Nigeria.

Example	Problem	Species	Kind of trial	Treatments	Results			
2	low fertility	Azadirachta	field trials	different fertilizer:	Mean tree height (m) at 3 research stations			
N-Nigeria	(2% clay)	indica	over 2 years	2 kg farmyard		1	2	3
Ferric		(2,5 yrs old)		manure and				
Luvisol				84 g NPK	Manure	4.2	4.5	4.9
(KADEBA,				(15-15-15)	NPK	4.3	4.4	4.6
1990/91)				per tree	Control	3.7	3.8	4.0
3	low wood	Gmelina	greenhouse	different N-sources:	2.5 g N	Tree	Specific	Fibre
S-Nigeria	quality	arborea	trials over	NO_3-N as KNO_3	per seedling	growth	gravity	length
"Latosol"	and growth	(seedlings)	5 months	NH_4-N as $(NH_4)_2SO_4$				
(OGBONNAYA,				NH_4NO_3-N	NO_3-N	210 %	0.62	0.59
1993)				as $CaNH_4(NO_3)_3$	NH_4-N	200 %	0.57	0.42
				Urea-N	NH_4NO_3-N	300 %	0.64	0.57
					Urea-N	240 %	0.61	0.62
					Control	100 %	0.56	0.55

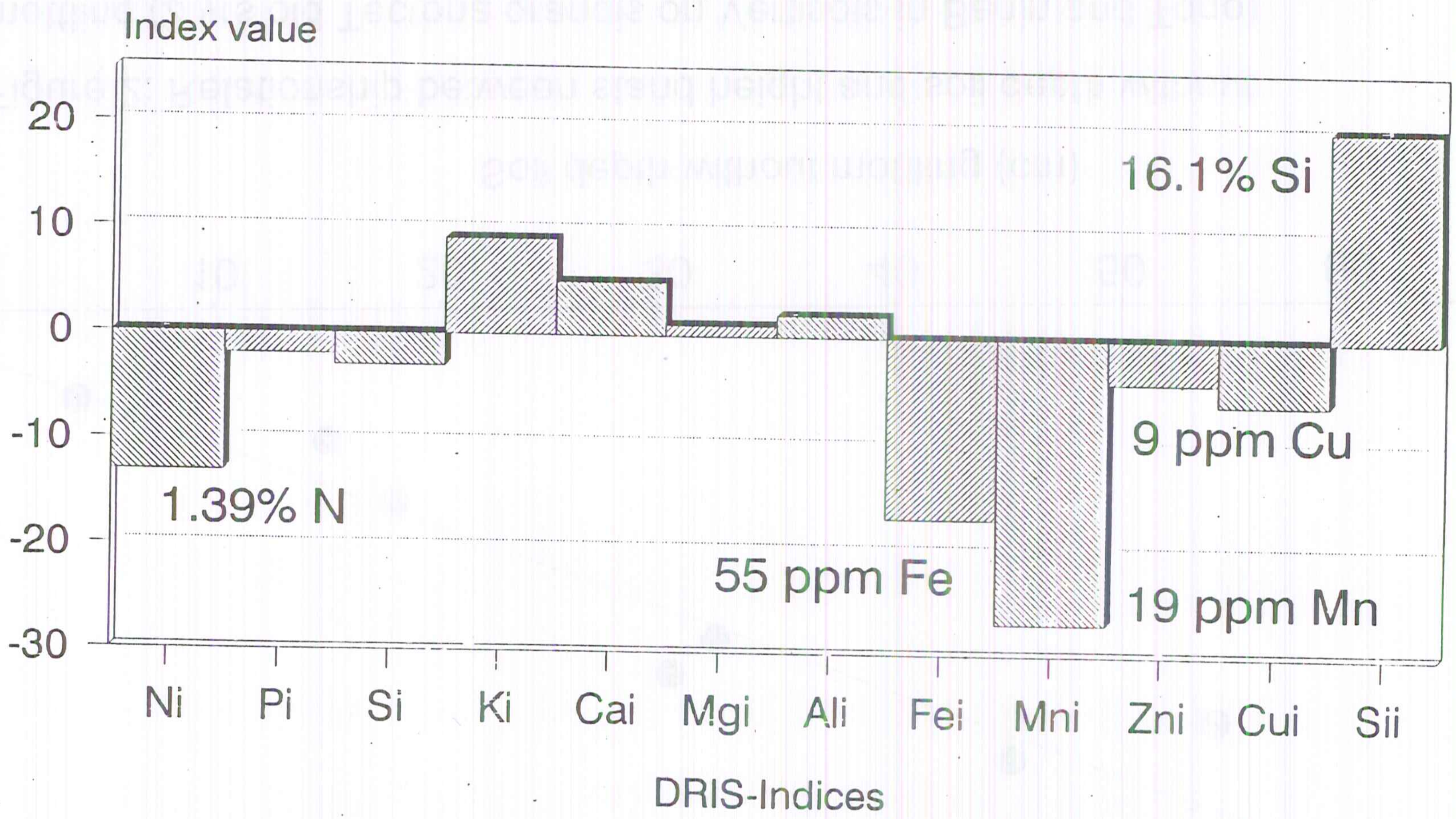

Figure 1: DRIS indices of Tectona grandis with intercostal chloroses on site 21/Togo (DRECHSEL, unpubl.).

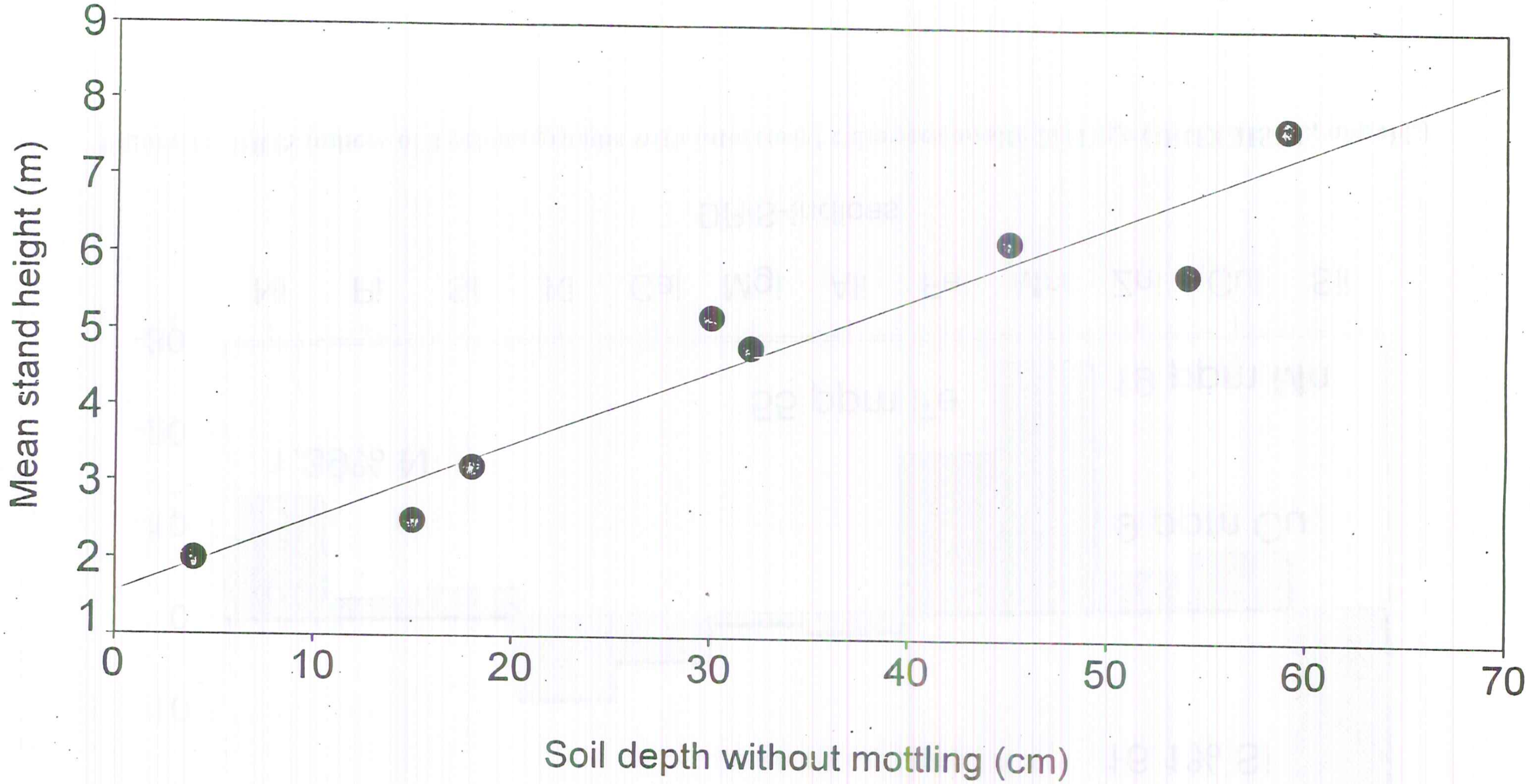

Figure 2: Relationship between stand height and soil depth without mottling (2 yrs old Tectona grandis on Vertisols in Benin and Togo)

LONGTERM STUDIES OF SOIL FERTILITY IN CACAO-SHADE TREES-AGROFORESTRY SYSTEMS / RESULTS OF 15 YEARS OF ORGANIC MATTER AND NUTRIENTS RESEARCH IN COSTA RICA

Hans W. Fassbender

ABSTRACT

In the frame of the research activities of the agroforestry cooperation project GTZ/CATIE (German Agency for Development , Gesellschaft für Technische Zusammenarbeit / Centro Agronomico Tropical de Ensenanza , Turrialba , Costa Rica) long term studies have been carried out at the " Experimento Central " to determinate the productivity and the soil fertility (organic matter and nutrients) in agroforestry systems.

In this paper results are presented and discussed as examples of sustainable agroforestry,using the systems of cacao (Thoeobroma cacao) under Laurel (Cordia alliodora) or Poro (Erythrina poeppigiana) as an example. The following productivity and soil fertility parameters were founded:

- The average cacao bean harvest during 15 years is very stable reaching average values of 718 and 745 kg.ha-1.a-1 under C.alliodora and E.Poeppigiana respectively.

- The growing rates for Cordia alliodora are very high , reaching 30 cm DAP and 20 m hight and a timber volume of 140 m-3.ha-1 at age 15 years.

- The accumulation of organic matter, measured for the different species (leaves, branches, trunks, roots, fruits and litter) at an age of 5 years (1982) and of 10 years (1987) are as follows : 50.3 and 110.6 t.ha-1 for T. cacao/C.alliodora and 39,1 and 87.3 for T. cacao/E.poeppigiana respectively.

- The net primary production between ages 6 and 10 of the systems are in average 28.2 and 36.3 t.ha-1.a-1 for T. cacao/C.alliodora and T.cacao/ E.poeppigiana.

- The natural leaf fall and residues of prunings , studied at age 6 to 10 and also at age 14 to 15 years indicate a total production of plant residues of 11.4 and 22.9 t.ha-1.a-1 for the given agroforestry systems. The later value under

E.poeppigiana is especially related to the pruning-management of the leguminose tree.

- The soil organic matter increased in the first ten experimental (1977 - 1987) years equivalent to 15.3 and 41.6 t.ha-1.a-1. The soil N-reserves also increased, specially under E. poeppigiana.

- The losses of nutrients by leaching are negible.

Therefore the conclusion is reasonable that the analyzed agroforestry systems maintain soil organic matter and promote efficient nutrient cycling. There are also sustainable and appropiate for soil fertility conservation.

INTRODUCTION

High expectations have been raised in recent years about the potential of agroforestry as a major land management alternative for sustainable production and for the maintenance of soil fertility in the tropics (Beer et al., 1987; Beer et.al., 1990; Fassbender et.al.,1988, 1991; Fassbender, 1993; Nair, 1987; Sanchez, 1987; Young, 1987). Most recently the discussion on appropiate land use systems in the tropics has been dominated by the term of " sustainability ". The CGIAR-TAC-report describes sustainable agriculture as one which " involves the necessful management of resources for agriculture to satisfy changging human needs while maintaining or enhancing the quality of environment and conserving natural resources " (Javier and Rendborg, 1988). Its essential feature is the link between conservation and production. A sustainable land-use systems requires continuos production and conservation of resources. In this framework a soil conservation - sustainable-based system should :

- ensure a long term continuosly production
- control the soil erosion
- mantain the soil organic matter
- asure the maintenance of biological, chemical (nutrients) and physical conditions of the soil, avoiding their degradation and/or decline.

The management and improvement of agroforestry systems should be based on a satisfactory understanding of their structure and function. This is a complex task, since these systems (and especially the interactions) are complicated and many aspects must be taken into consideration; therefore, long term studies on the production of the systems and on the conservation of soil fertility has to be attempted. These studies finaly result with the interpretation of all paramenters in the postulation of models for organic matter, nutrients and water and balances for the description of the behavior of the systems (Nair,1984; Fassbender et.al.,1988,1991 ; Fassbender,1993). Figure 1 represents a model for the organic matter and nutrient cycle for cacao (Theobroma cacao) under shade trees (Alpizar et.al.,1986, Fassbender, 1993) and sumarized the long term measurements for the evaluation of the system productivity and for the quantification of the maintenance of organic matter and nutrients in the soil. The system components are described according to their compartments (leaves, branches, trunks, roots,fruits, flowers). The flows between the system components include the deposit of plant residues and the pruning of the shade trees. The inputs to the system include photosynthesis, rainfall (water and dissolved elements),fertilization and the microbial fixation of nitrogen. The outputs from the system include the water responsible for the leaching of nutrients, and the harvests of fruits and timber.

In the frame of the reseach activities of the agroforestry cooperation project GTZ/CATIE (German Agency for Development, Gesellschaft für Technische Zusammenarbeit / Centro Agronómico Tropical de Investigación y Enseñanza, Turrialba, Costa Rica) long term studies has been carried out in the Experimento Central of CATIE to provide a basis for the evaluation of systems productivity and soil fertility conservation with models of organic matter, water and nutrient cycles for the following agroforestry systems:

- Cacao (Theobroma cacao) with shade of Laurel (Cordia alliodora) or Poro (Erythrina poeppigiana);
- Coffee (Coffea arabica) under the same shade trees and
- Stargrass (Cynodon plectostachyus) associated with the same shade trees.

In this paper, the tree and crop production values along with the distribution and fluxes of organic material and nutrients in the systems of Theobroma cacao with Cordia alliodora and Erythrina poeppigiana are presented, synthesized into models and discussed as examples of sustainable agroforestry systems for the lowland humid tropics. The methods and results are presented in the sequence which was follow for the evaluation and interpretation of

- Productivity parameters
- Cocoa production
- Timber production
- Crop and tree biomass production
- Net primary production of the system, and
- Soil fertility parameters
- Litter production and decomposition
- Models of maintenance of organic matter
- Nutrient accumulation and tranfers in the system
- Balances of organic matter and nutrients.

METHODOLOGY FOR THE EVALUATION OF SYSTEMS PRODUCTIVITY AND SOIL FERTILITY

The " Experimento Central " of CATIE

Details of the " Experimento Central " at CATIE, Turrialba, Costa Rica, in which the systems were studied, have already been described (Alpizar et.al.,1986; Beer et.al, 1987, 1990; Fassbender, 1993 ; Fassbender et.al., 1988, 1991 ; Heuveldop et.al., 1988 ; Imbach et.al., 1989).

The Turrialba region is located at 9o 53 min N and 88o 38min W and has an altitude of 600-650 m above sea level. The annual average temperature (23 years) is 22.3 oC; the minimum and maximum temperatures reach 17.7 oC and 27.0 oC respectively. The average annual rainfall (38 years) is 2648 mm with an average of 246 days of rain per year. Average monthly rainfall of under 100 mm was recorded only in the month of March (70 mm). The monthly average relative humidity is 87.6 percent.

The soil of the experimental site belongs to the normal Institute series. It is classified as typic humitropept, fine, halloysitic and isohyperthermic. The texture is clay loam. The soil has level topography, poor drainage, and is of fluvial-lacustrine origin. See Table 1 for soil analysis.

In August 1977 cacao (Theobroma cacao) hybrids (Catongo x Pound) were planted at 3 x 3 meter spacing (1111 trees.ha-1) with shade trees of laurel (Cordia alliodora) and poro (Erythrina poeppigiana) interplanted at 6 x 6 meter spacing (278 trees.ha-1) in two split plots measuring 18 x 36 meters in random blocks.

The agronomical treatment of the experiments is representative for the farms in the Turrialba region. An initial application of fertilizer (13.9 kg N.ha-1, 18.2 kg P. ha-1, 11.5 kg K. ha-1) was given, later the fertilisation changes and in the long term evaluation the annual rate of application averages 87.5 kg N, 34.6 kg P and 34.9 kg K per hectare.

EDAPHOLOGICAL MEASUREMENTS

Before starting the experiment (1977) four mixed mineral soil samples were taken with 10 cores per plot at depths of 0-15,15-30 and 30-45 cm and anlysed for the characterisation of physical and chemical properties of the soil. The apparent density at the depths cited were measured using cylinders of 250 cm3 volume with eight samples per depth. Based on this data, the organic matter and nutrients per hectare were calculated.

In the same plots and using the same techniques soil samples were taken in 1982 (5 years) and in 1986 (9 years) and analysed in order to evaluate the changes in the total reserves of organic matter and nutrients.

The soil samples were analyzed for total nitrogen (Kjehldal), total phosphorus (nitroperchloric acid digestion) ; potassium, calcium and magnesium exchangeable with ammonium acetate (pH 7.0) and pH in CaCl2 (Álpizar et.al.,1986).

The soil texture was determined using the Bouyucos method. For the evaluation of available water the tension curve was prepare using the standard suction plate method in different tension level (0.33 and 1.5 Kpa) (Imbach et.al., 1989).

COCOA PRODUCTION

Theobroma cacao pods were harvested every 15 days from the second experimental year (June 1979) until 1994. Separate fresh weights of beans and husks, produced by each of 32cacao trees per plot, were determined from 1979-83 in order to determinate the procentual distribution of both fruit parts. Over two years (1981 and 1982) samples were taken from each harvest to determine oven dry weigths.

Immature pods were not measured during the 1982 and 1987 inventories of biomass accumulated in either system (see measurements of biomass). The record of the cacao production represent a long term evaluation of 15 years, the values are dimentionated as cocoa beans dry weigth per hectare and year.

GROWTH RATES AND TIMBER PRODUCTION OF LAUREL (CORDIA ALLIODORA)

Diameter at breast height (DBH; cm) and total height (h; m) of eight C. alliodora per plot have been measured at different intervals (once or twice per year) since 1978, and the average annual growth rates (MAId and MAIh) for each year were calculated. Stem volume (V) increments were determined with a volume table using d and h values (Somarriba an Beer, 1978). Therefore the timber production is evaluated for a period of 15 years.

MEASUREMENTS OF THE BIOMASS

Standnig biomass accumulation of the three species, (compartments: leaves, branches and trunks) was measured in February I 982 at age 5 and again in May and June 1987, at age 10 (Alpizar et.al. 1986 ; Beer et.al., 1990).

In order to measure the biomass of Theobroma cacao in 1982 (age 5, Alpizar et.al.,1986), 16 trees were chosen per system (i.e., 8 per plot) from the plots central rows. The heights and diameters of the trunks and branches were measured. The volume was then multiplied by the specific weight of the wood (0.33 g.cm-3, estimated from samples taken with a Pressler borer). The number of leaves per tree were counted. From ten samples of 10 leaves, the moisture content was determined (using a forced ventilation oven at 70 oC for 24 h). Thus the dry above ground biomass of each hectare was calculated.

The data for the Erythrina poeppigiana biomass was based on the volume measurement of all the trunks in the plot, and the specific weight of the wood (0.24 g.cm-3) estimated from samples taken with a Pressler borer). The biomass of branches and leaves is based on the material from the pruning of 8 trees (4 trees per plot) in March and September 1982 in which all of the material above 2.6 m was cut. The fresh weight of the leaves and branches was recorded. Sixteen samples were oven-dried, the moisture content was measured, and the dry weight per hectare calculated.

The biomass of the Cordia alliodora trunks was calculated from the heights and diameters of all of the trees and the specific weight of the wood (0.44 g.cm-3). Eight trees were cut down in order to determine the biomass of the leaves and branches. The branches and leaves were weighed and with the data of moisture content from 16 samples, the organic reserves per hectare were calculated.

To determine the biomass of fine roots (<20 mm in diameter). a metal ring (27.4 cm in diameter and 15 cm in height) was introduced into the soil at depths of 0-15, 15-30, and 30-45 cm with 16 repetitions per treatment. The roots were separated from the soil with water at normal pressure and were classified into two groups: smaller than 5 mm; and between 5 and larger than 20 mm. The samples were dried and their dry weight per hectare calculated.

The description is of the methodology used in 1987 (age 10 years) was described by Beer et.al. (1990) and involves some adaptations of the methodology above reported. Non-destructive techniques were used together with measurements of pruned branches (basal diameters T. cacao larger than 5 cm; C. alliodora , 10 cm). Oven-dry weight determinations of leaf material or woody material from suckers or branches were made from four 500 g samples per plot (T. cacao), from one sample per tree (E.poeppigiana) or one sample per branch (C. alliodora). The predictive models were statistical high significant.Average biomass values per tree were converted to per hectare values using the tree densities per hectare of each species.

LITTER PRODUCTION

To determine natural litterfall (leaves and branches), twelve collecting traps (1 m-2) were randomly placed in only one plot of each system. Weekly measurements were made continuously from November 1981 until October 1987 at age 6 to 10 years of the systems (Heuveldop et.al.,1988). With some little changes in the collecting traps the litterfall was studied one again between june 1992 and june1993, at age 15 years of the systems (unpublised)

Total pruning residues per tree were determined from the same T. cacao and E.poeppigiana which were measured during the 1987 standing biomass inventory. Measurements of pruning residues were made for T. cacao between March 1985 and May 1987 (3 prunings in 26 months) and for E.poeppigiana between June 1986 and November 1987 (3 prunings in 17 months). During december 1990 and december 1992 the prunning biomass was again determinated. Annual production values were derived from the totals produced over these periods.

DETERMINATION OF RESIDUE DECOMPOSITION

Residue decomposition can be determined by exposing bags or wooden boxes containing the residues and periodically remaining samples to measure the weight loss. Chemical analyses of the samples determination of the corresponding rate of mineralization. For this experimental study, 200 g samples of fresh leaves were exposed on the soil in wooden boxes (50 x 50 x l0cm, with 1mm mesh plastic frame) for 1,2,4,6,8, 10 and 12 months (Heuveldop et.al., 1988). The proportion of the residues produced in the first year of study of litterfall was found to be:

T.cacao l00g / C. alliodora l00g
T.cacao 120 g / E.poeppigiana 80 g

Therefore decomposition samples were initially prepared with this ration of fresh components. The samples collected were dried (105 oC 24 h) and the decomposition curve obtained from the dry weights.

DETERMINATION OF NUTRIENTS IN BIOMASS AND LITTER

During the above described biomass determinations mixed plant samples from the different compartiments, separated by species (T. cacao, C. alliodora, E. poeppi-giana). were dried and prepared for chemical analysis by passing them through a Milley mill with a 40 mesh. Litter samples were treated in the same way. The following analysis methods (Alpizar et.al., 1986) were utilized:

- Nitrogen was determined by the Kjehldal method, digested with sulphuric acid and titrated with boric acid.
- Phosphorus, digested with a mixture of nitric acid and perchoric acids, and determined by the sulpnur-molybdenum blue complex.
- Potassium, calcium and magnesium determined by atomic absorption spectrophotometry on the solution from the nitroperchloric digestion.

HYDROLOGICAL FLOW MEASUREMENTS

A metereological station is funtioning since 1983 at the " Experimento Central " and providing data of temperature, precipitation and evaporation. A water model for the studied agroforestry systems was prepared based on determinations of soil miosture content during 4 years (1982 - 1986),determinations of soil water suction with tensiometers and determinations of the interception of rainfall and throughfall of the plant species of the given agroforetsry systems, Imbach et.al. (1989).

In order to determinate the nutrient input with rainfall, precipitation samples were collected daly at the study site from february 1982 to january 1984. During the same time samples of throughthfall were collected and analysed.

During one year (march 1986 - march 1987) the solution of lixiviated nutrients was sampled with porcelain lysimetric capsules placed in the soil at 100 cm depth, using 8 repetitions for each agroforestry system. Weekly samples were extracted with a constant vacuum (80 kPa), provided by a hand vacuun pump and analysed for pH, N, K, Ca. and Mg in the CATIE laboratories. Leaching losses were calculated from nutrient concentration and the with the water modell calculated volume of percolates water (Imbach et.al., 1989).

RESULTS AND DISCUSSION

Physical and chemical characteristics of the soil

Tables 1 and 2 contains the results from the soil analysis of the plots of T cacao under the E. poeppigiana at the beginning of the experiment (1977). The pH values are homogeneous and acid. The content of organic mater is high and decreases normaly with soil depth. These characteristics are similar for total nitrogen and phosphorus. The values of the exchangeable bases are uniformly high, especially of potassium.,The anotated standard deviations generate high coefficients of variation of all of the findings, ranging between 10 and 50 percent.

The changing values on organic matter, nitrogen and exchangeable bases (K, Ca and Mg) after nine years of the experimient are also sumarized in table 2.The differences are going to be interpreted later in the acapite on nutrient balances. The high variabilty coefficients of the results leads to difficulties in interpreting the chemical changes of the soil as a function of time.

PARAMETERS OF SYSTEMS PRODUCTIVITY

T. cacao production

In both systems T. cacao production started at age 2 years and gradually increased to age 6 years (1983), after which it stabilized (Table 3). On average, the cocoa beans made up 41% of the dry pod weights. The long term average production values over 15 years in both systems (1978-1994) are 718 and 745 kg.ha-1.a-1 of cacao beans under C.alliodora and E.poeppigiana respectively. The values are statistical comparable, there are no differences in the production of cacao of both systems. The respective value for the non-utilizable husk is also comparable for both systems, around 1000 kg.ha-1.a-1.

National cocoa production averages (kg.ha-1.a-1) for commercial farms in 1978/79 were: Brasil 650; Columbia 480; Dominican Republic 380 and Ecuador 380 (Enriquez, 1985) and for the Central American region 250 - 350. The results at the Experimento Central evidence that the studied systems are sustainable for Costa Rica.

Growth rates of laurel (Cordia alliodora)

The average data of diameter and hight of the Cordia alliodora from Table 4 are the basis for the calculated values for timber production. The average diameter of almost 30 cm at age 15.6 years is typical for C. alliodora in the Atlantic zone of Costa Rica but the average height of 18 m is less than would be expected. As a consequence the BHD-h relationship at this study site is only just within the measured distribution for this species in this zone (Somarriba and Beer,1987).

At age 10.5 years, estimated C.alliodora stem volumes totalled 77.6m-3.ha-1, equivalent to a growth rate of 7.4m-3.ha-1.a-1, those at age 15 years corresponded to 140m-3.ha-1 and 9.0 m-3.ha-1.a-1 (Table 4). The inventory data at age 10 (see latter), gives also a value of 9 m-3.ha-1.a-1, which corroborates the estimated growth rate even though it is based on a volume table (Sommarriba and Beer, 1987), which may not be applicable to the abnormal BHD-h relationship at this site.

Biomass in T. cacao and shade trees

The accumulation of organic matter in the biomass of the studied agroforesty system has been sumarized for the determination at age 5 and 10 years in Figure 2 and also in total values in Table 5. In the last five years, the increase in the standing T. cacao biomass (excluding roots) under C. alliodora was apparently greater than the increase in shade tree biomass (Figure 2) but the latter value was affected by the seasonal shade tree leaf fall. The increase for T. cacao was due to a large change in branch biomass (20 t.ha-1), the compartment which showed the greatest increase between age 5 and 10 in this system. The increase in T. cacao biomass under E. poeppigiana was significantly less than under C. alliodora (18.9 vs 26.1 t.ha-1) and there was significantly less T. cacao biomass under E.poeppigiana at age 10 years. Nevertheless, in percentage terms (1982-87 increments as % of 1982 values, Figure 2) the corresponding increases in total, stem or branch biomass of T. cacao are similar in both systems. The apparently much smaller percentage increase in T.cacao leaf biomass (25% both systems), as compared to the change in branch biomass may be partly a consequence of pruning secondary branches and suckers, the different methodologies used to measure crop leaf biomass in 1982 and 1987 and of the phenological differences due to seasonal and climatic variations. However, even when allowing for these factors, it appears that crop leaf biomass is increasing at a much lower rate than branch biomass and may have reached a stable value by 1982. On the other hand, it is interesting to note that the different understory light regimes, consequence of the different shade tree characteristics and management, did not result in intersystem differences in T.cacao leaf biomass in 1982 or in 1987 nor in different growth rates.

In the literature there are only a few data on biomass of T. cacao plantations. Aranguren et.al. (1982) reported from Venezuela for 30 year old T.cacao a total biomass value of 24.4 t.ha-1. From Cameroun, Boyer (1973) calculated values of 10 -15 t.ha-1.a-1. Thong and Ny reported from Malaysia a biomass of 36.1 kg.tree-1, assuming a density of 1000 trees per hectare, the biomass would be 36 t.ha-1. All this values are in the range of the data from Experimento Central.

Stem wood biomass of C. alliodora at age 10 is 40.3 t.ha-1 (Figure 2),equivalent to 9 m-3.ha-1.a-1 (specific density 0.45 gm.cm-3). During the last five years the total biomass increase of E. poeppigiana stems was not significantly different to that of C. alliodora stems (21.2 and 16.6 t.ha -1), respectively) even though the E. poeppigiana are subjected to regular intensive pruning. The annual accumulation of wood (stems plus branches) of C.alliodora was not significantly different between ages 0-5 and 6-10 years (5.7 and 4.0 t.ha-1.a -1, respectively). The corresponding values for E. poeppigiana (excluding pruning residues; see section Litterfall) are 2.8 and 4.4 t.ha-1.a-1, again indicating the ability of this species to maintain productivity despite heavy pruning.

As a consequence of the relatively faster stem growth of E. poeppigiana compared to C. alliodora during the second five year period (Figure 2; 1982-87 increment as % of 1982 value gives 228 vs 70% respectively) the interspecies difference in biomass distribution disappears completely. Stem biomass is 75-80% of the species total for C.alliodora at ages 5 and 10, while for E.poeppigiana the corresponding values are 60 and 80%. This storing of organic material and some of the nutrients in the effectively worthless E.poeppigiana stems could lead to the suggestion that frequent replacement of this shade tree species would increase organic material and, to a lesser degree, nutrient cycling. Such a suggestion would not of course be logical for C.alliodora, whose stems provide valuable timber after rotations which are currently between 17 and 27 years (Somarriba and Beer, 1987). Neither is it practical for E. poepigiana when replanting costs and the continuous shade requirement of T.cacao are taken into account. Replanting E. poeppigiana would also result in a temporary suspension of biomass and nutrient cycling.

The deciduous species C.alliodora generally drops its leaves between March and May. This explains why the leaf biomass of C.alliodora is much less at age 10 then at age 5, since the measurements were taken in the months of June and February, respectively

(Figure 2)

The amount of litter (15.2 t.ha-1) found in this system in 1987 is partly a product of the same phenomenon. Between I 982 and 1987, C.alliodora branch biomass increases (75%) in the same proportion as standing biomass (70%). Both branch and leaf biomass of E. poeppigiana decrease in this period due to the different intensity of earlier prunings.

PARAMETERS OF SOIL FERTILITY MAINTANENCE

Litter production and decomposition

The values in Table 6 demostrate the variability of the natural litterfall in both studied systems at age 6 to 10 years. The pruning litterfall is presented as the average of the different years of studies. The total amount of litter production in these age (6 to 10 years) averaged 11.40 and 22.86 t.ha-1.a-1 for T.cacao/C.alliodora and T.cacao/ E.poeppigiana respectivety. The results in natural and pruning residues at age 14 to 15 years reached a total of 10.69 and 19.34 t.ha-1.a-1 respectively and are between of the variability founded for age 6 to 10 years.

In both systems, T.cacao produces approximately half of the total natural litterfall (Table 6). In spite of being regularly pruned, the E. poeppigiana produces more natural litterfall (due to greater leaf fall) than the C.alliodora. Nevertheless, the totals for natural litterfall are similar because T.cacao litterfall is apparently greater under C.alliodora and partially compensates for lower shade tree litterfall in the totals. Ling (1984) found a much larger significant difference in natural T.cacao litterfall when shade density was reduced in a wide range of conditions (67-537 trees of Gliricidia sepium per hectare).

The total deposition of organic material (natural litterfall plus pruning residues) is much greater in the E. poeppigiana system due to the average input of 9.8 t. ha-1.a-1 of leaves plus branches from the pruning of this shade tree. This shade tree pruning regime, which is principally designed to regulate the light reaching the understorey crop T. cacao, also provides large amounts of mulching material for the soil and thus has a critical influence on organic material cycling. The T. cacao is also regularly pruned to remove suckers and unwanted secondary branches, and thus produces an additional 3-4 t.ha-1.a-1 of organic residues (no inter-system difference).

The values for natural litterfall in Table 6 are within the range of published values (8 sites), of 5.2-20.9 t.ha-1.a-1 in T.cacao plantations (Beer, 1988, Ling, 1982). More specific comparisons are of limited value in view of differences between sites and methodologies. The only comparable published values for E. poeppigiana come from studies in several Coffea arabica plantations in the Turrialba area, where prununing residues (2 to 3 pruning per year) provides 8 - 14 t.-ha-1.a-1 (Beer, 1988) which corroborates the value of 10 t.ha-1.a-1 determined in this study.

According to Heuveldop et.al. (1988) the decomposition rate is exponential, after a year the plant resudues are decomposed and incorporated to humus and mineral nutrients in the soil.

The ecological sustainability of tropical forests depends upon the maintenance of their internal nutrient cycles (Jordan, 1985). Average published values for natural litterfall in lowland tropical forests are 9.57 (mean of 33 sites (Jordan, 1983) and 10.46 t.ha-1.a-1 (mean of 52 studies; calculated by Fassbender (1993) from Proctor (1984). The similarity of these values to the 8.11 and 9.29 t.ha-1.a-1 recorded in the C. alliodora and E. poeppigiana systems, respectively, provides part of the explanation of why these perennial crop systems are more easily maintained. under low intensity management, than is continuous cultivation of annual crops. When pruning residues are included, the organic material inputs via litterfall are doubled in the E. poepigiana system when compared to natural forests.

Models of organic matter

Figure 2 shows the five-yearly models (age 6 to 10) for organic matter in the agroforestry systems T.cacao / C.alliodora and T.cacao/E.poeppigiana in

Turrialba, Costa Rica.The reserves are the average of the biomass measurements, litter anh humus at ages 6 and 10 ; the transfer values are the averages of the determinations during the five year period. Values of T.cacao pods are shown in Figure 2 in brackets to indicate that the cacao pod biomass was not allways present but is transitory and the data refer to the removal of biomass as an annual mean over five years (1983 - 1987).

Besides the information directly available in Figure 2, from the model other important criteria can be derived for the characterisation of the agroforestry systems as:

- Net primary production
- Productivity and export indices
- Recycling indices

Net primary productivity (NPP), between ages 6 to10 years, was calculated by adding the following average annual values in t.ha-1.a-1 for the principal parameters:

- Biomass accumulation (both standing and roots); derived from the difference between the 5 and 10 year inventories.
- Root turn-over; annual regeneration of all fine roots (<5 mm) was assumed, using the average value between age or between age 5 and 10.
- T. cacao production (husks and beans) for the period 1983-1987.
- Plant residue production; litterfall and pruning residues (leaves and branches) as the value is an average of the annual measurements during this period (1983 -1987).

All the total biomass and net primary productivity (NPP) values reported in this paper are underestiniated since destructive sampling to measure the principal lateral roots (d over20 mm) and tap roots was not possible in this on-going experiment. The NPP does not differ greatly when comparing systems the quinquennial period (Table 5). The main reason for this temporal increase is the large increase in the annual production of organic residues (especially pruning residues). It is again worth noting that the annual phytomass accumulation of T.cacao exceeds or equals that of the shade trees during the second period in contrast to the first five juvenile years.

During the second quinquennial period, the values for standing biomass accumulation, fine root turn-over and litterfall, for T.cacao/C.alliodora, are siniilar to the highest published values for tropical humid lowland forests (Fassbender, 1993) which is to be expected given the natural fertility and management (drainage, fertilization) of these plots. In the same period, the NPP of 35 t.ha-1.a-1 for the E. poeppigiana / T.cacao system is equal to the maximum of the range of values for the NPP of tropical rain-forests (10-35 t.ha-1.a-1, Fassbender, 1993, Jordan, 1983, 1985), again demonstrating the potential biomass productivity of this leguminous tree. Nevertheless, values of 40-50 t.ha-1.a-1 have been estimated as the maximum NPP for C3 plant canopies (roots not included), such as fast growing tree plantations in the tropics (Kira and Kumura, 1983). Net production rates for C4 crop canopies can be much higher: 70-90 t.ha-1.a-1 for Pennisetum purpureum and Saccharum officinarum (Kira and Kumura, 1983, Westlake, 1963). NPP in even-age tree plantations reaches a maximum after a few years, when canopies close, before declining. At the same time, leaf biomass tends to attain a constant value. Thus, the stabilization of T. cacao leaf biomass values (Figure 2) may be a sign that the NPP rates have also reached their maximum values in these agroforestry systems.

The export index can be used as other parameter for the characterisation of the productivity and sustainability of the systems, it can be calculated as the percent of biomass extracted with yields of the system. The annual harvest export of I'. cacao pods as a proportion of the total biomass (Figure 2) is only 3.1 and 4.2% for the Cordia alliodora and Erythrina poeppigiana systems respectively, or when expressed as a proportion of the NPP (Table 5) 9 and 7% respectively. However, if the C.alliodora stems are also exported, then the value for this system increases to 20 percent.

The recycling index represents the procentual value of litter production (natural and pruning) of the biomass. The annual production of above-ground plant residues as percentages of standing biomass (Fig. 2) are as follows:

	C.alliodora	T.cacao	E.poeppigiana	T.cacao
by species	9.1	33.6	56.7	43.4
by system	17.9		51.4	

Calculation of the proportion of the NPP that is deposited as residues, gives values of 40 and 63% for the C.alliodora and E. poeppigiana systems, respectively. Cycling of T.cacao and E. poeppigiana biomass is clearly faster and thus the return of stored nutrients to the soil surface is accelerated in the system which includes both these components. On the other hand nutrient storage and loss, in the standing biomass of the C.alliodora system, is a possible problem if timber is exported from the site but this may only be alimitation when considering sustainability over more than one rotation of the timber trees. Although a much higher proportion of the biomass is recycled in the T.cacao/E.poeppigiana system, even in the C.alliodora system 50% of the above-ground biomass produced each year is recycled, within the range of the data on forest ecosystems reviewed by Olson (1963) and Jordan (1983).

Each shade species produces both detrimental as well as beneficial effects on the underlying crop (Beer, 1987) and any one criteria, such as cocoa production, only reflects the balance of these interactions which changes from site to site.Thus the absence of a clear cocoa yield advantage, under E. poeppigiana in these conditions, does not necessarily imply the absence of beneficial effects on the nutritional status of the T. cacao. From these results, it can be hypothesized that in the absence of fertilisation, or on lower fertility sites, cocoa yields should be greater under E. poeppigiana than under C.alliodora, which agrees with many farmer's empirical observations that C.alliodora is a more competitive shade tree than the other traditional alternatives which include Erythrina spp, Inga spp, etc. Another hypothesis, to explain the absence of any yield advantage under E. poeppigiana is that competitive effects cover any beneficial effects because of the unusually high shade tree densities (278 trees per hectare) maintained in this experiment.

Soil organic material

There is a general tendency for soil organic material concentrations to increase with time (Figure 1, Table 1), the highest values being attained in the Erythrina system. However, these temporal increases are not statistically significant, (5% level), in part because the soil organic material concentrations (0-15 cm; 4%) were relatively high (Fassbender and Bornemisza, 1986) at the initiation of this experiment.The apparently large inter-system difference in soil organic material reserves in 1977 (Fig.1:0-45 cm; 30 t.ha-1) is also not significant due to the high variance of the data (Table 1). Intra-site variability may be a consequence of pre-experiment spatial differences in management (e.g. burning of sugar cane trash) and/or pockets of poor drainage (2 m deep ditches were dug before 1977).

Soil organic material reserves, apparently increase more (1977-87) under E.poeppigiana (41.6 t.ha-1) than under C. alliodora (15.5 t.ha-1) but again the differences are not significant. However in 1987, there were some significant inter-system differences when comparing the same soil horizons (0-15; 30-45 cm), presumably attributable to the greater litter inputs (pruning residues) under E. poeppigiana (Figure 2). Inter-system differences in rates of litter decomposition and mineralization of soil organic material could also obviously lead to differences in soil organic material reserves. The only definite conclusion which can be made is that both agroforestry systems, at the least, maintain soil organic material concentrations under continuous cropping which indicates the potential for long-term ecological sustainability.

Nutrient pools in the agroforestry systems

In order to studie other aspects of soil fertility similar evaluations and models can be compiled for nutrients in agroforestry systems (Fassbender, 1993; Fassbender et al.,1988). However, nutrient models are more complex because of the different forms (total, extractable, available) of the nutrients in the mineral soil, management practices (fertilization, liming), and some important ecological processes (N fixation by legumes, input with rainfall and output with leaching water).

The accumulation of total N in biomass shows fairly well defined tendencies for each system (Table 5). At age 5, T. cacao/C.alliodora accumulated 447kg.ha-1 of N compared to 393 kg.ha-1 for T.cacao/E.poeppigiana. At age 10 the respective values were 765 and 722 kg.ha-1 of N. Thus the difference in N uptake during the 10 year experimental period was 43 kg.ha-1 of N in favour of T.cacao/C.

alliodora, as a result of extra accumulation in the stems and branches of the shade tree.

The very small values for P accumulation indicate the low mobility of this element in agroecosystems. Available P, which may gradually be accumulated in the vegetation, is a very small fraction of total P (Fassbender and Bornemisza,1987).

The average values of K uptake at age 10 years were 419 and 520 kg.ha-1 for T.cacao in association with C. alliodora and E. poeppigiana, respectively. Without fertilization this would imply a notable depletion of the original exchangeable soil K (1977:577 and 713 kg ha-1, respectively).

Nutrient internal transfers, inputs and outputs

The rates of nutrient transfer for the T.cacao/E. poeppigiana system were normally higher than those of the T.cacao/C.alliodora system, largely because of pruning of the leguminous tree (Table 8). The total value of deposting N to the soil with the plant residues (natural litter and pruning) shows a tremendous difference in favour of the T.cacao/E.poeppigiana system (447.1.kg.ha-1.a-1) as compared with T.cacao/ C.alliodora (169.1 kg.ha-1.a-1). Assuming that the annual rate of decomposition of plant residues ist almost comparable with those of deposition (Heuveldop et.al.,1988), the turn over of N is very important. The export of N from the systems with cocao yields reached 23.1 and 28.4 kg N ha-1.a-1 for the studied systems respectively and are only a short fraction of the accumulated or circulating in the agroforestry systems. The input of N with rainfall, reaching 5.0 kg.ha-1.a-1 is comparable with other values founded in the literature for other sites in tropical conditions (Fassbender, 1993, Jordan,1985).

The values recorded for P for the inputs and outputs from the systems are more or less comparable. There is one exception,those of the input with pruning materials, reaching 22.1 and 4.1 kgP.ha-1.a-1 for T.cacao/E.poeppigiana and T.cacao/alliodora respectively.

The transfer rates of K with plant residues is once again larger under Erythrina (151.5 kg K.ha-1.a-1) as under Cordia (35.4 kg K.ha.a.1). Therefore, the nutrient cycles for T.cacao/E.poeppigiana turnover are faster for all nutients in comparison with T.cacao/C.alliodora.

Nutrient balances in the agroforestry systems

Figure 4 summarizes all details of the nitrogen balance for the system T.cacao/ E.poeppigiana for the 10 first years of studies. The N accumulated in the biomass resulting fron N uptake from the soil, during the 10 years studies reached 722 kg-1.ha-1 (crop 249, tree 206, litter 204 and roots 63). Adding the value of N export with the cacao yiels (206 kg.ha-1.10a-1), the total N uptake from the soil represents 986 kg N.ha-1.10a-1. This value is comparable to the rate of fertilisation (962 kg N.ha-1.10a-1). The rate of input with rain fall (50 kg N.ha-1. 10a-1) is almost equal of the rate of leaching with percolating water (60 kg N.ha-1.10a-1), It is very important to observe that the N-reserve in the soil increased in the 10 years of studies for 1409 kgN.ha-1.10a-1 (1987 : 10964, 1977 : 9555 kg.ha-1). This accumulation may be a result of the N fixation by the leguminous tree. The values for the chemical analysis of nitrogen shown very high variation coefficients (Table 2), therefore the N increase in the soil in not statistical significant and the postulated increase is only hypothetical. In all the cases no decline of the N-reserves is recorded and herewith the maintenace of the soil fertility can be certicated.

Conclusions, perfomances of the systems and both shade trees

In the experimental conditions of this study, which include normal of farmers used fertilization rates, the agroforestry systems of E. poeppigiana or C. alliodora with T. cacao have reached large both agricultural production and timber production and net primary production during the studies, thus showing that the production of these systems is sustainable for at least 15 years.

The apparent increase in soil organic material and nitrogen, especially under E. poeppigiana, also gives evidence for the ecological sustainability of these systems over longer periods. Although litter inputs and soil organic material levels are lower under C. alliodora, they are at the very least maintained. When the C.alliodora timber production of 9.0 m-3.ha-1.a-1 is added to the cocoa production of 0.7 t.ha-1.a-1, then there is a clear economic advantage in using this species rather than the leguminous tree E. poeppigiana (management cost for C. alliodora are estimated to be less than the costs of using E.poeppigiana). However, if nutrient export in C. alliodora timber, together with crop damage during tree felling is taken into account, then there may be no long-term economic advantage in using C. alliodora. Organic material and hence nutrient cycling is greater under E. poeppigiana and on sites where management intensity (especially fertilization) and/or site fertility is less,then the relative advantages of using E. poeppigiana would increase.

Finally the conclusion is reasonable that the analyzed agroforestry systems maintain soil organic matter and promote nutrient cycling and therefore are also sustainable and appropiate for the soil conservation.

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Table 1 : Physical characteristics of the soil of the T.cacao/E.poeppigiana system

Depth (cm)	Apparent density g.cm-3	Sand %	Silt %	Clay %	Moisture content at 1.5 kPa	Moisture content at 0.33 kPa	Available water %
0 - 15	1.15	29	32	38	21.0	40.7	19.7
15 - 30	1.29	32	31	37	31.1	44.0	12.9
30 - 45	1.24	26	31	43	25.7	42.1	16.4

Table 2 : Chemical characteristics of the soils of the T.cacao / E.poeppigiana system (standard deviations in parenthesis)

Depht (cm)	pH 1977	pH 1986	% Humus 1977	% Humus 1986	% Total nitrogen 1977	% Total nitrogen 1986	ppm Total P 1977
0 -15	3.80(0.08)	4.26(0.05)	4.76(0.58)	5.50(0.49)	0.22(0.02)	0.25(0.01)	583(49)
-30	3.88(0.09)	4.22(0.03)	3.87(0.32)	4.23(o.56)	0.19(0.01)	0.19(0.02)	616(68)
-45	4.12(0.22)	4.22(0.07)	2.23(0.29)	3.40(0.52)	0.11(0.01)	0.16(0.02)	559(57)

	exch. K meq.100g soil 1977	exch. K meq.100g soil 1986	exch. Ca meq.100 g soil 1977	exch. Ca meq.100 g soil 1986	exch. Mg meq.100 g soil 1977	exch. Mg meq.100 g soil 1986
0-15	0.57(0.20)	0.28(0.04)	2.40(0.23)	3.29(0.63)	0.95(0.13)	1.34(0.26)
15-30	0.27(0.04)	0.17(0.05)	2.65(0.21)	2.62(0.38)	0.98(0.05)	1.09(0.22)
30 -45	0.17(0.06)	0.10(0.04)	3.27(0.30)	1.88(0.85)	1.03(0.05)	0.78(0.28)

Table 3. Annual Theobroma cacao production under the shade of Cordia alliodora or Erythrina poeppigiana (Dry weights cocoa beans; kg.ha-1.a-1)

	Cordia alliodora	Erythrina poeppigiana
1979	105	72
1980	452	474
1981	284	579
1982	691	758
1983	962	1040
1984	977	992
1985	909	1134
1986	1370	995
1987	960	1123
1988	851	831
1989	783	527
1990	837	711
1991	491	662
1992		
1993		
1994		
Average 15 years(0 - 13)	718	745

Table 4 : Growth of Cordia alliodora (Diameter , d ; hight h and mean annual increase , MAI) associated with Theobroma cacao (n = 16; standard deviation in parenthesis)

Age	Diameter		Height		Stem
	d	MAI	h	MAI	volume *
(yr)	(cm)	(cm.a-1)	(m)	(m.a-1)	(m3.ha-1)
1.2	4.1(1.6)	3.4	-	-	-
1.5	5.8(1.7)	5.7	5.0 (1.2)	3.3	
2.2	8.7(1.7)	4.1	6.3 (1.1)	1.9	
3.7	14.0 (2.1)	3.5	8.7 (1.0)	1.6	
4.5	16.1(2.1)	2.6	10.1(1.1)	1.7	22
5.3	17.8 (2.2)	2.1	10.6 (1.4)	0.6	32
5.8	17.7 (2.7)	0.0	10.9 (1.3)	0.6	32
6.3	18.7 (2.4)	2.0	11.5 (1.7)	1.2	39
7.3	20.1 (2.9)	1.4	12.6 (2.5)	1.1	47
8.3	21.7(3.2)	1.6	13.7(2.8)	1.1	61
9.3	22.8 (3.5)	1.1	13.7 (2.7)	0.0	66
10.5	24.1 (3.8)	1.1	15.0 (2.8)	1.1	78
12.4	26.6 (4.1)	1.3	15.9 (2.8)	0.5	100
13.3	27.2 (4.1)	0.7	16.5 (3.1)	0.6	110
14.8	28.6 (4.3)	0.9	17.5 (3.0)	0.8	127
15.6	29.6 (4.5)	1.2	18.0 (3.1)	0.5	140

* Estimated from volume table using the average values of d and h , Somarriba and Beer (1987)

Table 6 : Natural litterfall and pruning residue inputs in the systems of Theobroma cacao with Cordia alliodora and Erythrina poeppigiana (t.ha-1.a-1)

	T. cacao / C.alliodora				T. cacao / E.poeppigiana			
	leaves	leaves	branches	TOTAL	leaves	leaves	branches	TOTAL
Age 6 - 10 years								
Natural								
6 years	2.96	2.26	0.34	5.56	3.16	4.83	0.71	8.70
7 year	4.31	2.43	0.37	7.11	3.73	5.36	0.72	9.81
8 year	5.46	3.03	0.70	9.19	4.78	4.77	0.88	10.43
9 year	4.35	3.95	1.04	9.34	4.13	4.98	0.75	9.86
10 year	4.94	2.71	1.72	9.37	3.83	3.08	0.66	7.57
Average	4.40	2.88	0.83	8.11	3.93	4.62	0.74	9.29
Pruning by species	3.29	----		3.29	3.80		9.77	13.57
SYSTEM TOTAL			11.40				22.86	
Age 14 - 15 years								
Natural	l.73	4.22	1.58	7.53	2.22	3.24	0.87	6.33
Pruning	3.13	------		3.13	3.69	9.32		13.01
SYSTEM TOTAL			10.69				19.34	

Table 7 : Net primary production between ages 6 and 10 for the systems of Theobroma cacao with Cordia alliodora or Erythrina poeppigiana (t.ha-1.a-1)

Product	System	
	T.cacao/C.alliodora	T.cacao/E.Poeppigiana
Phytomass increase		
Crop	5.22	3.78
Tree	3.56	4.46
Roots	1.12	0.78
Agricultural production		
Cacao harvest	2.52	2.54
Production of residues	11.40	22.86
Fine root renewal	4.36	1.83
Total	28.18	36.25

Table 8 : Nutrient inputs and outputs in the systems of Theobroma cacao with C.alliodora or E. poeppigiana at age 6-10 years (kg.ha-1.a-1)

	T.cacao/ C.alliodora			T.cacao/ E.poeppigiana		
Transfer	N	P	K	N	P	K
Internal transfer						
Natural litterfall	129.0	19.8	37.7	198.3	17.6	25.8
Pruning residues	40.1	4.1	35.4	248.8	22.1	151.5
Total	169.1	23.9	73.1	447.1	39.7	177.3
Outputs						
Cacao yield	23.1	4.7	34.3	28.4	4.7	29.5
Leaching	6.0	0.6	2.2	6.0	0.7	1.8
Total	29.1	5.3	36.5	34.4	5.4	31.3
Inputs						
Rainfall	5.0	0.2	2.5	5.0	0.2	2.5
Fertilization	87.5	34.4	32.4	87.5	34.4	32.4
Total	92.5	34.6	34.9	92.5	34.6	39.9

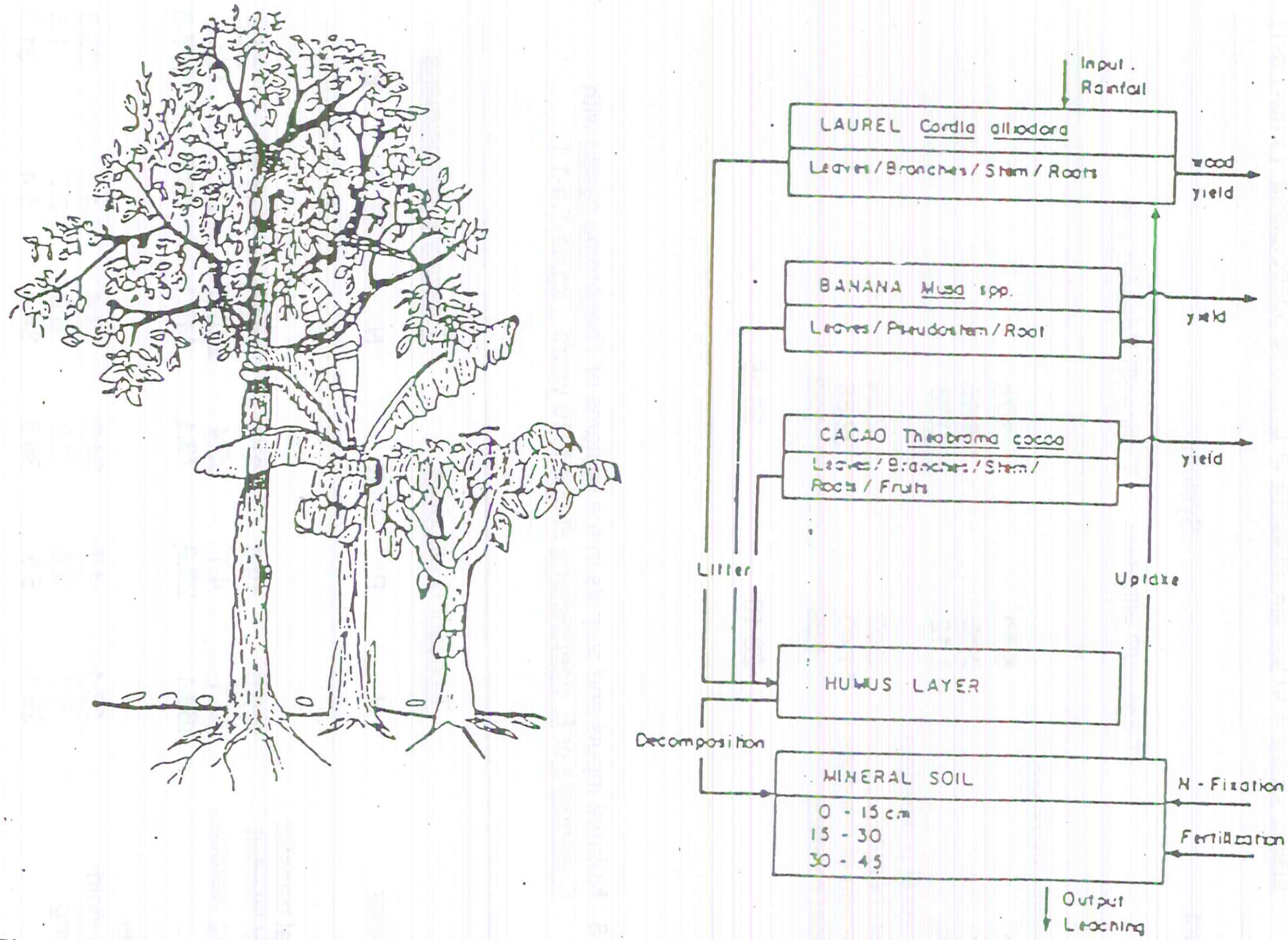


Figure 1. Schematic representations of an agroforestry system of cacao in association with shade trees and the model for organic matter and nutrients.

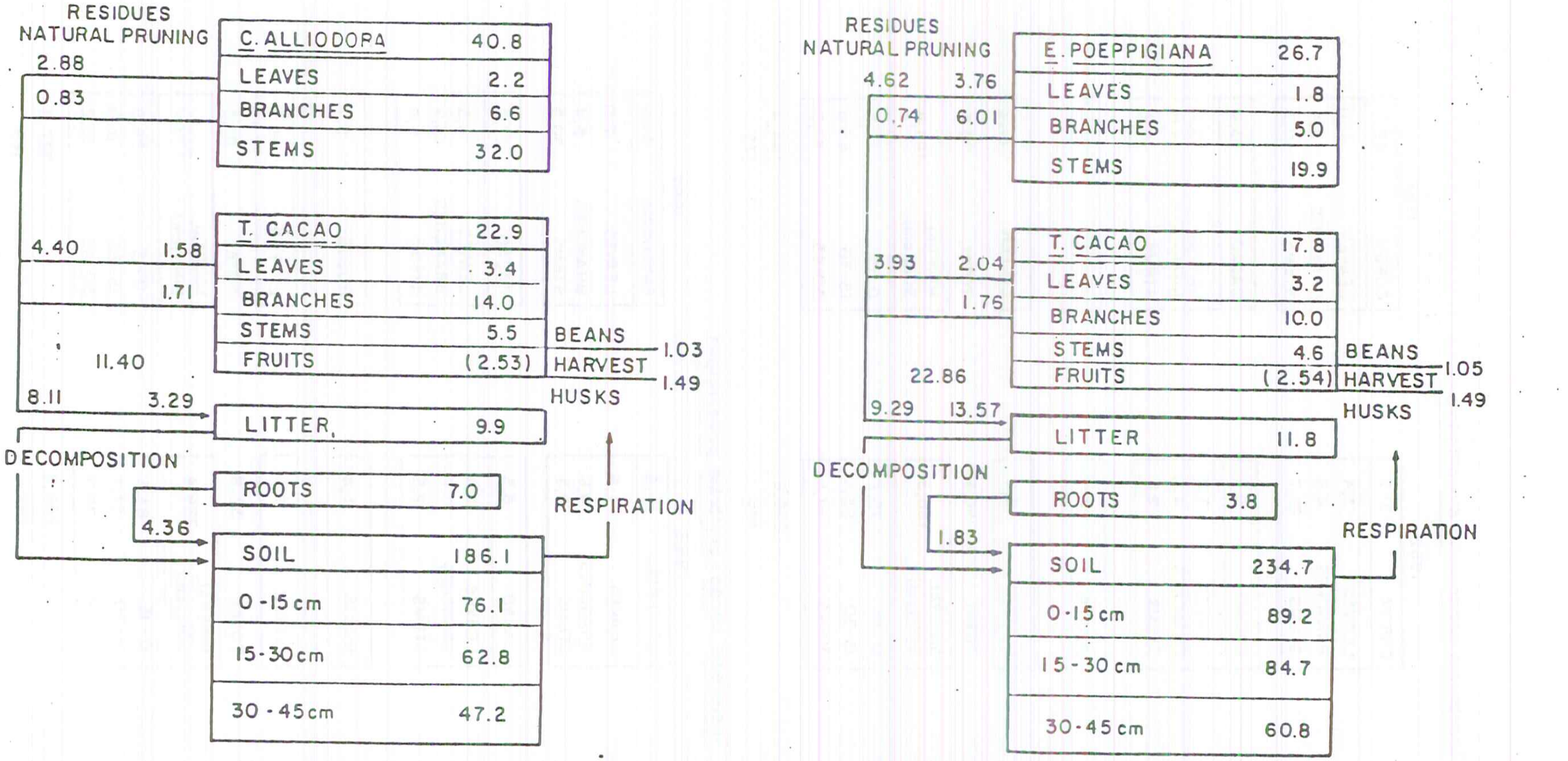
Theobroma cacao – Cordia alliodora

	1977	1982	1987
CORDIA		31,9	49,7
LEAVES		3,4	1,0
BRANCHES		4,8	8,4
STEMS		23,7	40,3
CACAO		9,8	35,9
LEAVES		3,0	3,7
BRANCHES		4,0	24,0
STEMS		2,8	8,2
ROOTS		4,2	9,8
LITTER		4,4	15,2
TOTAL		50,3	110,6
MINERAL SOIL (cm)	168,3	188,3	183,8
0-15	71,0	75,7	76,5
15-30	56,3	65,5	60,0
30-45	41,0	47,1	47,3
TOTAL	168,3	238,6	294,4
RELATIVE VALUE	100	142	175

Theobroma cacao – Erythrina poeppigiana

	1977	1982	1987
ERYTHRINA		15,6	37,9
LEAVES		1,6	2,0
BRANCHES		4,6	5,4
STEMS		9,3	30,5
CACAO		8,3	27,2
LEAVES		2,8	3,5
BRANCHES		3,0	16,9
STEMS		2,5	6,8
ROOTS		1,8	5,7
LITTER		7,1	16,5
TOTAL		32,8	87,3
MINERAL SOIL (cm)	198,4	229,4	240,0
0-15	81,7	83,5	94,9
15-30	75,0	87,4	81,9
30-45	41,7	58,5	63,2
TOTAL	198,4	262,2	327,3
RELATIVE VALUE	100	132	165

Fig. 2. Organic material reserves in the agroforestry systems *Theobroma cacao-Cordia alliodora* and *Theobroma cacao-Erythrina poeppigiana* at ages 5 and 10 years ($t.ha^{-1}$).



Phytomass: Average of two determinations, 1982 (5 years old) and 1987 (10 years old)
Soil reserves: Average of two determinations, 1982, 1986
Cacao harvest: Average of five years (1983-1987)
Residue production: Natural litterfall average of five years (1983-1987)
Pruning residues, average of two years (1985-1987)

Fig. 3. Quinquennial average models for organic matter in the systems *Cordia alliodora-Theobroma cacao* and *Erythrina poeppigiana-Theobroma cacao* (Reserves t.ha^{-1}; Transfers t.ha^{-1}.a^{-1}).

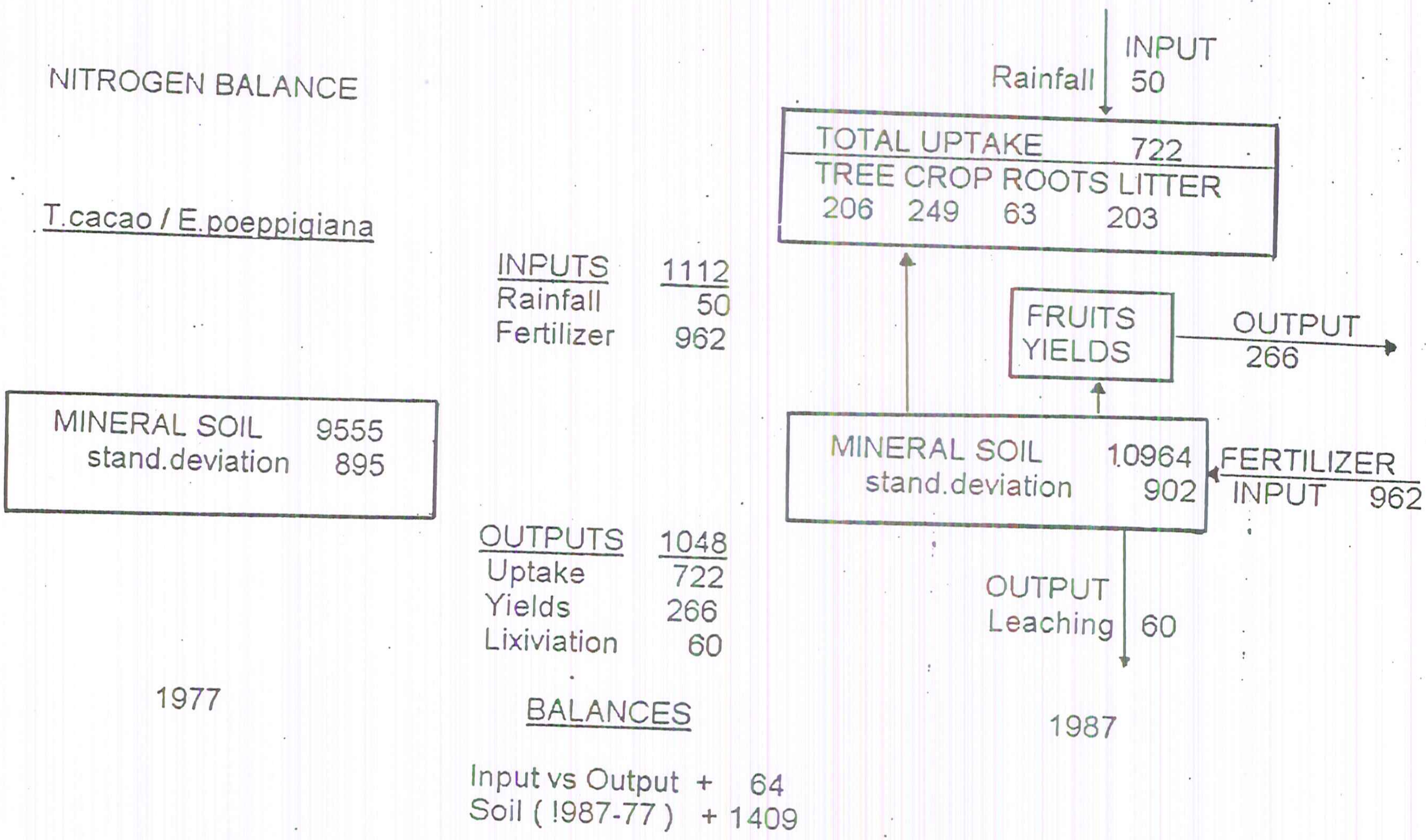


Figure 4 : Ten years balance of nitrogen for the agroforestry system of T.cacao with E.poeppigiana
(Soil reserves : kg.ha-1 ; Tranfers kg.ha-1.10a-1)

AMELIORATION OF SOIL ACIDITY IN TROPICAL SOILS WITH AGROFORESTRY RESIDUES

Mike T.F. Wong[1,2] and Stephen Nortcliff[1]

ABSTRACT

Over many decades it has been observed that the addition of organic residues to acid tropical soils results in an improvement in crop yields. These improvements have generally been ascribed to the increased provision of plant nutrients or the improvement of soil structural properties. Analysis of many of the experiments undertaken in the tropical zone show that the provision of nutrients in the added residues does not fully account for the improvement in yields. Within these regions the performance of crops is frequently limited by low soil pH. Soil pH is in many respects a master variable and low values (acidity) result in toxicities of aluminium and manganese and deficiencies of calcium, magnesium, phosphorus and molybdenum, and other nutrients. The first step therefore in improving the quality of the soil with respect to crop growth is to relive the problems imposed by acidity. This study reports field and laboratory evidence of the effects of adding residues from agroforestry tree species, *Calliandra calothyrsus, Grevillea robusta* and *Leucaena diversifolia* to an Oxisol in Burundi, in terms of the reduction in soil acidity and Al-saturation, and an improvement in field yields of maize. The improvement in yield is strongly associated with the decrease in Al-phytotoxicity. The potential of the plant residues to decrease the aluminium effect varies markedly with plant species. Laboratory analysis of the residues, in particular the ratio of soluble polyphenol and nitrogen contents, has provided a partial explanation for the differences in response. It has become apparent that when applying agroforestry residues to soil, in addition to the nutrient inputs from the residues, consideration must be given to the potential effects of these residues in reducing acidity and Al-phytotoxicity. In tropical soils where the major constraint to crop production is often acidity and Al-phytotoxicity the decisions concerning choice of agroforestry tree should consider the potential of the tree residues to ameliorate these problems. The ability of the agroforestry tree residues to ameliorate soil acidity and Al-phytotoxicity might be considered an important additional entry in any database on agroforestry trees.

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1. INTRODUCTION

Over many decades it has been observed in acid tropical soils that additions of organic matter to the soil results in improvement in crop yield and overall system productivity (see for example NYE and GREENLAND, 1960; YOUNG, 1989). These improvements have generally been ascribed to the increased provision of plant nutrients or the improvement of soil structural properties (see for example LAL and GREENLAND, 1979; LAL and KANG, 1982; SWIFT and SANCHEZ, 1984). Analysis of many of the experiments undertaken in the tropical zone show that the addition of nutrients in the added residues does not fully account for the improvement in yields. In addition there are few consistent quantifiable improvements in soil structure which can be related to yield improvement or stability. Within these regions however the performance of crops is frequently limited by low soil pH. Soil pH might, in many respects, be considered a master variable within these systems, and low values (acidity) result in toxicities of aluminium and manganese and deficiencies of calcium, magnesium, phosphorus, molybdenum and other nutrients. An important, and probably the first, step to be taken in the management of acid tropical soils is to relieve the problems imposed by acidity. Once this problem is addressed the resolution of many of the other limitations is generally more straightforward.

In mineral soils the activities of Al in solution is generally controlled by the dissolution of clay sized minerals such as gibbsite, amorphous aluminium oxide and kaolinite (ROWELL, 1988). The solution Al activity in turn influences the exchangeable Al content of the soil (REUSS, 1983). Protons are consumed during dissolution of Al-bearing minerals and this results in a strong dependence between the activity of Al in solution and the soil pH. Decomposition products of organic residues can however react with Al and decrease its activity in solution (BARTLETT and RIEGO, 1972; HUE et al., 1986; HUE and AMIEN, 1989). WONG and SWIFT (1995) showed that the decreased Al activity with organic matter was due to decreased solubility of the soil aluminium minerals. The treated soils also had a greater selectivity for exchangeable Al. When there is a control on Al activity by mineral dissolution, cation exchange reactions should buffer the activity of Al in the soil solution. By decreasing both the solubility of the soil aluminium and increasing the selectivity for exchangeable Al, the organic matter treatment should lead to lower Al activities.

WONG et al. (1995) showed that additions of tree prunings reduced the concentration of monomeric inorganic aluminium in the soil solution. They noted reductions from 2.92 mg Al dm^{-3} in control plots to 0.75 mg Al dm^{-3} in plots to which 6 t ha^{-1} of *Calliandra calothyrsus* residues were incorporated in the 0-5 cm layer of an Oxisol in Burundi. They also showed that plant materials added to the soil differed in their ability to ameliorate soil acidity.

This study seeks to show, for an Oxisol in Burundi, the yield response in maize to additions of two levels of organic matter additions in the form of residues from agroforestry trees. The variability in the yield response to the addition of agroforestry residues indicates, in part, that the plant residues differ in their ability to ameliorate soil acidity.

Plant materials consist chiefly of cellulose, lignin, proteins and a range of polysaccharides. All these materials have the ability to complex aluminium, but their complexing capacity is generally small. Decomposition of these compounds with the soil system results in oxidation and the formation of organic compounds with more oxygen containing functional groups. These functional group, especially the carboxyl and phenolic groups have high affinities for aluminium (STEVENSON and VANCE, 1989). It would therefore appear likely that the composition factors which affect plant residue decomposition will also affect the aluminium bonding capacity. Much of the emphasis on decomposition of organic residues in tropical farming and agroforestry systems has focused on the mineralisation of the nitrogen from these residues. The phytochemistry of the material will determine the rate of release of nitrogen from the residues. Many workers have suggested the C:N ratio, nitrogen and lignin contents of the residues are linked with decomposition rates and nitrogen release (TENNEY and WAKSMAN, 1929; JENSEN, 1929; FRAKENBERGER and ABDELMAJID, 1985). With many tropical leguminous plant materials the soluble polyphenol content interferes with mineralisation by forming complexes with proteins (DAVIES et al., 1964; VALLIS and JONES, 1973; PALM and SANCHEZ, 1991; FOX et al., 1990; TIAN et al., 1992). Lignin will also degrade to simpler phenolic compounds and these compounds will also combine with plant proteins and amino acids to form humic polymers that are capable of binding aluminium (HAYNES, 1986; WONG and SWIFT, 1995). The plant nitrogen, soluble polyphenol and lignin content are therefore expected to influence the potential of plant materials to ameliorate soil acidity by influencing the formation of decomposition products with functional groups capable of binding aluminium.

2. MATERIALS AND METHODS

2.1 Site description

The field experiment was conducted and soil samples taken at a high altitude site (1600m) at Karuzi in Burundi (3.04 S and 30.09 E). The soil at the site is an Oxisol. The site had been under bush regrowth for a number of years. Table 1 provides a brief summary of the characteristics of the soil. The clay mineralogy is dominated by kaolinite and gibbsite with minor amounts of goethite, vermiculite and quartz. The sum of exchangeable cations (ECEC) at the start of the experiment was 3.31 $cmol_c\ kg^{-1}$. The rainfall for the study year was 1010 mm and the rainy season extended from September to May.

Table 1

2.2 Soil treatment

Calliandra calothyrsus, *Grevillea robusta* and *Leucaena diversifolia* were planted in pure stands to produce prunings for this experiment. The treatment plots were arranged in three blocks with 7 treatments allocated randomly to each block. The equivalent dry weight rates of treatments given each season to the test crop were

1. *Calliandra* at 3 t ha^{-1}
2. *Calliandra* at 6 t ha^{-1}
3. *Grevillea* at 3 t ha^{-1}
4. *Grevillea* at 6 t ha^{-1}
5. *Leucaena* at 3 t ha^{-1}
6. *Leucaena* at 6 t ha^{-1}
7. Control with no crop residues

Tree prunings consisted of small twigs and leaves cut to approximately 1.5 cm pieces. The prunings were shallowly mixed within the surface 0-5 cm. In addition to organic residues the maize received 60 kg N ha^{-1} as urea, 30 kg P ha^{-1} as triple superphosphate and 30 kg ha^{-1} as KCl. The fertilisers were applied to minimise the compounding effects of nutrients returned by the prunings. The maize crop was a second crop on this land, the first crop of beans having failed due to moisture stress during drought.

2.3 Incubation experiment

Soil samples from the Oxisol were incubated with young prunings of *Calliandra calothyrsus*, *Grevillea robusta* and *Leucaena diversifolia*. The prunings were air dried, passed through a 2mm sieve and used at the rate of 4.5 g prunings in 145.5 g soil (3% by weight). The blank soil had no prunings added. Each treatment was replicated three times. The soil samples were incubated in open polythene bags and maintained at -10 kPa water tension and 30°C. The samples were aerated and the water potential adjusted daily. The incubated soils were sampled at 14, 42 and 98 days to evaluate the duration of the organic matter effect.

2.4 Soil analysis in the incubation experiment

The soil pH was measured in 2 mM $CaCl_2$ using a 1:1 weight ratio. the soil was extracted with 1 M KCl using a soil to solution ratio of 1:5 and extractable calcium and magnesium were measured by atomic absorption spectrophotometry (THOMAS, 1982). Total extractable acidity was measured by titration with sodium hydroxide. The solution was then treated with excess sodium fluoride to release hydroxyl ions from the aluminium hydroxide produced. The released hydroxyl ions were titrated with sulphuric acid to give the exchangeable aluminium content of the soil and the exchangeable protons content by difference (ROWELL, 1994).

2.5 Analysis of prunings

Representative samples of the prunings of the tree species were analysed by acid peroxide digestion followed by measurement of Ca and Mg by atomic absorption spectrophotometry (THOMAS, 1982), K by emission spectrophotometry and P by colorimetry (Table 2). The Kjeldahl method was used to measure the nitrogen content of the samples by steam distillation (BURESH et al., 1982). Carbon was measured by dry combustion using a Leco furnace. Lignin contents were determined by acid detergent fibre method of VAN SOEST and WINE (1968). The methanol soluble polyphenol contents were determined by the Folin-Denis method (ANDERSON and INGRAM, 1993).

Table 2

3. RESULTS:

3.1 Field Experiment

The yield of maize increased with the application of prunings (Table 3). The yield improvements at 3 t ha^{-1} were significantly higher than the control, but there were no significant differences between the 3 treatments. For applications at 6 t ha^{-1} the yields were significantly higher than for applications at 3 t ha^{-1}, but the increase for *Grevillea* residues was small. The residues may be broadly ranked in terms of the 'yield improving' effect in the order, *Calliandra* > *Leucaena* > *Grevillea*. The relative limited effect of *Grevillea* may be accounted for by the lower nutrient content of the prunings (see Table 1).

Table 3

3.2 Incubation Experiment

3.2.a. Exchangeable aluminium

The largest decrease in exchangeable aluminium content occurred during the first 14 days of incubation (Table 4). The effect of *Leucaena* was marked, there was no exchangeable aluminium after 14 and 42 days incubation, and whilst there was exchangeable aluminium after 98 days incubation the level was still low. The patterns exhibited by the other two treatments were complex. The peak reduction recorded with *Grevillea* was after 42 days, and *Calliandra* residues showed marked effects at 14 and 42 days with a sharp increase at 98 days. At 98 days although there was a reversion to more acid conditions (see below) and a commensurate increase in exchangeable aluminium there was still a reduction when compared to the untreated soil. The duration of this soil amelioration, although varying between residues was observed for the three residues and should last for the production of many crops and this may be reflected in the results obtained in the field experiment. In this study the residues may be ranked in their effectiveness in decreasing exchangeable aluminium in the soil in the following sequence: *Leucaena* > *Calliandra* > *Grevillea*. It should be noted that the order is different from that for yield improvements, but *Grevillea* is considered poorest in both cases.

Table 4

3.2.b. Soil pH

Following incubation of the Oxisol with tree prunings, the pH of the Oxisol increased from a mean value of 4.11 in the untreated soil to a value of 5.31 in the soil treated with *Leucaena* residues (Table 5). WONG et al. (1996) have shown that the exchangeable aluminium decreased to zero at pH 5.00 for this soil. This pattern of change in exchangeable aluminium with pH is typical of many tropical soils (THOMAS and HARGROVE, 1984). The organic matter effect in this experiment went beyond this critical value of pH 5.00 when *Leucaena* prunings were added. Exchangeable aluminium alone cannot be used to discriminate between the most effective species for soil amelioration and yield improvement once pH > 5.00 is achieved and exchangeable aluminium was completely eliminated. (Soil pH appears to be a better index of soil ameliorating quality because there was no upper limit to its value. This increased according to the prunings ability to neutralise acidity.) The ranking of the residues with respect to their ability to improve pH varied through time; at 14 days the ranking was *Leucaena* > *Grevillea* > *Calliandra*; at 42 days *Leucaena* > *Calliandra* > *Grevillea*; and 98 days *Calliandra* > *Leucaena* > *Grevillea*.

Table 5

3.2. Composition of the residues

The C:N ratios of Calliandra (15) and Leucaena (16) were similar and lower than that of Grevillea (27). These ratios could not be related to the pH of the incubated soil. The soil pH varied in a complex manner during incubation as was shown above. The average soil pH over the 14, 42 and 98-day incubation period was 4.71 for *Grevillea*, 4.81 for *Calliandra* and 5.31 for *Leucaena*. These pH values ranked in the same way as the polyphenol: nitrogen ratios which were *Leucaena* (0.65) < *Calliandra* (0.79) < *Grevillea* (1.04). This ratio seems better linked to average soil pH than the C:N ratio because the polyphenol content of the material is expected to influence decomposition rates and the formation of oxygen containing functional groups that are able to complex aluminium. The polyphenol to nitrogen ratio of the plant residues appears to have a varying effect through time. The best relationship between ranking of soil pH and polyphenol to nitrogen ratio was obtained at 42 days. The prunings from *Leucaena* produced a significantly stronger ameliorating effect particularly during the first 14 days, and the ameliorating effect of these residues was still high after 42 days. After 98 days there was no significant advantage shown with the *Leucaena* prunings

The use of the ratio of soluble polyphenols plus lignin to nitrogen ratio of the residues showed no clear relationship with the changes in pH or exchangeable aluminium. This lack of a clear relationship may be due to the fact that young prunings with a low lignin content were used in this experiment. With old materials, the lignin content will increase and the proportion in the added residues may have a significant influence on the potential ameliorative effects of adding the residues (see for example FOX et al., 1990; HANDAYANTO et al., 1994).

4. CONCLUSIONS

The aim of this paper was to determine whether the yield improvements observed in the field in Burundi were due to the improvement of soil fertility through the addition of nutrients or as a result of the partial neutralisation of acidity. The data presented illustrate the complex nature of this problem and suggest there is a need for further detailed investigations in to the mechanisms operating in these acid soils if the ameliorating potential of tree residues is to be fully realised.

The data in Table 1 show that the level of aluminium saturation in the untreated soil is expected to severely limit maize growth. The addition of the organic tree residues decreased this aluminium saturation to low levels and therefore is a contribution to the improvement in maize yields. The addition of nutrients in the prunings should have less effect since a basal fertiliser application was used. This further reiterates the point made above that many experiments which are currently using organic residues as additions to acid tropical soils should include an assessment of the changes in soil pH and aluminium.

The amelioration of soil acidity is shown to be a complex process and the ranking of the effectiveness of the three materials considered here varied with time of incubation. The results obtained at 98 days incubation appeared best related with the performance of the prunings in the field. These findings were obtained under controlled laboratory conditions and ignore field processes such as leaching which will be expected to influence the performance of prunings in soil acidity amelioration. We must take steps to calibrate the laboratory methods in the field as is being done for liming recommendations.

5. ACKNOWLEDGEMENTS

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Table 1. Selected soil properties of the Oxisol from Burundi

Clay	Sand	Organic-C	pH (H_2O)	Al^{3+}	Ca^{2+}	Mg^{2+}
	%				$cmol_c\ kg^{-1}$	
65	15	4.47	4.4	2.46	0.58	0.16

Table 2: Chemical composition of prunings of tree species used for incubation

Trees	*Ca*	*Mg*	*K*	*Sum Cations*	*C*	*N*	*polyphenol*	*Lignin*
		mol$_c$	*kg^{-1}*				%	
Calliandra	0.78	0.23	0.24	1.25	46.0	3.01	2.39	4.30
Grevillea	0.44	0.13	0.37	0.94	47.6	1.76	1.84	16.7
Leucaena	1.68	0.25	0.32	2.25	42.3	2.60	1.68	3.10

Table 3: The yield effects on maize grain yields ($t\ ha^{-1}$) following applications of prunings.

Treatment	**3 t ha^{-1}**	**6 t ha^{-1}**	**Mean**
Calliandra	1.367	2.151	1.759
Grevillea	1.237	1.306	1.272
Leucaena	1.345	1.609	1.477
Control	0.644	0.644	0.644

Table 4. Exchangeable aluminium ($cmol_c\ kg^{-1}$) at 0, 14, 42 and 98 days of incubation with agroforestry residues

Treatment	Incubation days			
	0	14	42	98
Calliandra	1.8	0.39	0.44	0.97
Grevillea	1.8	0.76	0.62	0.78
Leucaena	1.8	0.0	0.0	0.39

Table 5: Soil pH at 0, 14, 42 and 98 days incubation with agroforestry residues

Treatment	Incubation days			
	0	14	42	98
Calliandra	4.11	4.81	4.80	4.83
Grevillea	4.11	4.86	4.74	4.55
Leucaena	4.11	5.99	5.26	4.68

EFFECT OF FERTILIZING ON ESTABLISHMENT AND EARLY GROWTH OF TREE PLANTATIONS ON IMPERATA CYLINDRICA DOMINATED GRASSLANDS

Antti Otsamo[1]

ABSTRACT

Effects of fertilizer combinations on early growth of fast growing plantation tree species were tested in two separate experiments on *Imperata cylindrica* dominated grasslands in South Kalimantan, Indonesia. Effects of commercial NPK and locally made NPK mixtures on the growth of *Acacia mangium*, *Gmelina arborea*, *Paraserianthes falcataria* and *Swietenia macrophylla* were tested. In the second experiment the effects of N, P, K, and their combinations with micronutrients on the growth of *A. mangium*, *G. arborea* and *Eucalyptus deglupta* were tested. Two years after planting different NPK-mixtures did not have significant effect on the growth of *A. mangium* and *S. macrophylla*. Response of *P. falcataria* and *G. arborea* was strongest with the commercial NPK. In the second experiment significant differences in growth of *A. mangium*, *G. arborea* and *E. deglupta* between sites and fertilizer treatments were detected. Responses were strongest to the treatments where phosphorous-component was included. *A. mangium* had steady performance compared to *G. arborea*, *P. falcataria* and *E. deglupta*, which were more sensitive to fertilization treatments and site effects. Fertilization is important on forest plantations on grasslands as it clearly speeds up the early growth that is important for gaining site control over the grass. Phosphorous component must be included in the fertilization treatments on grasslands. NPK-fertilization is recommended as a standard solution if detailed information on the site is not available.

Keywords: fertilization; fertilizer; plantation; reforestation; afforestation; phosphorous.

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1. INTRODUCTION

Grasslands dominated by Imperata cylindrica (alang-alang) have developed after forest clearing and the subsequent fires, and they cover large areas of former forest land throughout moist tropical regions, particularly in Southeast Asia. In Indonesia alone, the total area of Imperata grasslands is estimated at 20 million ha (ITTO 1990).

In Indonesia forest plantations will be the major source of wood supply for forest industries in 10-20 years. Therefore, large areas have been allocated for forest plantations on degraded forest lands, which include vast areas of grass- and bushlands. However, there have been several failures in plantation projects. The survival rate in rehabilitation of forest land has been estimated at 57% (PANDLEY, 1992). Therefore, reliable knowledge on the factors affecting the plantation success is needed.

Imperata grasslands are difficult to reforest because of grass competition and allelopathy, fire susceptibility and soil degradation (DELA CRUZ, 1986, OHTA, 1990). Promising results in grassland reforestation have been achieved by using Acacia-species and Gmelina arborea. Considering the relatively high establishment costs of forest plantations on Imperata grassland, the mean annual increment of a profitable timber or pulp plantation should be at least 25 $m^3ha^{-1}a^{-1}$ (RISSANEN, in press).

Grasslands have generally low nutrient levels compared to natural forest soils. Especially phosphorus levels have been noted to be low (OHTA, 1990). Furthermore, soil compaction is probably one of the factors making Imperata grasslands unfavorable sites for forest plantations. These factors can at least partly been overcome by intensive site preparation and initial fertilization with NPK-fertilizer as recorded by OTSAMO et al. (in press) (Fig.1).

(Figure 1)

The aim of the study was to test the effects of different fertilization combinations on some promising fast-growing tree species used for the reforestation of Imperata cylindrica dominated grasslands. The emphasis was in monitoring the early effects of fertilization on plantation establishment.

2. MATERIAL AND METHODS

2.1 Study area

Riam Kiwa trial plantation area is located in South Kalimantan, Indonesia (3°30'S; 115°E). Topography is undulating and the altitude 100-200 m above the sea level.

Mean annual rainfall in 1988-1994 was 2043 mm (1574-2364 mm). The long-time average is 2128 mm with a dry season from May to September, with only 20 %of the annual rainfall occurring during this period.

Soils are deeply weathered, heavy textured and acid, suffering from various degrees of degradation. They belong to the red-yellow podzolic type, with low pH-values and comparatively low levels of nutrients (SIMPSON, 1992). Parent material consists of igneous rocks. Compared to several other Imperata-dominated areas in Asia, soil at the study site is relatively deep and fertile and suitable for tree plantations (JUSOP and HANIF, 1992). The good growth potential of the site was confirmed, as the growth of Acacia auriculiformis in Riam Kiwa was higher than in any other site, as seven sites in Indonesia, Malaysia, Thailand and Taiwan were compared in an international provenance trial (AWANG et al., 1994). Details of the soil characteristics on experimental sites are presented in Table 1.

(Table 1)

Vegetation on the trial site was dominated by Imperata cylindrica grass (height 1-1.5 m; above ground dry biomass 10-20 t ha^{-1}), which has covered the area since the Second World War, probably even longer.

2.2 Nursery practices

The seedlings were grown in plastic containers (Enso-pot; 183 cm^3) in a mixture of peat and rice husk (70:30), and tended according to standards used for seedling production of acacias.

2.3 Site preparation

The trial sites were treated by plowing the whole area twice (5 and 3 months before planting) with a disc plow, reaching the depth of 25 cm, during the dry season, and harrowing once before planting. Site preparation was started during the dry season in July and the planting was done in December, one month after the start of the rainy season.

2.4 Experiment 1

Experiment 1 consisted of separate trials for Acacia mangium, Gmelina arborea, Paraserianthes falcataria and Swietenia macrophylla respectively. Each species had the following fertilizer treatments:

1) Control (no fertilizers)
2) Commercial NPK (15:15:15) (150 g $tree^{-1}$)

3) Mixed NPK (48.9 g Urea, 48.9 g TSP and 37.5 g KCl)
4). Mixed NPK (48.9 g Urea, 24.5 g TSP, 45 g Rock phosphate and 37.5 g KCl)

Planting was done by the plots of 25 (5 x 5) trees at the spacing of 2 x 2 m (2500 seedlings ha^{-1}). Randomized complete block design with 3 replications was used. Fertilization was applied 12 months after planting.

Survival was assessed from the whole plot, whereas height, diameter at breast height and crown diameter were measured 24 months after planting from nine inner trees in each plot. For indicating the differences between treatments, tree volume estimates were calculated by using stem form factor 0.45, determined for Acacia mangium (SADONO and SETYARSO, 1992). Therefore, volume estimates were not included in statistical analysis and should not be considered absolute values or used for comparison of different species.

The plot means data for other variables was analyzed by analysis of variance. Pairwise significant differences were analyzed by using Tukey's HSD-test of means.

2.5 Experiment 2

Acacia mangium, Gmelina arborea and Eucalyptus deglupta were used in the trial. Planting was done by the plots of 25 (5 x 5) trees at the spacing of 3 x 3 m (1111 seedlings ha^{-1}). Factorial layout trial was established at 3 sites: 1) yellow podzolic, 2) red podzolic, 3) alluvial, with two replications on each site. Eucalyptus deglupta was planted on sites 1 and 2 only. The fertilizer treatments were as follows (nutrients as kg ha^{-1}): 1) Control (0); 2) N (N50); 3) P (P50); 4) K (K50); 5) NP (N50+P50); 6) NK (N50+K50); 7) PK (P50+K50); 8) NPK (N50+P50+K50) 9) All (N50+P50+K50+Ca107+Mg74+ Cu5+Zn5+B5)

Fertilizers used were triple superphosphate TSP (20.7% P), Urea (46% N), KCl (50% K), Dolomite (13% Ca and 9% Mg), Copper sulphate monohydrate (35.5% Cu), Zinc sulphate (36% Zn), and Borax (11.4% B).

One third of the total dose of fertilizers was applied immediately after planting, and two thirds 12 months after planting.
Survival, height, diameter at breast height and crown diameter were measured 24 months after establishment. Survival was assessed from the whole plot, whereas other variables were measured from nine inner trees only. Tree volume estimates for Acacia mangium were calculated by using stem form factor 0.45. The effects of fertilization and site within each species were analyzed with two-way ANOVA. Pairwise differences were tested by Tukeys HSD-tests of means.

3. RESULTS

3.1 Experiment 1

Survival for all the species was 100%. Fertilization treatments did not have any statistically significant effects on the growth of Acacia mangium and Swietenia macrophylla. However, clear significant difference between treatments for Paraserianthes falcataria was detected, as the commercial mixture of NPK more than doubled the basal area growth compared to control. Mixed NPK-treatments also had significant effects, which were not as strong as with the commercial fertilizer (Table 2, Fig. 2). For Gmelina arborea the fertilization effects showed similar trend with Paraserianthes falcataria, but the differences were not as distinct and not statistically significant ($p<0.05$) (Table 2).

(Table 2)

(Figure 2)

3.2 Experiment 2

Statistically significant differences in growth of Acacia mangium between fertilization treatments were detected (Table 3, Fig. 3). The lowest basal area (control) was 49% of the highest recorded value (NPK+micronutrients). There were also significant differences between the sites ($F=8.528$; $p=0.000$ for basal area; $F=16.410$; $p=0.000$ for stand volume) but no interaction between sites and fertilization. The mean (all treatments pooled) basal area (S.E) was 7.1 (0.7), 9.0 (0.5) and 5.7 (0.5) m^2ha^{-1}, and stand volume (S.E.) 25.4 (2.9), 32.0 (1.9) and 19.2 (2.1) m^3ha^{-1} at sites 1, 2, and 3 respectively.

(Table 3)

(Figure 3)

Statistically significant differences in growth of Gmelina arborea between fertilization treatments were detected (Table 4). The lowest basal area (K) was 24% of the highest recorded value (NPK). There were also significant differences between the sites ($F=23.666$; $p=0.000$ for basal area) but no interaction between sites and fertilization. The mean (all treatments pooled) basal area (S.E.) was 5.3 (0.7), 3.4 (0.6) and 0.6 (0.1) m^2ha^{-1} at sites 1, 2, and 3 respectively.

(Table 4)

Statistically significant differences in growth of Eucalyptus deglupta between fertilization treatments were detected (Table 5). The lowest basal area (K, NK) was 10% of the highest recorded value (NPK). There were also significant differences between the sites on height ($F=8.703$; $p=0.000$) and DBH ($F=4.610$; $p=0.001$), but not on basal area. No interaction between sites and fertilization was detected. The mean (all treatments pooled) basal area (S.E.) was 0.7 (0.2) and 1.1 (0.2) m^2ha^{-1} at sites 1 and 2 respectively.

(Table 5)

4. DISCUSSION

Acacia mangium had reasonably steady performance on all sites and the responses to fertilizers were less distinct compared to other species tested (except Swietenia macrophylla). Gmelina arborea and Paraserianthes falcataria were more sensitive to fertilization treatments and site effects, which indicates need for careful site selection and supplementary fertilization. Performance of Eucalyptus urophylla was poor, which is in line with the earlier records on eucalypts on the area (OTSAMO et al., in press). However, the response to fertilizer treatments was stronger than with any other species. Site differences for the species could not be effectively analyzed, as it was not planted on alluvial site.

The low response of Swietenia macrophylla to fertilizer treatments confirms the earlier records on the same area (OTSAMO et al., in press). The lack of response of Swietenia macrophylla may be due to the young age of the stands and characteristically slower growth compared to other species.

Commercial NPK-mixture outperformed locally made mixtures in early responses, which is probably due to the more even release of different components.

With all the species responses were strongest to the treatments where phosphorous-component was included. This result is well in line with results of OHTA (1990), which indicate that phosphorous levels on grasslands are low. On the contrary to the conclusions of SIMPSON (1992), potassium treatment did not have any positive effect on any of the species.

The results of this study were obtained on a reasonably fertile Imperata-grassland site. However, the random variation within treatments was quite distinct, which may be an indication of considerable microvariation within sites. The differences on growth between the three different sites indicate the difficulty in accurate growth prediction on large-scale forest plantations on grasslands and further emphasize the need for careful site evaluation before planting operations.

The results of the study present the early responses on young stands. This information is especially important, as the maximum growth right after planting is considered essential on forest plantations on Imperata grasslands, so that grass competition can be minimized and later eliminated with closed canopy. The results of the study indicate the importance of early fertilization in ensuring plantation establishment and vigorous early growth. Long-lasting effects on actual wood production during the whole rotation cannot be predicted from these results. However, according to the review of SCHÖNAU and HERBERT (1989) on eucalypts the effects of early fertilization are usually long-lasting and will last the whole rotation period. This would be logical, as fertilizer input on poor sites like Imperata grasslands increases the total nutrient level on the site that remains in the nutrient cycle of the stand until harvesting. The optimal amounts and application schedules are probably highly site- and species-specific and need well-organized field research combined with disciplined construction of theoretical models on nutrient cycling.

The study concentrated on presenting the effects of fertilizing from the silvicultural point of view. However, if the results are applied on effective wood production programs, detailed cost-benefit analyses have to be included in order to assess the profitability of fertilizing. According to RISSANEN (in press) even a reasonable small increase in yield is worth considerable investment. The results of this study indicate that fertilization is an effective means to increase yield, which supports the idea of fertilizing on forest plantations on grasslands as a profitable operation.

5. CONCLUSIONS

Fertilization plays an important role in forest plantations on grasslands as it clearly speeds up the early growth which is important for gaining site control over the grass. Despite differences between sites, the response to fertilizers had the same pattern on all sites. Therefore, these results can be applied on other grassland sites as well, even though the magnitude of response must be studied site by site.

It is evident that phosphorous component must be included in the fertilization treatments on grasslands. NPK-fertilization is recommended as a standard practice for grassland reforestation if more detailed information on the site is not available. More detailed studies are needed on the long-term effects of fertilizers and the interactions between different tree species and the soil.

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Table 1. Soil characteristics on the trial sites of fertilizing trials in Riam Kiwa, South Kalimantan, Indonesia.

Site	pH 1	pH 2	C-org %	N-tot %	P-avl ppm	CEC	K	Na	Ca	Mg	Al	H+	Clay %	Silt %	Sand %
							meq/100 g of soil						Texture		
Exp 1	4.0	4.2	0.7	0.03	0.3	21.0	0.03	0.23	0.2	0.18	1.15	1.52	56.1	15.3	28.7
Exp 2.1	4.9	4.3	3.6	0.18	4.45	22.1	0.35	0.39	3.9	1.20	0.56	0.36	49.1	25.4	25.4
Exp 2.2	4.4	4.0	2.7	0.15	3.02	20.1	0.38	0.36	2.0	1.06	3.42	0.60	41.2	28.3	30.5
Exp 2.3	5.1	4.6	2.5	0.15	1.73	22.3	0.22	0.19	2.4	3.6	0.24	0.23	26.4	36.8	36.8

avl available
tot total
CEC cation exchange capacity
ph 1 in H_2O
ph 2 in KCl

NOTE: On the site of experiment 1 soil samples were collected as a composite sample at dephts of 1-80 cm, whereas on the three sites of experiment 2, only topsoil samples were collected at the depth of 1-20 cm.

Table 2. Height, diameter at breast height (DBH), basal area and crown diameter of Acacia mangium, Gmelina arborea, Paraserianthes falcataria, and Swietenia macrophylla 24 months after planting in sites with control and three different NPK treatments. Standard error of mean in parentheses.

Species	Treatment	Height (m)	DBH (cm)	Basal area ($m^2 ha^{-1}$)	Crown diameter (m)
Acacia mangium	Control	7.5 (0.5)	6.4 (0.5)	9.0 (1.3)	2.9 (0.1)
	NPK 1	8.0 (0.2)	6.4 (0.5)	9.2 (1.4)	3.0 (0.5)
	NPK 2	8.3 (0.4)	7.1 (1.0)	10.7 (2.8)	2.8 (0.1)
	NPK 3	7.9 (0.2)	6.5 (0.3)	9.0 (1.2)	2.9 (0.3)
	F	1.462	0.837	0.816	0.147
	p	0.316	0.521	0.530	0.928
	HSD	-	-	-	-
Gmelina arborea	Control	3.4 (0.3)	5.5 (0.6)	6.6 (1.3)	3.2 (0.2)
	NPK 1	4.4 (0.3)	7.5 (0.5)	11.7 (1.5)	3.2 (0.1)
	NPK 2	4.3 (0.3)	7.4 (0.5)	11.6 (1.5)	3.1 (0.0)
	NPK 3	4.2 (0.1)	7.0 (0.2)	10.6 (0.8)	3.1 (0.1)
	F	4.571	3.837	3.018	0.100
	p	0.054	0.076	0.116	0.957
	HSD	-	-	-	-
Paraserianthes falcataria	Control	3.4 (0.2)	4.7 (0.4)	4.8 (0.9)	2.8 (0.3)
	NPK 1	6.1 (0.2)	7.6 (0.1)	11.7 (0.3)	3.8 (0.1)
	NPK 2	4.6 (0.6)	6.2 (0.9)	8.5 (2.2)	3.8 (0.4)
	NPK 3	4.9 (0.2)	6.6 (0.4)	9.5 (1.4)	4.2 (0.2)
	F	12.874	9.230	9.128	2.342
	p	0.005	0.012	0.012	0.173
	HSD	1.5	2.0	4.7	-

CONT FROM PREVIOUS PAGE

Swietenia macrophylla	Control	2.2 (0.2)	3.1 (0.2)	2.1 (0.2)	0.9 (0.1)
	NPK 1	2.4 (0.2)	3.3 (0.2)	2.4 (0.3)	1.0 (0.1)
	NPK 2	2.7 (0.3)	4.2 (0.4)	3.5 (0.6)	1.1 (0.2)
	NPK 3	2.1 (0.3)	3.4 (0.4)	2.4 (0.4)	0.8 (0.1)
	F	1.057	3.308	2.904	1.317
	p	0.434	0.099	0.123	0.353
	HSD	-	-	-	-

Table 3. Effect of different fertilizer combinations on survival, height, diameter at breast height (DBH), basal area, and crown diameter of Acacia mangium measured 24 months after planting on Imperata grassland in South Kalimantan, Indonesia. Pooled results from three sites. Standard error of mean in parentheses.

Fertilizer	Survival (%)	Height (m)	DBH (cm)	Basal area (m^2ha^{-1})	Crown diameter (m)
Control	100 (-)	6.7 (0.2)	7.0 (0.7)	4.7 (0.9)	3.0 (0.2)
N	100 (-)	7.1 (0.3)	7.6 (0.6)	5.4 (0.8)	3.2 (0.2)
P	100 (-)	7.7 (0.5)	9.4 (0.8)	8.3 (1.2)	3.4 (0.2)
K	96 (2)	6.8 (0.3)	7.5 (0.6)	4.9 (0.7)	3.2 (0.2)
NP	100 (-)	8.1 (0.2)	9.4 (0.5)	8.0 (0.8)	3.5 (0.1)
NK	100 (-)	7.0 (0.5)	8.3 (0.8)	6.5 (1.1)	3.3 (0.2)
PK	100 (-)	7.8 (0.2)	9.9 (0.4)	8.9 (0.7)	3.6 (0.2)
NPK	100 (-)	7.8 (0.1)	10.1 (0.5)	9.3 (0.9)	3.6 (0.2)
NPK+micro	100 (-)	8.0 (0.1)	10.3 (0.3)	9.6 (0.6)	3.7 (0.1)
F	-	3.262	7.029	8.528	4.317
p	-	0.010	0.000	0.000	0.002
HSD	-	1.4	2.3	3.3	0.5

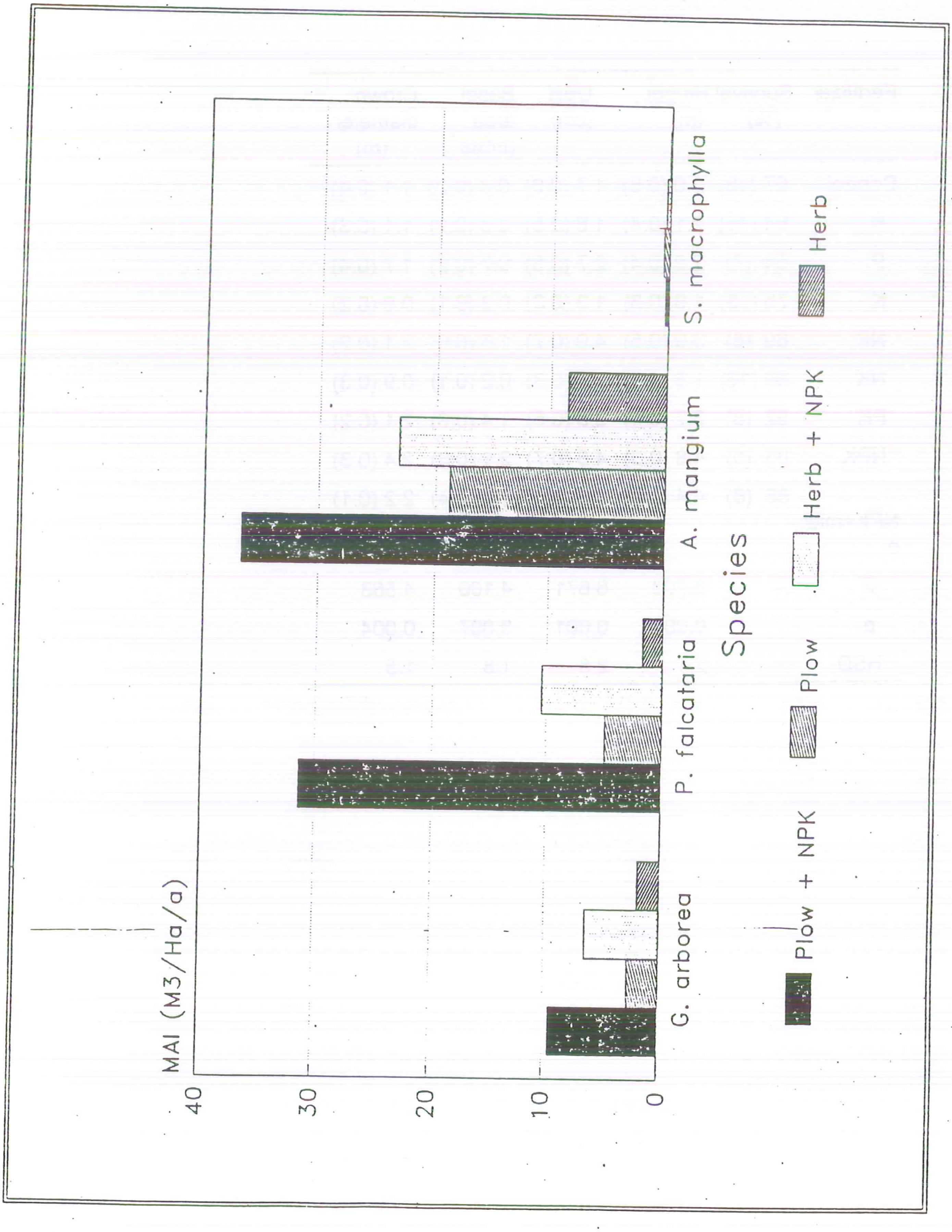
Table 4. Effect on different fertilizer combinations on survival, height, diameter at breast height (DBH), basal area, and crown diameter of Gmelina arborea measured 24 months after planting on Imperata grassland in South Kalimantan, Indonesia. Pooled results from three sites. Standard error of mean in parentheses.

Fertilizer	Survival (%)	Height (m)	DBH (cm)	Basal area (m^2ha^{-1})	Crown diameter (m)
Control	87 (8)	3.0 (0.6)	4.1 (0.9)	1.9 (0.7)	2.8 (0.4)
N	84 (6)	2.8 (0.5)	3.7 (0.9)	1.7 (0.7)	2.5 (0.4)
P	85 (11)	3.6 (0.8)	5.4 (1.1)	3.1 (1.2)	3.3 (0.6)
K	93 (4)	2.7 (0.3)	3.2 (0.4)	1.1 (0.3)	2.6 (0.2)
NP	98 (2)	3.9 (0.6)	6.1 (1.1)	4.1 (1.3)	3.4 (0.3)
NK	87 (9)	3.0 (0.7)	4.4 (1.3)	2.6 (1.3)	2.9 (0.5)
PK	93 (7)	3.7 (0.8)	5.8 (1.5)	4.1 (1.5)	3.3 (0.5)
NPK	93 (5)	3.8 (0.8)	6.2 (1.5)	4.6 (1.6)	3.0 (0.5)
NPK+micro	95 (6)	4.0 (0.7)	6.5 (1.1)	4.5 (1.3)	3.3 (0.3)
F	-	1.452	2.590	2.397	1.270
p	-	0.221	0.031	0.043	0.300
HSD	-	-	2.1	2.6	-

Table 5. Effect on different fertilizer combinations on survival, height, diameter at breast height (DBH), and crown diameter of Eucalyptus deglupta measured 24 months after planting on Imperata grassland in South Kalimantan, Indonesia. Pooled results from two sites. Standard error of mean in parentheses.

Fertilizer	Survival (%)	Height (m)	DBH (cm)	Basal area (m^2ha^{-1})	Crown diameter (m)
Control	67 (18)	2.0 (0.6)	1.7 (0.6)	0.3 (0.2)	1.1 (0.4)
N	64 (16)	2.1 (0.4)	1.8 (0.5)	0.3 (0.1)	1.1 (0.3)
P	84 (7)	2.9 (0.4)	2.7 (0.5)	0.7 (0.2)	1.7 (0.4)
K	75 (15)	1.9 (0.3)	1.3 (0.3)	0.2 (0.1)	0.9 (0.2)
NP	89 (8)	3.9 (0.5)	4.0 (0.7)	1.6 (0.6)	2.1 (0.2)
NK	56 (18)	1.6 (0.5)	1.5 (0.3)	0.2 (0.1)	0.9 (0.3)
PK	92 (5)	3.7 (0.4)	3.8 (0.5)	1.4 (0.3)	2.1 (0.2)
NPK	86 (5)	4.8 (0.3)	4.8 (0.7)	2.1 (0.6)	2.4 (0.3)
NPK+micro	86 (8)	4.4 (0.4)	4.3 (0.4)	1.6 (0.4)	2.2 (0.1)
F	-	8.703	6.671	4.100	4.583
p	-	0.000	0.001	0.007	0.004
HSD	-	2.1	2.6	1.8	1.5

Figure 1. Mean annual increment estimates of <u>Gmelina arborea</u>, <u>Paraserianthes falcataria</u>, <u>Acacia mangium</u> and <u>Swietenia macrophylla</u> 36 months after planting on sites with four different site preparation methods (Otsamo et al. in press).



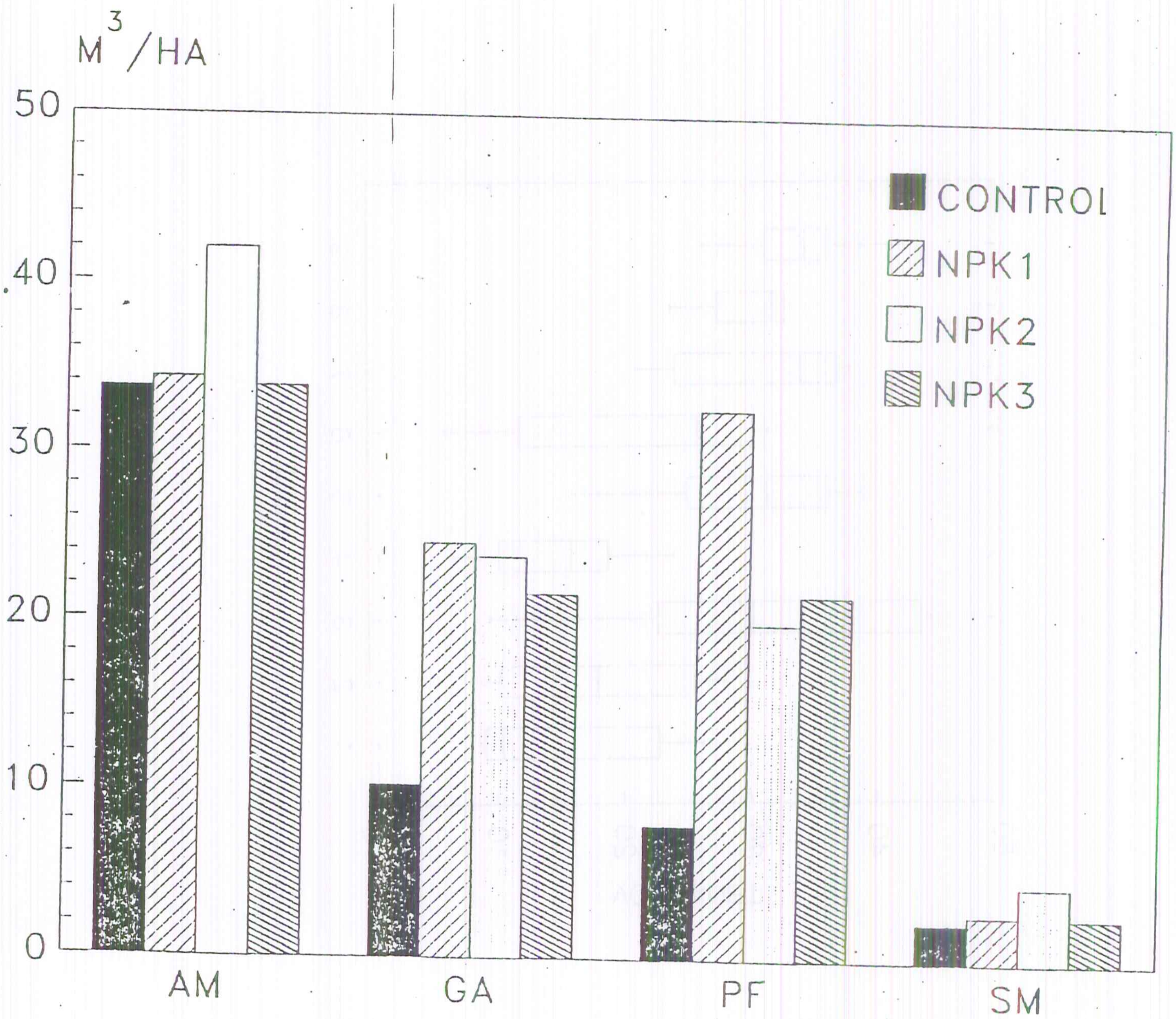
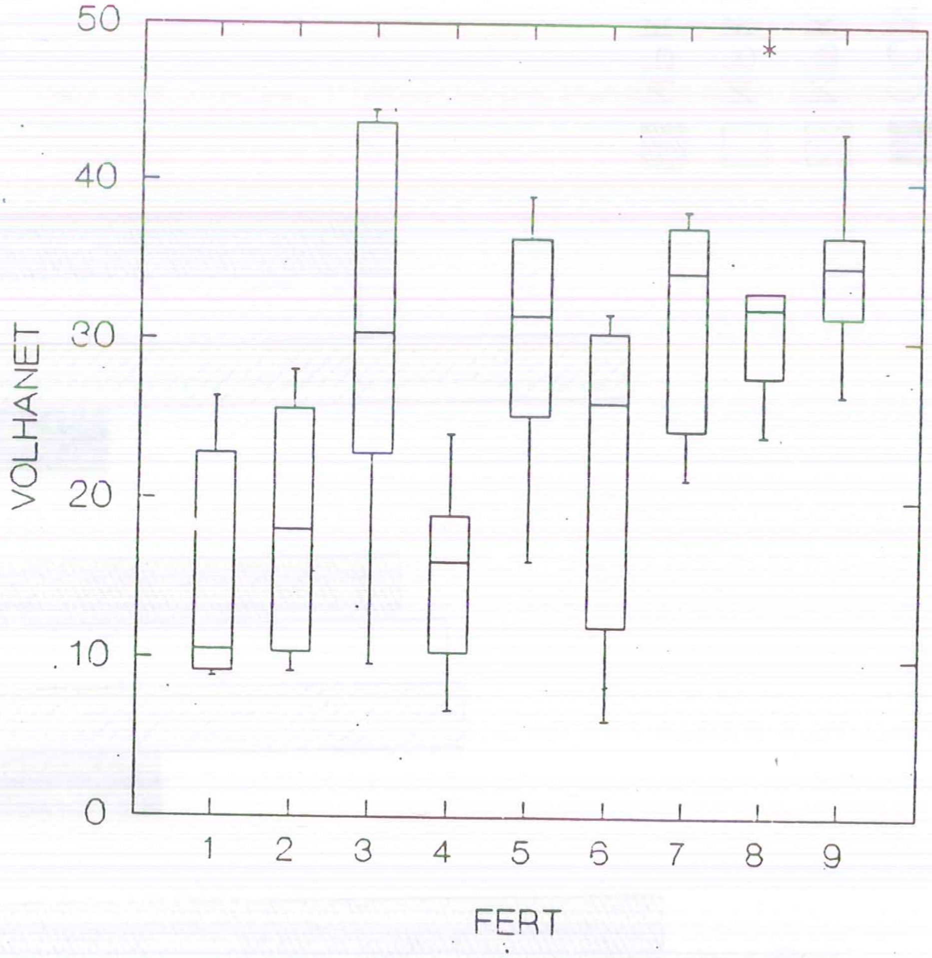


Figure 2. Effect of four different NPK-fertilizers on stand volume estimates of Gmelina arborea, Paraserianthes falcataria, Acacia mangium and Swietenia macrophylla 24 months after planting.

Figure 3. Effect of different fertilizer combinations on stand volume of Acacia mangium measured 24 months after planting on Imperata grassland in South Kalimantan, Indonesia. Pooled results from three sites. (1=control; 2=N; 3=P; 4=K; 5=NP; 6=NK; 7=PK; 8=NPK; 9=NPK+micronutrients)



SITE-SPECIFIC FERTILISER REQUIREMENTS OF EXOTIC PINE PLANTATIONS IN QUEENSLAND

John Simpson[1]

ABSTRACT

The Queensland Forest Service manages in excess of 130 000 hectares of exotic pines, predominately slash pine (*Pinus elliottii* Engelm. var. *elliottii*) and Honduras Caribbean pine (*P. caribaea* var. *hondurensis* Barr. & Golf.). Since 1991 the hybrid between these two species has been planted exclusively in the south. The plantations are established essentially on the coastal lowlands on infertile, light-textured acid soils derived from either granitic outwash material or from sedimentary materials. Drainage varies from good on the low ridges to poor in the lower-lying areas. The success of the plantation programme is dependent upon the wide-scale use of fertilisers especially phosphorus. Lesser responses to nitrogen applied at planting occur on a range of sites under particular conditions and severe deficiencies of potassium and copper are common on the podzols. Fertiliser prescriptions based on soils and site history are described.

Current prescriptions have evolved over a long period and have been updated as research information has become available, species and sites planted have changed and fertiliser cost and availability have altered. Major nutrient problems have been effectively solved by the efficient use of fertiliser. More sophisticated nutrient management on a site-specific basis is required to maximise productivity at minimum cost and to maintain or improve site productivity in the long term while minimising any adverse consequences of fertiliser addition or nutrient manipulation.

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1. INTRODUCTION

The Queensland Forest Service commenced planting exotic pines in 1925 to provide utility timbers to meet anticipated demands. Today the exotic pine estate is the second largest in Australia. Little expansion of the planted area is envisaged and increases in productivity and profitability will rely on improving silviculture and management efficiency.

The major exotic pine plantation centres are located on the infertile coastal lowlands of south-east Queensland with lesser plantings near the major centres of population in the northern parts of the State (Figure 1). The climates range from humid subtropical to humid tropical with mean annual rainfall in the range 1 337 mm (at Tuan) to 2 138 mm (at Cardwell). There is a strong summer incidence at all centres. Mean annual temperatures vary from 20.2 °C (Toolara) to 24.2 °C (Cardwell).

(Map)

The total exotic pine estate as at 30th June 1994 was 130 669 hectares. Slash pine (*Pinus elliottii* Engelm. var. *elliottii*) constituted 45% of the plantings and Honduras Caribbean pine (*P. caribaea* var. *hondurensis* Barr. & Golf.) constituted 42% (QUEENSLAND DEPARTMENT OF PRIMARY INDUSTRIES - FOREST SERVICE, 1995). Since 1991 the hybrid between slash pine and Honduras Caribbean pine has been planted exclusively in the southern coastal lowlands and it now forms 9% of the exotic pine estate. Less than 2% of the estate is loblolly pine (*P. taeda* L.). Still smaller areas of radiata pine (*P. radiata* D. Don) and patula pine (*P. patula* Schltdl.) have been established in the southern highlands. The potential of other taxa, *e.g.* the hybrid between Honduras Caribbean pine and Tecun Uman pine (*P. tecunumanii* Eguiluz & J.P. Perry), are currently being investigated.

(Figure 1)

Soils of the major planting areas on the south-east coastal lowlands are derived chiefly from Mesozoic sandstones and Quaternary sands. North of the Tropic of Capricorn, plantation soils are chiefly derived from granitic outwash material. Most soils are coarse-textured, acid to very acid, and have low nutrient status. Drainage varies from good on the broad low ridges, to poor in lower-lying areas. Clay B horizons underlie most soils at depths ranging from 20 cm to more than 100 cm.

Early plantings were confined to the better-drained sites, where depth to clay was the basis for determining plantability and species to be used (ROGERS, 1957). As a result of work by PEGG (1967) in relating site index* to site variables, and with the advent of improved site preparation techniques, plantings were extended in 1970 to include the generally less fertile soils with poor drainage. [* Site index tables are based on the average height (in metres) of the tallest 50 trees per hectare at age 25 years.]

Prior to 1983, virtually all sites carried low-quality native forest before being cleared for plantation establishment. Since then, sites formerly developed to pastures for cattle grazing have been acquired and planted with pines. General descriptions of the major exotic pine-planting areas as well as aspects of management of the plantations have been described by HAWKINS and MUIR (1968) and in updated form by the QUEENSLAND DEPARTMENT OF FORESTRY (1987).

This paper defines the broad land resources and development of fertiliser prescriptions currently used in establishing and managing the exotic pine plantations in Queensland, Australia.

2. LAND RESOURCES

The land resource in Queensland established with exotic pines can be broadly classified into four main categories or classes, that is well-drained or poorly drained sites, each of which may be derived from either granitic outwash materials or sedimentary materials (Mesozoic sandstone or Quaternary sands). The proportion of the forest estate in each class, the major soil types (Australian Great Soil Groups) associated with each, and their approximate equivalents in two international systems published as "Soil Taxonomy" (SOIL SURVEY STAFF, 1975) and the "Soil Map of the World" (FAO, 1974) are summarised in Table 1.

(Table 1)

Superimposed on the land resource classes are three site history classes, *viz.* first-rotation ex-native forest sites, first-rotation ex-pasture sites and second-rotation sites. It is the combination of land resource class and site history class that determines the fertiliser regime for a particular species.

A summary of the plantation resources by site history and by period of establishment is presented in Table 2. The land resource classes established with exotic pines have changed over time. During the period 1927-70 predominantly well-drained soils carrying native forests were cleared for planting, but after this period a wider range of sites including poorly drained sites were also planted. Sites initially developed for cattle grazing and subsequently acquired for exotic pine planting now constitute 12 per cent of the estate. The rapidly increasing proportion of annual plantings established on second-rotation areas is a reflection of the increasing areas of plantation approaching maturity and of the increasing dependency of industry on plantation material.

(Table 2)

The drainage condition of the soil as reflected by the soil type is of prime importance as it predetermines many of the silvicultural requirements of the site and, in particular, species selection, site preparation and fertiliser requirements. Slash pine was planted on the poorly drained sites as it tolerates waterlogging. Honduras Caribbean pine was confined to the better-drained ridge sites because of its intolerance of waterlogging and its susceptibility to wind damage particularly on wet sites. The hybrid between these two, now planted exclusively in the south-east, combines the continuous growth habit of Caribbean pine with the tolerance of wet sites characterisatic of slash pine. FOSTER and COSTANTINI (1991a,b,c) have described the field survey for site preparation planning and site design (1991a), site preparation classes (1991b) and the site preparation and design (1991c) for the establishment of exotic pines in Queensland.

3. FERTILISER RESPONSES

Each year fertilisers are applied to more than 3 000 hectares of exotic pine forests in Queensland to increase forest growth and value. The increased productivity and financial yeild make fertilising an attractive investment. Although the benefits of fertilisation are clearly demonstrable, implementing the optimum prescription on a site-specific basis to maximise benefits remains a difficult challenge. Experimentation in Queensland over a long period has tested many soils for limiting elements and examined many combinations of forms, rates, timing of applications and combination of elements with a view to providing the background data necessary to enable preparation of specific fertiliser schedules for particular sites.

Most of the experimental work underpinning the current fertiliser prescriptions was carried out on first-rotation sites. The results of these investigations are very relevant to second-rotation sites currently being planted, as it has been shown that although some residual benefits from first-rotation fertilising (essentially attributable to phosphorus additions) can be detected in the second rotation, carry-over effects are small and do not substantially alter fertiliser regimes. With attention to nutrient conservation practices and particularly to residue management, nutrient depletion of the site is minimised and the fertiliser regimes designed for first-rotation sites should not need to be supplemented for the second rotation.

Considerable efforts has gone into investigation of pine genotypes (at species, variety, provenance, progeny and more recently clone levels) by fertiliser interactions. An understanding of these interactions enables maximum benefit to be gained from early work which used test species now of lesser commercial interest. Optimum fertiliser regimes are now better tailored to specific genetic material on particular sites.

A summary of nutrient responses of exotic pines for the major site-history classes is outlined below.

3.1 Establishment fertiliser responses of first-rotation exotic pines on ex-native forest sites

3.1.1 Phosphorus

In the early 1930s, phosphorus (P) was recognised as the major element affecting the growth of exotic pines (YOUNG, 1935) and it is clear that the viability of the exotic pine plantation programme is dependent upon the broad-scale use of phosphate fertiliser. Initially, in the late 1930s, soil sampling to determine the total P content of the surface ten centimetres of topsoil was carried out in conjunction with plantability surveys, and Nauru rock phosphate was broadcast to bring the soil P to the required level, which was calculated to be 48 mg/kg for slash pine and 57 mg/kg for loblolly pine. With an expanding planting programme covering a wider range of sites, this approach proved unreliable and was replaced in the early 1950s by a blanket application of Nauru rock phosphate to all sites in south-east Queensland. The application, up to three years after planting, supplied P at the rate of 50 kg/ha. From 1970 to 1987 superphosphate or triple superphosphate replaced Nauru rock phosphate as the major source of P used, and aerial application was introduced to cater for the expanded planting programme. The rate of application was increased to 60 kg/ha P to compensate for uneven distribution associated with the use of aircraft (QUEENSLAND DEPARTMENT OF FORESTRY, 1987). The importance of P for soils derived from both sedimentary or granitic outwash materials is illustrated in the rate/response curves in Graph 1.

(Graph 1)

This graph summarises data from a range of experiments carried out since the early 1950s. In all situations there has been a major response to the addition of P applied at planting. The magnitude of the response varies with the edaphic conditions, with the greatest responses occurring on the less-fertile sites, *i.e.* the sedimentary derived soils in the case of Honduras Caribbean pine, or the poorly drained soils in the case of slash pine. It is interesting to note that the optimum rate of phosphorus applied at planting (*viz.* 50 kg/ha) is similar for each situation.

Plantations of Honduras Caribbean pine in coastal central Queensland on granite- derived soils were only fertilised where the estimated site index at 7 to 11 years of age fell below 30. A mixture of superphosphate and Nauru rock phosphate (1:3) was broadcast over these areas to supply 73 kg/ha P. Since 1970, plantings at Byfield have extended on to wetter sites and to poorer soils derived from mudstones, shales or sandstones and the fertiliser prescription was changed so that all sites received 60 kg/ha P as triple superphosphate at planting.

The early plantings of Honduras Caribbean pine on ridge sites in the north of the state were not fertilised. From 1982 the ridge sites received 60 kg/ha P while the poorly drained sites received a mixed fertiliser containing a similar amount of P.

3.1.2 Nitrogen

In the 1960s, research using slash and loblolly pines as the test species demonstrated that an ephemeral growth response to nitrogen (N) fertilisers could be obtained on a range of sites under certain conditions. Optimum response was obtained on cultivated, weed-free sites when the N was applied to individual trees at planting along with an available source of P (RICHARDS and BEVEGE, 1967). FRANCIS and BACON (1983) reported improved growth and root/shoot ratios and, as a consequence, better wind stability in cyclonic winds for young slash pine where N fertiliser had been applied together with P. From 1982 N has been applied operationally on podzol sites to stimulate early growth and keep the pines above the vigorous heath regrowth on these sites. With the improved availability and competitive pricing of the ammonium phosphates, MAP (mono ammonium phosphate) has, since 1987, been widely used as the major source of N and P applied to exotic pines in Queensland.

3.1.3 Potassium

The potassium (K) status of many soils derived from Mesozoic sandstone or Quaternary sands is marginal, and deficiencies of K in exotic pines are known to occur on many of the podzols.

With the increased areas of podzols planted since 1970, investigations of K deficiency intensified. It was demonstrated that once the gross deficiencies of P on these sites were corrected, significant growth responses to K were achieved. Volume growth has been increased by between 10 and 110% by the addition of 50 kg/ha K (SIMPSON and GRANT, 1991).

3.1.4 Other elements

In 1975 deficiencies of copper (Cu), manifested by gross stem and branch malformation and in severe cases by very poor growth, were identified in young slash pine plantations established on poorly drained humus podzol soils. This finding led to the inclusion of 5 kg/ha Cu in the fertiliser mix applied to all podzols from 1975. Deficiencies of Cu are most pronounced during the first three to five years after planting and heavy dressings of N fertiliser exacerbate the deficiency. Of the species planted, Honduras Caribbean pine is particularly sensitive to low Cu levels. Cu deficiency appears to be under strong genetic control.

Low foliar zinc (Zn) levels have been recorded in some plantations but in the absence of any growth response to added Zn in any of the field experiments, this element is not included in any operational fertiliser schedules.

Boron, calcium, magnesium, manganese, molybdenum and sulphur deficiencies have not been confirmed as growth-limiting factors in any of the commercial plantings.

3.1.5 Current establishment fertiliser practices

The current fertiliser schedules for newly planted pines have been derived from a wide range of fertiliser trials and, for ex-native forest sites, are summarised in Table 3. Improvements in the schedules have been based on research findings (in particular long-term growth responses from multi-site trials and foliar nutrient data) as well as on fertiliser cost and availability.

(Table 3)

3.2 Post-establishment fertiliser responses of first-rotation exotic pines on ex-native forest sites

The need to re-apply fertilisers to established plantations is continually being assessed. The initial P dressing applied at planting is essentially designed to ensure satisfactory establishment. Given the range in quality of sites and species planted, it was not expected that the initial dressing would be adequate for all stands for the full rotation length. Foliar analysis techniques have been developed to identify stands that are nutritionally stressed. Critical or acceptable foliar nutrient levels have been established for the major exotic pine taxa planted in Queensland and are used as a guide to the nutrition status of a stand (SIMPSON and OSBORNE, 1993). Numerous attempts have been made at identifying areas requiring re-fertilising using foliar analysis techniques. Where intensive foliar sampling has been undertaken, the approach has been useful; however, for extensive plantations the technique has met with only limited success.

Data collected over a period of up to 14 years from 110 plots of slash pine re-fertilised with P (30 to 500 kg/ha) indicated that basal area increment was increased by 20% after re-fertilising with P. Growth simulation suggested that wood yields at the end of the rotation are increased by 9% and 14%, and there were real rates of return of between 9% and 16% on money invested in re-fertilising. All slash pine plantations over 10 years of age have now been re-fertilised. Similar information is being investigated for Honduras Caribbean pine experiments, but to date there is no evidence to suggest that re-fertilising of this species is necessary.

A series of experiments has been conducted to investigate the N response applied after the first commercial thinning of established slash and Honduras

Caribbean pine stands. Only in one situation has the application of N (200 kg/ha) produced a significant growth response. Because of the cost of N fertiliser and the limited growth response no wide-scale use of N fertiliser is undertaken in established stands.

Potassium is a very mobile element in both the soil and the plant and is now applied operationally at planting to all podzol sites. All established stands on podzols were fertilised with either 50 or 100 kg/ha K in the late 1980s. The maintenance of adequate K status is being monitored.

Until recently no evidence existed to suggest that it might be necessary to apply other nutrient elements to assist in establishing plantations. The recent occurrence of stem malformation in the crowns of established fast-growing Honduras Caribbean pine suggests that inadequate Cu nutrition may be implicated and further investigations are being made.

3.3 Establishment fertiliser responses of first-rotation exotic pines on ex-pasture sites

The Forest Service has, since 1977, acquired large areas of improved pasture land for conversion to exotic pine plantations (SIMPSON, 1991). Typically, such sites had received heavy applications of P (100 to 250 kg/ha), K (100 to 380 kg/ha), and smaller (or nil) applications of N. As these quantities are well in excess of those normally used in forestry it was expected that additional P fertilising would not be generally required at the time of plantation establishment. However, since the residual value of P is dependent *inter alia* upon the quantity and timing of application, allowance has been made for pastures that have received only limited dressings well before plantation establishment to determine the need to apply the normal 60 kg/ha P. While the guidelines may overestimate the area requiring early fertilising, they allow for small errors in previous agricultural applications and for the fact that the later applications to pastures may have been minor.

(Table 4)

3.4 Establishment fertiliser responses of second-rotation exotic pines

Virtually all future plantings will be on second-rotation sites. Design of second-rotation fertiliser schedules must take into account any changes in site fertility as a result of the first rotation. Responses of second-rotation crops to P applied more than 30 years earlier to the first rotation have been detected but these responses are of insufficient magnitude to eliminate the need for P fertilising for the establishment of second-rotation stands.

The response of exotic pines on second-rotation sites to elements other than P is currently being researched. Early indications are that, given adequate attention to nutrient conservation measures in management and in the conversion of rotations, the fertiliser schedules developed for the first-rotation sites will be appropriate for second and subsequent rotations. The exception is for ex-pasture sites where it is expected that phosphorus fertiliser will be required to optimise establishment of the second rotations.

3.5. Fertiliser requirements of exotic pines re-established on fire-killed plantation areas

Severe wildfires in the exotic pine plantations in 1991 and 1994 resulted in more than 6 000 hectares of plantation of various ages (2-35+ years) being destroyed. Redevelopment plans for these areas have been formulated and fertiliser schedules have been tailored to specific situations

(Table 5)

These schedules have taken into account site characteristics, the quantity and timing of previous nutrient additions and the residual value of fertiliser applied to the burnt stand.

4. CONCLUSIONS AND FUTURE DIRECTIONS

The success of the exotic pine plantation programme in Queensland is inextricably linked to the use of fertilisers. The current fertiliser schedules have evolved over a long period and are based on a sound research background. While the major nutritional problems have been resolved by the effective use of fertilisers and efficient operational strategies put in place, there is an increasing need for more sophisticated nutritional management to maximise productivity at minimum cost, to maintain or improve site productivity in the long term and to ensure that there are minimum adverse off-site consequences of any fertiliser (or nutrient manipulation) operations. Greater attention is being paid to site-specific silviculture and given the existing site fertility variation across the exotic pine estate, considerable investigation must still be done to “fine tune” the nutrient management for specific sites on silvicultural regimes.

The wide-scale use of P fertiliser in the exotic pine programme will continue, but a greater understanding of N dynamics and the complex interaction governing the N response is required. The duration of the K response on podzols is being followed with interest. Conditions under which symptoms of Cu deficiency are expressed are not fully understood and will continue to be investigated.

Large local databases are now available which contain soil and stand nutritional and fertiliser response data. It is now timely to review these data and to use the information to develop mathematical models which can be incorporated into decision support-systems. Being able to model both cost and yield responses for various fertiliser scenarios will enable identification of more sophisticated fertiliser regimes to maximise productivity at minimal cost.

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Table 1: Land resource classes for exotic pine plantations in Queensland, their extent and soil classification categories

Land resource class	Proportion of forest estate (%)	Australian Great Soil Groups (Stace *et al.* (1972)	Approximate equivalent international soil group types	
			"Soil Taxonomy" (Soil Survey Staff, 1975)	"Soil Map of the World" (FAO, 1974)
Well-drained soils of sedimentary origin	49	Red Earth	*Paleustalf, Haplustalf,* Torrox, Haplargid, Haploxeralf, Paleustult, Paleudult	*Eutric Nitosol, Ferric Luvisol,* Orthic Ferralsol, Luvic Yermosol, Dystric Nitosol
		Yellow Earth	*Haplustalf,* Paleustult, Haplargid, Paleustalf, Plinthustult, Palexeralf	*Ferric,* Albic and Chromic *Luvisol,* Ferric Acrisol, Luvic Xerosol, Plinthic Luvisol
		Red Podzolic Yellow Podzolic	*Haplustalf, Haplustult,* Paleustalf, Haploxeralf, Palcustult	*Albic Luvisol, Orthic* and Ferric *Acrisol*
		Lateritic Podzolic	*Palexeralf,* Plinthoxeralf, Paleustalf, Paleustult, Plinthustult, Haploxerult, Albaqualf	*Albic* and *Plinthic Luvisol,* Ferric and Plinthic Acrisol, Eutric Planosol
Poorly drained soils of sedimentary origin	33	Gleyed Podzolic	*Albaquult, Paleustalf,* Paleaquult, Ochraqualf	*Dystric, Eutric* and *Solodic Planosol,* Gleyic Acrisol
		Humic Gley	*Paleaquult, Albaquult,* Humaquult, Haplaquept	*Gleyic Acrisol,* Humic and Dystric Gleysol
		Podzol	Troporthod, Haplorthod, Placorthod, Quartzipsamment	*Orthic* and *Placic* Podzol
		Soloth	*Natrustalf, Natrixeralf, Paleustalf,* Haplustalf	*Orthic Solonetz, Albic Luvisol,* Solodic Planosol
Well-drained soils of granitic origin	8	Red Earth	*Paleustalf, Haplustalf,* Torrox, Haplargid, Haploxeralf, Paleustult, Paleudult	*Eutric Nitosol, Ferric Luvisol,* Orthic Ferralsol, Luvic Yermosol, Dystric Nitosol
		Yellow Earth	*Haplustalf,* Paleustult, Haplargid, Paleustalf, Plinthustult, Palexeralf	*Ferric,* Albic and Chromic *Luvisol,* Ferric Acrisol, Luvic Xerosol, Plinthic Luvisol
		Yellow Podzolic	*Haplustalf, Haplustult,* Paleustalf, Haploxeralf, Paleustult	*Albic Luvisol, Orthic* and Ferric *Acrisol*
Poorly drained soils of granitic origin	5	Gleyed Podzolic	*Albaquult, Paleustalf,* Paleaquult, Ochraqualf	*Dystric, Eutric* and *Solodic Planosol,* Gleyic Acrisol
		Soloth	*Natrustalf, Natrixeralf, Paleustalf,* Haplustalf	*Orthic Solonetz, Albic Luvisol, Solodic Planosol*

This table is adapted from Moore *et al.* (1983). (The most common correlations are shown in italics in columns 4 and 5.)

Table 2: **Queensland Forest Service exotic pine plantation programme by site type (areas established in hectares)**

Period of Establishment	First-rotation sites			Second-rotation sites	Total
	ex-native forest		ex-pasture		
	Well-drained	Poorly drained			
Pre-1950	6 364	--	--	--	6 364
1951-1960	11 676	--	--	--	11 676
1961-1970	20 928	--	--	--	20 928
1971-1980	18 219	32 255	--	--	50 475
1981-1990	16 174	10 783	11 564	1 857	40 378
1991-2000*	1 336	891	1 419	15 532	19 178
2000-2010*	--	--	--	27 790	27 790
Total	74 697	43 929	12 983	45 179	176 789

* Figures are based on projections from Robinson (1990)

Graph 1. Response of slash and Honduras pines on different sites to phosphorus fertiliser

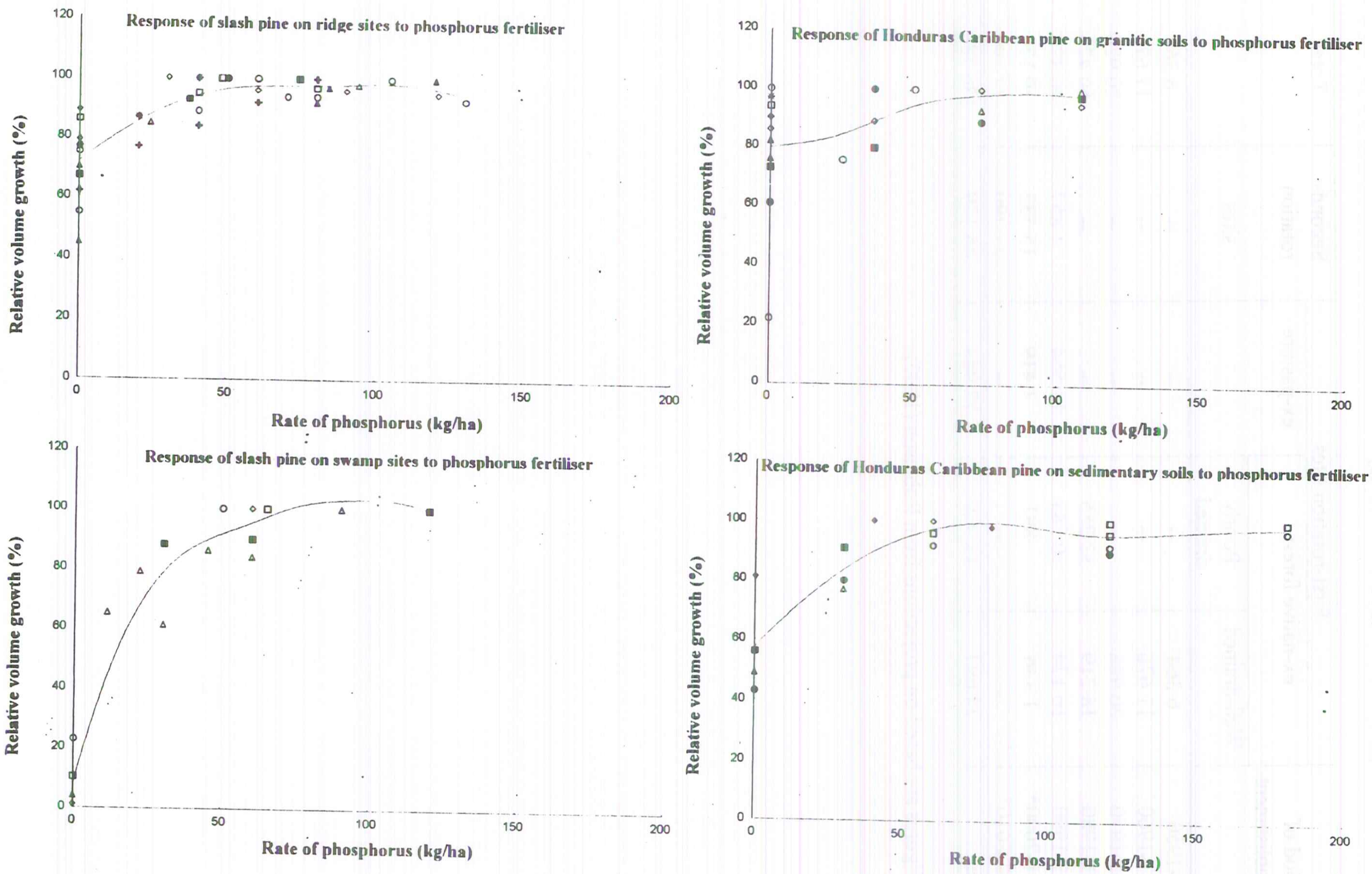

Table 3: Exotic pine fertiliser prescriptions for first-rotation, ex-native forest sites in coastal districts of Queensland

(Adapted from Simpson and Grant, 1991)

Location (Forestry District and State Forest)	Latitude (°South)	Area of exotic pine planted 1993/94 (ha)	Major species currently planted +	Predominant soil parent material (a) and soil type (b) (if special fertiliser prescription required) **	Fertiliser prescription codes ++
Atherton					
Kuranda	16°45'	-	PCH	(a) metamorphics	1
Ingham					
Cardwell/	18°16'	{ 326	PCH	{ (a) granitic outwash	1
Lannercost	18°40			(b) soloths	2
Rockhampton					
Byfield	22°50'	100	PCH	(a) granite/and	1
			PCH	sedimentary	1
			PCH	(b) podzols	2
Maryborough					
Wongi/	25°27'	{ 678	F_1 hybrid	{ (a) sedimentary	1
Tuan	25°40'			(b) podzols	3
Gympie					
Toolara	26°00'	647*	F_1 hybrid	(a) sedimentary	1
				(b) podzols	3
Beerburrum					
Beerwah/	26°50'	{ 613*	F_1 hybrid	{ (a) sedimentary	1
Beerburrum	26°57'			(b) podzols	3

+ Species Codes

PCH = Honduras Caribbean pine

F_1 hybrid = Hybrid between slash pine and PCH

++ Fertiliser Prescription Codes (kg/ha of element)

		N	P	K	Cu
1	=	23	50	-	--
2	=	23	50	-	5
3	=	23	50	50	5

Potassium and copper are applied on podzol sites only.
Higher rates of potassium (100 kg/ha K) are recommended for severely deficient podzol sites.

* Includes ex-pasture sites - see Table 4 for fertiliser schedule.

** Certain soil types at some State Forests have been identified as requiring special fertiliser prescriptions.

Table 4: Guidelines for fertilising exotic pines on ex-pasture sites

Total quantity of phosphorus applied to pasture (kg/ha)	Years since last fertiliser application 0-4	5-9	10+
0 - 60	Yes	Yes	Yes
60 - 100	No	yes	yes
100 - 140	No	No	Yes
140+	No	No	No

Table 5. Fertiliser recommendations for re-planting fire-killed areas

Original stand	Age class	Site type: All sites except podzols		Podzols			
Young	< 5yrs	N_{22} [a]	P_{25} [a]	N_{23} [b]	P_{50} [b]	K_{50} [c]	Cu_5 [d]
Semi-mature/ mature	> 5yrs	N_{23} [b]	P_{50} [b]	N_{23} [b]	P_{50} [b]	K_{50} [c]	Cu_5 [d]

Notes: Subscript numerals denote the quantity of element to be applied in kg/ha. All fertilisers to be applied as either individual tree or banded application at or soon after planting.

[a] N_{22} P_{25} Apply as DAP (18% N, 20% P) at the rate of 125 kg/ha
[b] N_{23} P_{50} Apply as MAP (Starterfos - 10% N, 21.9% P) at the rate of 228 kg/ha
[c] K_{50} Apply as muriate of potash (50% K) at a rate of 100 kg/ha
[d] Cu_5 Apply as copper sulphate

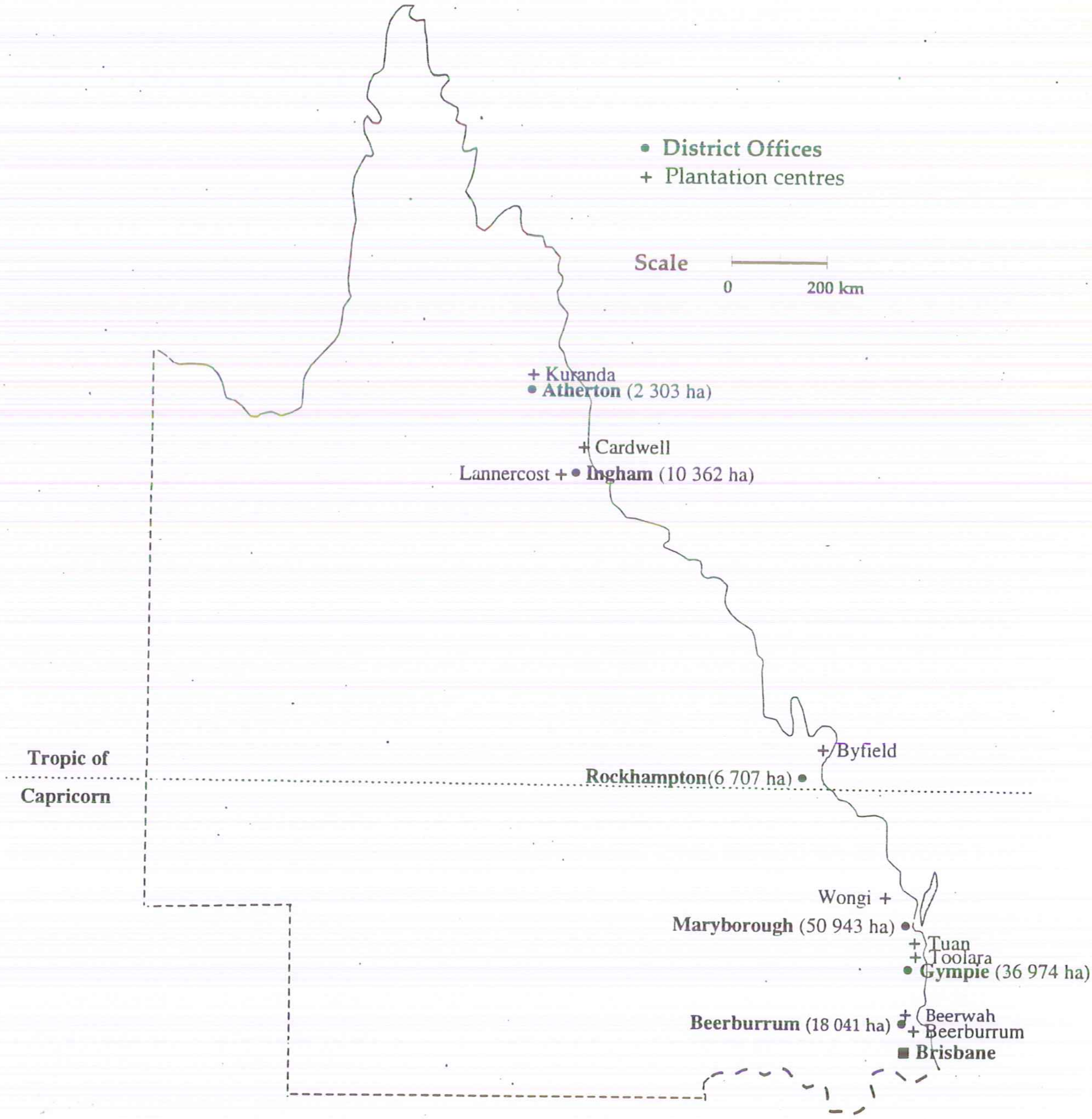

Figure 1. Map of Queensland showing location of the Queensland Forest Service's major exotic pine plantations. Area of plantation (as at 30th June 1994) shown by district in brackets.

GROWTH RESPONSE OF THREE RAINFOREST CABINET TIMBER SPECIES TO FERTILISER APPLICATION IN PLANTATIONS IN NORTH QUEENSLAND

Rodney Keenan, Alison Hambleton and Ken Robson[1]

ABTRACT

Rapidly declining supplies of cabinet-timber from natural stands of tropical rainforest and increasing world-wide demand for timber has led to significant interest in developing plantations of high-value cabinet timber species. However, our understanding of the appropriate silvicultural practices to achieve successful growth most cabinet-timber species in plantations is poor. The objective of this study was to determine the response to fertilisation of two native Australian and one exotic rainforest species at three sites in North Queensland: black bean (*Castanospermum australe* Cunn. ex C. Fraser), kauri pine (*Agathis robusta* C. Moore ex F. Muell.) Bailey, and West Indian cedar (*Cedrela odorata* L.).

Six fertilizer treatments were used at each site: control (no fertiliser), four different levels of P with basal application of macronutrients (N, K, S, Ca, Mg) and trace elements (Zn, Cu, Mn, fe, Mo, and B), and a treatment with the highest level of P with macronutrients but no trace elements. At the Atherton site P levels were 0, 100, 250 and 500 kg ha^{-1}. At Tully and South Johnstone P levels were 0, 50, 100, and 250 kg ha^{-1}. After 1.5 years there was little significant effect of fertilisation treatments in either height, volume or biomass (at the South Johnstone site). Lack of response was considered to be due to relatively high soil fertility, slow early-growth characteristics of black bean and kauri pine, and poor genetic quality of the faster-growing, but highly variable, West Indian cedar.

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1. INTRODUCTION

Tropical rainforests are an important economic and environmental resource that are utilised for a variety of purposes. In many places the area of natural rainforest is diminishing rapidly due to conversion to other landuses or degradation following uncontrolled harvesting. Large areas of forested land are being cleared for food production but continuing failure to recognise the importance of a tightly-linked, forest-soil nutrient cycle in maintaining soil productivity has resulted in declining crop production (Jordan 1993) and many of these cleared lands are being abandoned in a degraded form with reduced soil fertility. There are increasing pressures to reserve remaining natural forests and to develop sustainable systems for the production of forest products in plantations established on previously cleared or degraded land. Tropical rainforest in Australia have not escaped these impacts and clearing of natural forest vegetation began with European settlement in the mid 1800's and proceeds to the present day. Rainforest has been lost as a result of urban and agricultural development and other activities such as mining and road construction. In 1988, after protracted negotiations with the State Government the Federal Government unilaterally nominated North Queensland rainforests for inclusion on the UNESCO World Heritage List. This enabled the Federal Government to prohibit commercial logging and other activities seen as detrimental to World Heritage values, and logging of rainforest on State Forest and other crown land ceased in mid 1988.

Since World Heritage listing there has been a growing interest in developing plantations of native rainforest cabinet-timber species on cleared land withe the aim of developing a timber resource and re-establishing an industry to replace the one that was based on harvesting of native forests. The Community Rainforest Reforestation Program (CRRP) is an initiative by local, State, and Federal Governments for this purpose (QDPI-Forest Service 1994). However, our understanding of the silvicultural requirements of most native tropical species in plantations is poor. In particular, we lack knowledge of the nutrient requirements of different species on different soil types, and whether fertilisation can increase the early growth of cabinet timber species and facilitate successful establishment.

The objective of this study was to determine the response to varying rates of P fertilisation at establishment of two Australian and one exotic rainforest species at three sites in North Queensland: black bean (*Castanospermum australe* Cunn. ex C. Fraser), kauri pine (*Agathis robusta* C. Moore ex F. Muell.) Bailey, and West Indian cedar (*Cedrela odorata* L). P has been identified as a limiting nutrient in glasshouse nutrient omission studies at two of the three sites (Reddell and Webb 1994).

The study was part of a larger project funded by the Australian Centre for International Agricultural Research (ACIAR) that aimed to characterise the soils, identify nutritional deficiencies and mycorrhizal associations for a range sites and tree species in the Western Pacific region (Poa and Mazza 1995).

2. METHODS

2.1 Study Areas

The study was undertaken at three sites on different soil types near the towns of Tully, South Johnstone, and Atherton (between 17° and 18° S) in North Queensland (Fig. 1). Altitude and climatic conditions for the three areas are shown in Table 1 and soil characteristics in Table 2. All sites had been cleared for over 50 years. Tully and South Johnstone are situated on the coastal lowlands and Atherton is at the northern end of a broad plateau about 50 km from the coast.

The higher rainfall site at Tully had previously been used for sugar and more recently for paw paw (*Carica papaya*) farming. Soils were sandy-loam yellow earths (Thorpe series, Cannon *et al.* 1992) developed on a granite fan.

At South Johnstone soils were red podzolics (Galmara series, Cannon *et al.* 1992) derived from metamorphic rocks with light clay to clay loam texture. The site has been unused for over 30 years and contained a high proportion of the grass *Imperata cylindrica* and other weeds prior to site preparation.

The Atherton site was at a higher altitude (760 m) and received a lower rainfall than the other two sites. Soil were krasnozems (Ferrasols) of the Pin Gin series (Laffan 1988) derived from deeply weathered basalt with clay-loam to clay texture. The site was being used for maize cropping prior tothe experiment and had a history of fertilisation for cropping, and pasture and legume incorporation in pasture grasses.

2.2 Experimental design

The experimental design differed in each location because of the area available and the species used. Two species were used at South Johnstone (kauri pine and West Indian cedar) and Tully (kauri pine and black bean), and one species at Atherton (black bean).

At Atherton the design was a randomised complete block with four replicates each of six fertiliser treatments (24 plots in total). Plots consisted of 30 trees (three rows with 10 trees in each row). Spacing was 3 m between rows and 1.8 m along the row (1833 stems per ha). Measurements were undertaken on the eight internal trees in each plot with a buffer of one row around the measured plot that received the same treatment.

At Tully and South Johnstone the design was a randomised complete block of six treatment plots in four blocks (24 plots in total) with split plots for each of the two species used. Plots consisted of 40 trees (four rows of 10 trees). The two internal rows were planted with the target species while the outer buffer rows were planted with *Flindersia pimentaliana* treated in the same way as the measured plot.

2.3 Site preparation and planting

Site preparation varied with location. At Atherton the site was disc-ploughed and sown with the grass *Brachyaria*, and planting lines were ripped and sprayed with a residual herbicide. At Tully the site was slashed, raked and planting lines cultivated. At South Johnstone the site was burnt and sown with *Brachyaria*, ploughed and the planting lines cultivated with a rotary hoe. At all sites a 1 m strip was kept free of weeds using the knockdown herbicide, glyphosphate and the residual herbicide, simizine. Site preparation was completed by January 1992 and seedlings were planted during the wet season in January and February 1992. Seedlings used were about 1 yr old and developed from seed collected off wild trees. All seedlings were produced in the Queensland Forest Service nursery at Walkamin near Atherton.

2.4 Fertilizer treatments

Details of fertilizer treatments are shown in Table 3. Six fertilizer treatments were used at each site. These consisted of a control (no fertiliser) treatment, four different levels of P with basal application of macronutrients (N, K, S, Ca, Mg) and trace elements (Zn, Cu, Mn, fe, Mo, and B), and a treatment with the highest level of P with macronutrients but no trace elements. At the Atherton site P levels were 0, 100, 250 and 500 kg ha^{-1}. At Tully and South Johnstone P levels were 0, 50, 100, and 250 kg ha^{-1}. Fertilizers were applied in a split application, with half of the amount applied about 1 month after planting, and the remainder about 6 months after planting. Fertilizers were applied in measured amounts to individual trees and inserted in slits made with a spade about 20 cm from the base of each tree.

2.5 Measurements

Seedling heights were measured immediately after planting and height, diameter at ground level (dgl), and diameter at breast height (when trees had reached a sufficient size) were measured six, twelve and twenty months after planting.

Tree biomass was assessed a the South Johnstone site. Twenty months after planting two trees in two replications of each treatment were systematically selected and cut at ground level. Above-ground biomass was divided into leaves, branches and stem. These were weighed wet, and a ten percent sample of each material was weighed, dried (leaves for 24 h, and until no further weight loss for woody material) and reweighed to determine moisture content. All biomass data are presented on a dry weight basis.

2.6 Statistical analysis

A stem volume index (dgl^2*height) was used to integrate diameter and height data. For *Castanospermum australe* and *Agathis robusta* mean height, dgl, and volume index were calculated for each plot. Plot means for the four replicates of each treatment were used for statistical comparisons between treatments and for comparisons between sites. Because of the high level of variability in the *Cedrela odorata* planted at South Johnstone, which was possibly due to poor genetic quality of the seed source, the four tallest trees in each plot were used for analyses. Results were initially compared using ANOVA, and where significant differences were identified individual treatments were compared using Tukey's test. In some cases individual orthogonal contrasts were made. All analyses were carried out using SYSTAT (Wilkinson 1989).

3. RESULTS

3.1 Height growth

Mean heights after 20 months for each treatment at each site are shown in Fig. 2. There were significant differences (a <=0.05) between sites in the growth of each species. *Castanospermum australe* grew faster at Tully (mean across all treatments of 1.65 m) than at Atherton (mean of 1.08 m), and *Agathis robusta* grew faster at South Johnstone (mean of 1.68 m) than at Tully (mean of 0.95 m). The best performing species was the exotic *Cedrela odorata* planted at South Johnstone with an average height of (3.02 +/- 0.12 m) and dgl of (11.1 +/- 0.42 cm). The performance of individuals of this species was very good with the best trees reaching a height of (6.0 m) and dgl of (16.2 cm) after 20 months.

There were no significant effect (a <= 0.05) of fertiliser treatment on height growth for *Castanospermum australe* at Atherton, or either species at Tully. At South Johnstone, for both *Cedrela odorata* and *Agathis robusta*, there were significant differences between treatment 2 (complete, but no P) and treatment 6 (complete, 250 kg/ha of P, but no micronutrients). Although it was statistically significant for *Agathis robusta,* this height difference was small (0.32 m, or about a 20% increase). For *Cedrela odorata* the mean for treatment 6 was 1.22 m higher than the mean height for treatment 2, an increase of 40%.

There was also a significant difference between treatment 5 (N, 250 kg/ha of P, K and micronutrients) and treatment 6 (the same as 5, except that micronutrients were not added) for *Agathis robusta*.

3.2 Volume index

Results for the volume index (dgl^2*height) are shown on scale relative to the highest value treatment for each species at each site in Fig. 3. There was considerable variability in this index within treatments, and therefore no statistically significant differences were identified. There was a trend of increased growth with increasing levels of P fertilisation for *Castanospermum australe* at Tully (up to 100 kg/ha of P), and for *Cedrela odorata* at South Johnstone. For

Castanospermum australe at Atherton and Tully and for *Cedrela odorata* at South Johnstone there was higher mean volume for treatment 6 compared with treatment 5.

3.3 Biomass

Results of the biomass sampling from the South Johnstone site are shown in Fig. 4. As for height growth *Cedrela odorata* had significantly higher stem biomass than *Agathis robusta*, leaf and branch biomass were also higher. Variability in biomass was high, and because there were only a small number of trees sampled it was not possible to detect any statistical differences between treatments for each species.

4. DISCUSSION

Relatively good growth and survival in all treatments, including the nil fertiliser treatment, tend to indicate that there are no major nutritional limitations to establishment of plantations of these species on these soil types, despite the evidence from glasshouse omission trials that P was a potentially limiting nutrient at South Johnstone and Tully. This could be due to:

1. sufficient release of nutrients during the site preparation process to satisfy early nutritional demands,
2. carry over of residual nutrition from fertiliser treatments associated with farming practices, and
3. the growth characteristics of the species used in the experiments.

In some ways these results is not surprising as all sites were occupied by productive rainforest prior to their clearance for agriculture, and the degradation associated with agricultural practices has not been particularly severe. The growth characteristics of the species chosen for the experiment may not have been the best for discerning potential nutrient limitations. *Castanospermum australe* and *Agathis robusta* generally have a slow rates of growth early in their development, and their demand for nutrients in the first two or three years may not be very high because of this. Some other native rainforest species, including the widely-planted *Araucaria cunninghamii*, also have this characteristic. Limitations to growth in these species may therefore become more apparent during more rapid foliar biomass accumulation that takes place about two to six years after planting. Whether some of the initial fertiliser is retained in the system, either in trees, other plants, or the soil and might still be available to satisfy later demands will become evident from future growth results. However, it is more likely that if it has not been used by the trees at this stage, then it will have been lost to the system.

Cedrela odorata had more rapid initial growth and may have demonstrated potential nutrient limitations more effectively at these sites. However, variability in the growth of this species, even when the four shortest trees were removed from the analysis did not allow the statistical discrimination of treatment effects on height or volume growth. There is some indication from this species that, if fertiliser is applied, a balanced formulation is advisable. As the application of a complete mix without P may have a depressing effect on tree growth.

Better growth of trees in treatment 6 compared with 5 in some cases may have been due to a salt toxicity effect, as the addition of the 'complete' mix, high levels of P and micronutrients meant that around 1.7 kg of salts were being added to each tree in treatment 6.

There have been few published studies of fertilisation of plantations of native or exotic rainforest cabinet- timber species for comparison with these results (Evans 1993, Dreschel and Zech 1994). Evans (1992) suggests that fertilisers are applied for three reasons: to correct a deficiency, to facilitate establishment, to increase timber yields. Results from this study indicate that there are not likely to be nutritional deficiencies at the sites chosen for this study, and that establishment success, at least for the species chosen, will be more dependent on other factors such as planting stock quality, site preparation, timing of planting and post-establishment weed control. Whether the addition of fertiliser at establishment results in longer term growth stimulus will depend on future growth measurements. Further experiments have been established on these sites and on other important soil types to investigate fertilisation responses in a wider range of cabinet-timber species. The extent of nutrient uptake by trees, the fate of applied fertiliser, and examination of whether fertilisation can increase biomass accumulation in later stages of stand development will be investigated in future studies.

5. ACKNOWLEDGEMENTS

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Fig. 1 Map of North Queensland indicating the three experimental areas.

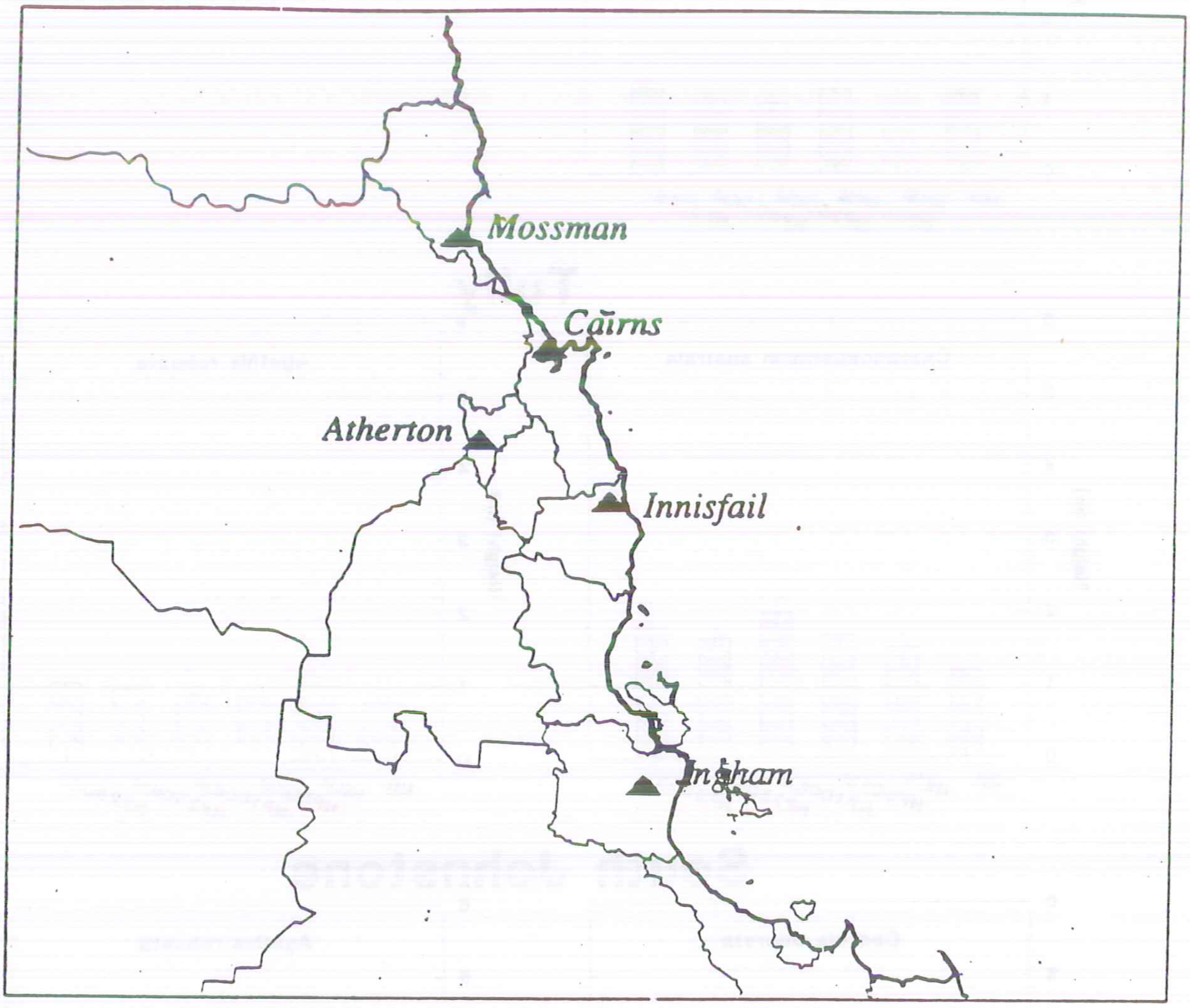

Fig. 2. Heights of black bean (*Castanospermum australe*), kauri pine (*Agathis robusta*), and West Indian cedar (*Cedrela odorata*) 20 months after treatment with varying levels of P fertilisation at three sites in North Queensland. See text for details of fertiliser treatments. Error bars are one standard error of the mean.

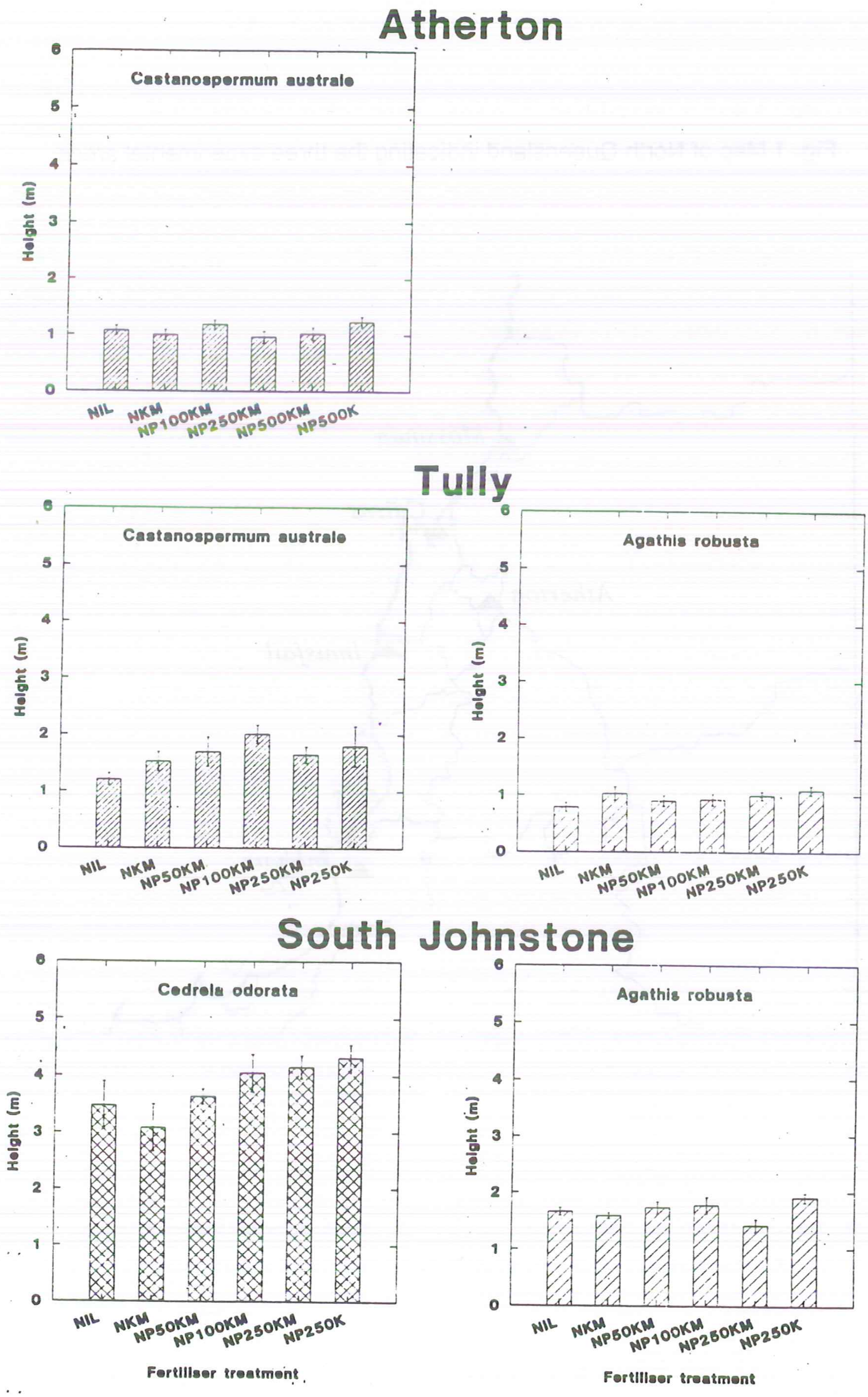

Fig. 3. Volume index (diameter^2 x height) for (*Castanospermum australe*), kauri pine (*Agathis robusta*), and West Indian cedar (*Cedrela odorata*) 20 months after treatment with varying levels of P fertilisation at three sites in North Queensland. See text for details of fertiliser treatments. Scale is relative to the treatment with the highest average volume at each site. Error bars are one standard error of the mean.

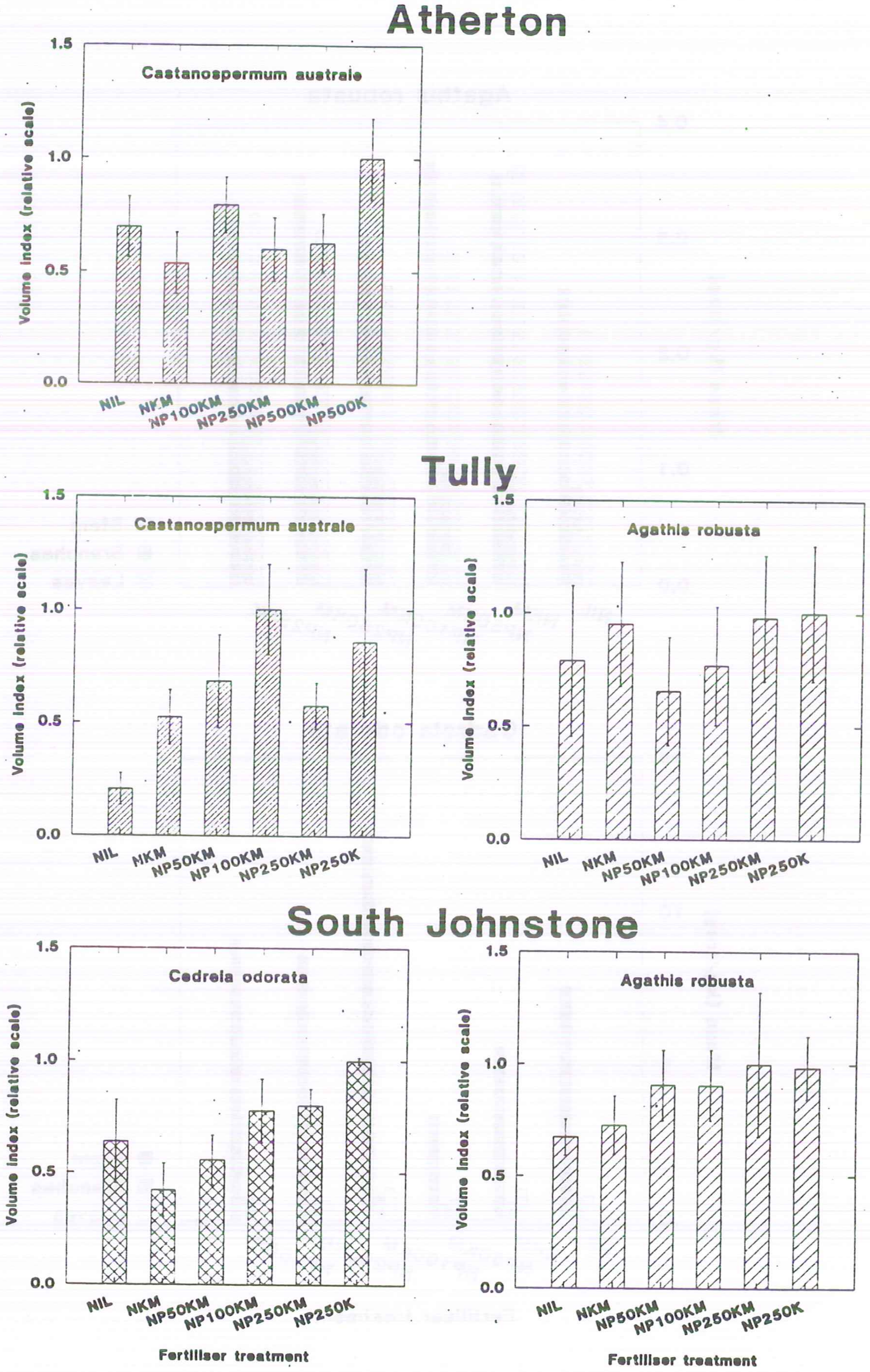

Fig. 4. Biomass in different above-ground plant components for kauri pine (*Agathis robusta*) and West Indian cedar (*Cedrela odorata*) 20 months after treatment with varying levels of P fertilisation at South Johnstone in North Queensland. See text for details of fertiliser treatments.

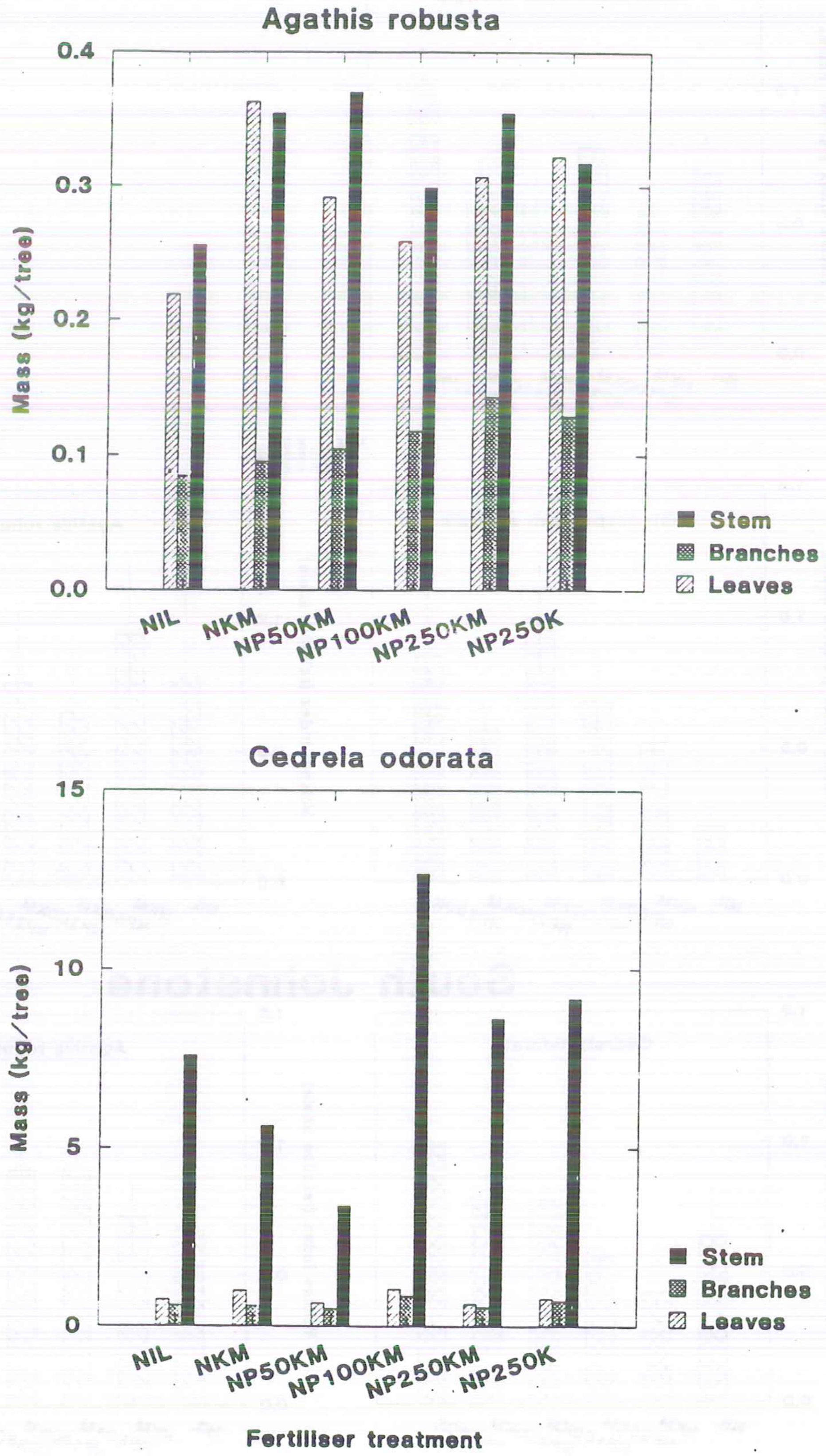

Table 1. Location and climatic variables for the three study sites.

Location	Latitude (S)	Longitude (E.)	Altitude (m)	Mean Annual Rainfall (mm)	Mean minimum temperature in coldest month (°C)	Mean maximum temperature in warmest month (°C)
Atherton	17°16'	145°29'	760	1425	10	30
South Johnstone	17°36'	146°00'	18	3625	15	30
Tully	17°56'	145°55'	10	4321		

Table 2. Soil characteristics for the three study sites.

Location	Geology	Slope (%)	Depth (m)	Texture	N%	P ($mg.g^{-1}$)	K	CEC ($cmol(c).kg^{-1}$)
Atherton	Basalt	3.5	> 2	clay loam	0.08	28	0.21	6.2
South Johnstone	Metamorphic	9	1.2	clay loam - light clay	0.06	2	0.07	1.6
Tully	Granite	7	1.5	sandy loam	0.05	19	0.11	2.4

Table 3. Fertiliser treatment formulations applied at to plantations of rainforest cabinet timber species at three sites in North Queensland

Treatment	Nutrient and form	Elemental rate kg /ha			Fertiliser rate kg /ha		
		Total	0 months	6 months	Total	0 months	6 months
Complete	N as Urea (46 % N)	100	50	50	217	108.5	108.5
	K as KCL (50 % K)	160	80	80	320	160	160
	S as Sulfur (99.5 % S)	120	60	60	120	60	60
	Ca as Dolomite (19 % Ca)	108	54	54	571	285.5	285.5
	Mg as Dolomite (7.8 % Mg)	44	22	22			
	Trace elements *				129	129	
P Treatments							
P50	P as Trifos (20.7% P)	50	12.5	12.5	241.5	120.75	120.75
P100	P as Trifos (20.7% P)	100	25	25	483	241.5	241.5
P250	P as Trifos (20.7% P)	250	125	125	1207	603.5	603.5
P500	P as Trifos (20.7% P)	500	250	250	2415	1207.5	1207.5

* Trace elements mix composed of the following by weight: $ZnSO_4$, $7H_2O$ 17 %; $CuSO_4$,$5H_2O$ 11%; $MnSO_4$,$5H_2O$ 19%; Fe SO_4, $7H_2O$ 35%; Na_2MoO_4, $2H_2O$ 1%; $Na_2B_4O_7$, $10H_2O$ 17 %.

FERTILIZATION AND FATE OF FERTILIZER ^{15}N APPLIED TO A SLASH X CARIBBEAN PINE HYBRID IN SUBTROPICAL AUSTRALIA

Zhihong Xu[1,2], Paul Saffigna[3], John Simpson[1] and David Osborne[1]

ABSTRACT

The response to fertilizers of the F_1 hybrid between slash pine (*Pinus elliottii* var. *elliottii*) and Honduras Caribbean pine (*Pinus caribaea* var. *hondurensis*) grown in subtropical Australia and the fate of fertilizer ^{15}N in the plantation ecosystem were examined in the first 14 months following fertilization. Basal fertilizers containing 60 kg P ha^{-1}, 74 kg K ha^{-1}, 5 kg Cu ha^{-1}, 5 kg Zn ha^{-1} and 2.5 kg B ha^{-1} were applied to the 4-month-old F_1 hybrid pine with or without 25 kg N ha^{-1}. Both stand height and above-ground biomass production of the F_1 hybrid pine improved with application of the basal fertilizers. This was largely attributed to improved P nutrition of the stands. Application of 25 kg N ha^{-1} as $(NH_4)_2SO_4$ or KNO_3 in the presence of the basal fertilizers further improved the stand development.

Recovery of fertilizer N in the above-ground biomass of the stands 14 months after N application was estimated by the difference method to be 33-36%. This compared with recoveries of 1.7-2.4% of fertilizer P and 12-17% of fertilizer K. Most of the N, P and K in the above-ground biomass were found in the foliage. By 14 months after fertilization, recovery of fertilizer ^{15}N applied at 25 kg N ha^{-1} as $(NH_4)_2SO_4$ or KNO_3 was 11-12% in the above-ground biomass, 1.3-1.6% in roots, 30-37% in soil, while 51-57% was apparently lost from the plantation ecosystem. The N recovery in the above-ground biomass estimated by the difference method was about 3 times that of fertilizer ^{15}N, indicating that caution would be required to interpret the N recovery determined by the difference method since it might substantially overestimate the fertilizer N recovery.

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INTRODUCTION

Fertilization is often an important silvicultural practice for the successful establishment and development of forest plantations. In most cases, application of either N or P or both nutrients is required to improve the mineral nutrition of plantation forests and increase the plantation productivity (CROMER *et al.*, 1993, NAMBIAR and BOWEN, 1986, THOMAS and MEAD, 1992, XU *et al.*, 1995a, b, c). In subtropical Australia, P has been identified by SIMPSON and OSBORNE (1993) and XU *et al.* (1995a, b, c) as the major growth-limiting nutrient of exotic pines such as slash pine and Honduras Caribbean pine, followed to a much lesser extent by N, K and Cu. With increasing plantation areas of the F_1 hybrid between slash pine and Honduras Caribbean pine, there is an urgent need to identify the nutrient requirements of the F_1 hybrid pine and quantify optimum application rates of the growth-limiting nutrients.

Fertilizer N applied to plantation forests may experience more pathways of losses from the soil and plant ecosystems than any other fertilizer nutrient. An understanding of the fate of fertilizer N applied in forest plantation ecosystems is necessary to improve N use efficiency by plantation forests (CLINTON and MEAD, 1994, THOMAS and MEAD, 1992). Stable isotope of ^{15}N tracing technique is useful in examining the fate of fertilizer N applied in forest ecosystems (MEAD and PRESTON, 1994, MEAD and PRITCHETT, 1975a). There has been a very limited number of publications reporting the distribution and fate of fertilizer ^{15}N in forest ecosystems compared with the extensive use of the ^{15}N technique in agricultural ecosystems. Overall, recovery of fertilizer ^{15}N by plantation tree species has been low (6-25%) in most situations (MEAD and PRITCHETT, 1975b, MUGASHA and PLUTH, 1994, NAMBIAR and BOWEN, 1986) as compared with that of 25-50% commonly found in agricultural crops (XU *et al.*, 1992, 1993a). After one growing season, little residual fertilizer ^{15}N can be further recovered by above-ground plants in either forest ecosystems (MEAD and PRESTON, 1994, PRESTON and MEAD, 1994) or agricultural ecosystems (XU *et al.*, 1993b).

Recovery of fertilizer ^{15}N applied in forest ecosystems can vary with fertilizer N forms and application methods (CLINTON and MEAD, 1994, NAMBIAR and BOWEN, 1986, KANG, 1985, THOMAS and MEAD, 1992). However, there is little information on the distribution and fate of fertilizer ^{15}N in tropical and subtropical forest ecosystems since most of the published studies using the ^{15}N technique have been conducted under temperate and Mediterranean climatic conditions. The objectives of this study were to examine (1) the growth response of the F_1 hybrid between slash pine and Honduras Caribbean pine in the first 14 months following fertilization of the 4-month-old stands and (2) the fate of fertilizer ^{15}N applied to the F_1 hybrid pine grown in subtropical Australia.

MATERIALS AND METHODS

Experimental site

The experiment was conducted at Toolara State Forest (Lat. 26^0 00' S Long. 152^0 49' E), Queensland, Australia. The site has a humid subtropical climate with a mean annual rainfall of 1354 mm, about 60% of which falls in the summer (December to March). The mean temperature ranges from 14.0 ^{0}C in July (mid-winter) to 24.9 ^{0}C in January (mid-summer).

The first rotation of slash pine planted in 1952 on the site was harvested in September 1988. The site was de-stumped and ploughed in June 1993. Following site preparation, open-root seedlings of the F_1 hybrid pine from Toolara Nursery were planted at a stocking rate of 1736 stems ha^{-1} (2.4 m ´ 2.4 m) on 21 June 1993. The site was managed as for local routine pine plantations except for the nutritional management which was carried out as specified treatments of interest. The soil is classified as Ferric Luvisol (FAO, 1974) or Typic Paleudalf (SOIL SURVEY STAFF, 1975) with its chemical and physical properties shown in Table 1.

(Table 1)

Fertilizer application

The experiment consisted of 8 treatments as follows (1) control without any fertilizers; (2) basal fertilizers (BF) containing 60 kg P ha^{-1} applied on 4 October 1993 as triple superphosphate, 74 kg K ha^{-1} as KCl, 5 kg Cu ha^{-1} as $CuSO_4.H_2O$, 5 kg Zn ha^{-1} as $ZnSO_4.7H_2O$ and 2.5 kg B ha^{-1} as borax; (3) BF + 25 kg N ha^{-1} as $(NH_4)_2SO_4$ applied on 4 October 1993; (4) 25 kg N ha^{-1} and 74 kg K ha^{-1} as KNO_3 applied on 4 October 1993 in the presence of 60 kg P ha^{-1} as triple superphosphate, 5 kg Cu ha^{-1} as $CuSO_4.H_2O$, 5 kg Zn ha^{-1} as $ZnSO_4.7H_2O$ and 2.5 kg B ha^{-1} as borax; and treatments 5 - 8 examining the second N application at 4 N rates (25, 75, 125 and 225 kg N ha^{-1}) 14 months after the first N application at 25 kg N ha^{-1} as $(NH_4)_2SO_4$ in the presence of BF. All the fertilizers were applied as an individual tree application, spread evenly within a 40-cm radius of each tree. The experiment was laid out as a randomized complete block design with 3 replications for each treatment. In each of the 24 plots (each 0.0368 ha) there are 64 trees (8 rows by 8 trees), of which the central 4 rows by 4 trees (net plot) have been periodically measured and sampled for foliar nutrient analysis.

^{15}N-labelled fertilizers, instead of unlabelled commercial fertilizers, were applied to 2 representative trees (with their mean height as 104% of plot mean height at 12 months after fertilization) within net plots of the treatments 3, 4 and 5 as described above. In treatment 3, ^{15}N-labelled $(NH_4)_2SO_4$ (20.5% N) with 6.59 atom % ^{15}N excess was applied on 4 October 1993 to 2 trees in the net plot at 25 kg N ha^{-1} in the presence of BF. With treatment 4, ^{15}N-labelled KNO_3 (13.4% N) with 5.54 atom% ^{15}N excess was applied on 4 October 1993 to 2 trees in the net plot at 25 kg N ha^{-1} and

74 kg K ha^{-1} in the presence of 60 kg P ha^{-1}, 5 kg Cu ha^{-1}, 5 kg Zn ha^{-1} and 2.5 kg B ha^{-1}. In treatment 5, ^{15}N-labelled $(NH_4)_2SO_4$ (20.5% N) with 6.12 atom % ^{15}N excess was applied first at 25 kg N ha^{-1} on 4 October 1993 in the presence of BF and then at 25 kg N ha^{-1} on 13 December 1994.

This paper reports the experimental results in the first 14 months following fertilization. Therefore, this experiment is considered to have effectively the first 4 treatments since the treatments 5-8 are the same as the treatment 3 before the second application of N fertilizer on 13 December 1994.

Stand growth measurement, plant and soil sample collection

Stand heights for trees in each net plot were measured at 2, 5 and 12 months respectively after fertilization. Foliar samples were collected as described by Xu *et al.* (1995b) at 2, 5 and 8 months after fertilization for the treatments 1, 2, 3 and 4. Briefly, 50 most recent, fully expanded needles were sampled from a branch on the northern side of the basal spring whorl immediately below the tip of each sample tree. Four trees in each net plot were sampled and needles combined to produce a composite foliar sample for each plot. Foliar samples were oven-dried at 70 ^{0}C immediately after collection and ground to pass through a 0.5-mm sieve for chemical analysis.

One ^{15}N-labelled tree in each plot of the treatments 3 and 4 was harvested 14 months after ^{15}N application by cutting it above ground and separating into foliage, branch and stem components. Similarly, one unlabelled but representative tree was also collected from each net plot of treatments 1 and 2 at the same time as for treatments 3 and 4, and separated into the same components. After harvesting, the tree component samples were oven-dried at 60 ^{0}C for dry matter determination and then ground for ^{15}N and total N, P and K analysis.

After harvesting the ^{15}N-labelled trees as described above, an area of 1.20 m by 1.20 m centered on each tree stump was excavated in 10-cm increments down to 30 cm depth. Following collection of tree roots with diameters larger than 2 mm (approx.), about 10 kg of moist soil excavated from each of the 0-10, 10-20 and 20-30 cm depths was collected for moisture determination and ^{15}N analysis after the soil in each layer was weighed and then well mixed. Soil samples collected from the top 30 cm soil included the fine roots (less than 2 mm in diameter) which were well mixed with soil before sampling. Cores of soil at 30-60 cm depth were obtained using a sampling auger 7.5 cm in diameter, at 4 places symmetrically distributed on a circle 80 cm in diameter centered on the stump. The 4 soil cores from the 30-60 cm depth were combined as a composite soil sample for total N and ^{15}N analysis. One core of soil from below 60 cm was sampled near the stump down to 180 cm depth and separated into 60-90, 90-120, 120-150 and 150-180 cm depths. The moisture content in each of the 0-10, 10-20 and 20-30 cm soil depths were determined after soil samples were oven-dried at 60 ^{0}C for 24 hours. Soil dry weight in the 30-60 cm depth was estimated with soil bulk density for the area of 1.20 m by 1.20 m with the stump in the centre and those of 60-90, 90-120, 120-150 and 150-180 cm depths for the area of circle with a radius of 40 cm from the stump, *i.e.* the fertilized area. All the soil samples were sub-sampled and then ground for total N and ^{15}N analysis. Weeds grown in the soil sampling area were also collected by cutting them above ground for dry matter determination and ^{15}N analysis. The stump in the top 60 cm of soil was excavated and combined with the larger roots collected from the top 30 cm soil as root samples. The ^{15}N-labelled root samples were oven-dried at 60 ^{0}C for dry matter determination and ^{15}N analysis.

Chemical, physical and statistical analysis

Plant N, P and K concentrations were determined as reported previously (Xu *et al.*, 1995b). Soil chemical properties (pH, organic C, total N, total P, total K, available P and K, CEC) and physical characteristics (electrical conductivity, clay, silt, coarse sand and fine sand content) were determined as described by Xu *et al.* (1995 a). ^{15}N analysis of both soil and plant samples was conducted on the mass spectrometer of Europa Scientific Roboprep CN (7001) / Tracermass system (9001). Statistical analysis of the Duncan's Multiple Range Test (DMRT) was performed using STATISTIX Version 4.0 (SIEGEL, 1992).

RESULTS

Stand growth response to fertilization

Fertilization of the F_1 hybrid pine at 4 months after planting significantly increased stand heights in the first 12 months after fertilizer application (Table 2). In the first 2 months following fertilization, stand height of the F_1 hybrid pine was improved by application of basal fertilizers (BF), but an additional 25 kg N ha^{-1} applied in the presence of BF did not result in a further improvement in the stand growth. At 5 months after fertilization, application of 25 kg N ha^{-1} either as NH_4^+-N or NO_3^--N in the presence of BF produced a further increase in stand height when compared with that of BF. At 12 months after fertilization, stand height (1.56 m) with BF applied was 32% higher than that of control without any fertilizers while application of 25 kg N ha^{-1} in the presence of BF resulted in a further increase of 19% in stand height compared with the use of BF only.

(Table 2)

Above-ground biomass development of the F_1 hybrid pine 14 months after fertilization is presented in Table 3. Dry matter (DM) production of foliage (1091 kg ha^{-1}) with BF applied was 159% greater than that of the control. Application of 25 kg N ha^{-1} in the presence of BF produced a further increase of 41% in foliage DM compared with the use of BF only. Foliage DM with 25 kg NH_4^+-N ha^{-1} applied in the presence of BF was not significantly different from that receiving both 25 kg NO_3^--N ha^{-1} and BF. DM production of both branch and stem responded to the fertilization in similar fashion to that of foliage. Overall, total DM production was increased by 174% from application of BF while additional 25 kg N ha^{-1} produced a further increase of 39%.

(Table 3)

Stand nutrient response to fertilization

Foliar nutrient concentration of the F_1 hybrid pine in the first 8 months after fertilization is shown in Table 4. Application of BF significantly increased foliar N concentration 2 months after fertilization while a further increase in foliar N concentration was obtained from addition of 25 kg N ha^{-1} in the presence of BF. There was no significant difference in foliar N concentration between N sources of NH_4^+-N and NO_3^--N. However, the fertilization effects on foliar N concentrations disappeared 5 and 8 months after fertilization. Foliar P concentration of 0.16% at 2 months after fertilization was the highest when BF was applied, followed by that of 0.12% where 25 kg N ha^{-1} was added in the presence of BF, with the lowest concentration of 0.07% for the control. By 5 and 8 months after fertilization, foliar P concentration improved only with application of BF.Overall, foliar K concentration in the first 8 months increased with application of BF with or without 25 kg N ha^{-1}.

(Table 4)

Nutrient uptake and distribution in the F_1 hybrid pine 14 months after fertilization are shown in Table 5. N content in foliage (11.2 kg N ha^{-1}) with BF was more than twice that of the control while application of 25 kg N ha^{-1} in the presence of BF resulted in a further increase of 62% in foliar N content. N contents in branch and stem were increased from the fertilizer application in the same fashion as that for foliar N content. Compared with 6.3 kg N ha^{-1} in total biomass above ground for the control, 14.3 kg N ha^{-1} was obtained from application of BF and about 23 kg N ha^{-1} from addition of 25 kg N ha^{-1} in the presence of BF. There was no significant difference in total biomass N content above ground between N sources of NH_4^+-N and NO_3^--N applied at 25 kg N ha^{-1}. Recovery of fertilizer N by plant tops was 33-36% as estimated by the difference method. Most (78-81%) of the total biomass N was found in the foliage. Both P and K contents in foliage, branch, stem and total biomass above ground were significantly increased from application of BF with or without 25 kg N ha^{-1} added. Recovery of fertilizer P in the above-ground biomass (1.7-2.4%) estimated by the difference method was generally low when compared with that of fertilizer K (11.9-16.9%). However, neither P nor K recovery was significantly affected by the additional 25 kg N ha^{-1} applied.

(Table 5)

Fate of fertilizer ^{15}N in the soil and plant ecosystem

Distribution of fertilizer ^{15}N in the 180 cm soil profile 14 months after ^{15}N application at 25 kg N ha^{-1} is shown in Table 6. Compared with 6.3% of fertilizer ^{15}N applied at 25 kg N ha^{-1} as KNO_3 in 0-10 cm soil, 11.9% was recovered in the same depth from the ^{15}N addition at 25 kg N ha^{-1} as $(NH_4)_2SO_4$. ^{15}N recovery was 3.7-4.8% in 10-20 cm, 2.6-3.0% in 20-30 cm and 1.2-3.3% in 30-60 cm soil respectively. With 7.2% and 1.4% of the ^{15}N applied as $(NH_4)_2SO_4$ recovered from 60-90 and 90-120 cm depths respectively, the corresponding figures from addition of the ^{15}N as KNO_3 were 18.5% and 2.7%. No fertilizer ^{15}N was detected below 120 cm soil.

(Table 6)

Fate of fertilizer ^{15}N in the soil and plant system 14 months after ^{15}N application is shown in Table 7. ^{15}N recovery was 8.9-9.5% in foliage, 0.7-0.8% in branch, 1.3% in stem, 10.8-11.6% in the tree-tops above ground, 0.3-0.7% in weed, 1.3-1.6% in root, and 29.5-37.1% in the soil respectively, with 51-57% of fertilizer ^{15}N apparently lost from the soil and plant ecosystem. The fate of ^{15}N applied at 25 kg N ha^{-1} as $(NH_4)_2SO_4$ was similar to that of ^{15}N added as KNO_3 in the pine plantation ecosystem.

(Table 7)

DISCUSSION

Fertilization of the F_1 hybrid pine grown the second-rotation site significantly improved stand development in the first 12-14 months after fertilization on the 4-month-old pine plantation. Application of basal fertilizers (BF) including 60 kg P ha^{-1}, 74 kg K ha^{-1}, 5 kg Cu ha^{-1}, 5 kg Zn ha^{-1} and 2.5 kg B ha^{-1} increased both stand height and above-ground biomass production. This increase in the stand development from application of BF was attributable to the significant improvement in P nutrition of the stands since foliar P concentration of the control without any fertilizers was generally below the optimum foliar P concentration of 0.093-0.110% established by XU *et al.* (1995c). This result is also consistent with our earlier findings (SIMPSON and OSBORNE, 1993, XU *et al.*, 1995a, b) that P deficiency is a major factor limiting the plantation production of exotic pines grown in subtropical Australia. Application of 25 kg N ha^{-1} either as $(NH_4)_2SO_4$ or KNO_3 in the presence of BF resulted in a further improvement in plantation growth, indicating that N fertilizer may be required to optimize the stand growth of the F_1 hybrid pine on second- rotation sites.

There were significant nutrient responses of the F_1 hybrid pine to application of BF with or without 25 kg N ha^{-1} in the first 14 months after fertilization. At 2 months after fertilization, foliar N concentration with BF applied was significantly higher than that of the control. This may have resulted from the improved root development due to better P nutrition of the stand with BF, so that more soil mineral N would be taken up by the trees. Addition of 25 kg N ha^{-1} applied in the presence of BF produced a further increase in foliar N concentration 2 months after fertilization. This suggests that application of additional N fertilizer improved N nutrition of the stands, which subsequently led to the increases in stand height and above-ground biomass DM production. However, the fertilization effects on foliar N concentration disappeared 5 and 8 months after fertilization due to the nature of N mobility in the soil and plant ecosystem. Compared with the short-term effects of fertilization on foliar N concentration, application of BF with or without 25 kg N ha^{-1} consistently increased foliar P and K concentrations in the first 8 months following fertilization. Foliar P concentration with either BF only or the combination of BF and 25 kg N ha^{-1} in the first 8 months following fertilization was above the optimum foliar P concentration of 0.093-0.110% for slash pine (XU *et al.*, 1995c).The stands would not experience K deficiency since foliar K concentration of the control was consistently above the acceptable foliar K concentrations of 0.30% for Honduras Caribbean pine and 0.40% for slash pine (SIMPSON and OSBORNE, 1993, XU *et al.*, 1995b). According to the difference method, 33-36% of fertilizer N 14 months after fertilization was taken up by the stands as compared with 12-17% of fertilizer K and 1.7-2.4% of fertilizer P.

About 20% of the ^{15}N applied at 25 kg N ha^{-1} as $(NH_4)_2SO_4$ was recovered in the top 30 cm of soil 14 months after ^{15}N application as compared with 13% of that from addition of 25 kg N ha^{-1} as KNO_3. On the contrary, about 25% of the NO_3^--^{15}N was leached below 30 cm soil as compared with 10% of the NH_4^+-^{15}N. It should be noted that ^{15}N recovery below 30 cm soil was estimated by the soil-coring method. In addition, soil total N below 30 cm (0.02-0.03%) was lower than that of 0.05-0.06% in the top 30 cm soil, which may lead to a larger analytical error by the mass spectrometer for total N and ^{15}N analysis. Nevertheless, it does indicate that a significant amount (10-25%) of the ^{15}N was leached below 30 cm soil with NO_3^--^{15}N being more susceptible to leaching than NH_4^+-^{15}N. Overall, 30% of the NH_4^+-^{15}N applied was recovered in the 180 cm soil profile compared with 37% of the NO_3^--^{15}N. This compares with 39-68% of urea-^{15}N recovered in the 90 cm soil profile 17 months after ^{15}N application to a 2-year-old radiata pine (*Pinus radiata*) plantation in New Zealand (THOMAS and MEAD, 1992). CLINTON and MEAD (1994) also reported that about 49% of the $^{15}NO_3^-$ or $^{15}NH_4^+$ applied to a 4-year-old radiata pine was recovered in the top 20 cm of soil 8 months after ^{15}N application.

Recovery of fertilizer ^{15}N 14 months after fertilization was 11-12% in plant tops of the F_1 hybrid pine and 1.3-1.6% in roots. This is similar to the findings of THOMAS and MEAD (1992) that 17% of the ^{15}N was recovered in the plant tops of radiata pine and 1.2% in the larger roots. Recovery of fertilizer ^{15}N in the above-ground biomass of forest plantations has also been reported to be 15% by CLINTON and MEAD (1994), 25% by MEAD and PRITCHETT (1975b), 6-9% by MUGASHA and PLUTH (1994) and 6-18% by NAMBIAR and BOWEN (1986). Fertilizer N recovery (33-36%) estimated by the difference method was about 3 times that of fertilizer ^{15}N detected in the above-ground biomass of the F_1 hybrid pine plantation. This suggests that caution would be needed to interpret the N recovery by the difference method since it might overestimate the fertilizer N recovery. This overestimation of fertilizer N recovery by the difference method may be attributed to the fact that more soil mineral N could be taken up by the improved stands with additional N fertilizer applied than that by the stands without any N fertilizer. In this study, we have found that 51-57% of fertilizer ^{15}N was not accounted for in the soil and plant ecosystem 14 months after ^{15}N application, possibly lost through denitrification and leaching. MEAD and PRITCHETT

(1975b) also reported that about 50% of fertilizer ^{15}N applied to an 11-year-old slash pine stand was lost from the soil and plant ecosystem after 2 growing seasons. Up to 41% of fertilizer ^{15}N has been reported by THOMAS and MEAD (1992) to be lost from the soil and plant system 17 months after ^{15}N application to a 2-year-old radiata pine plantation.

CONCLUSIONS

The P deficiency was a major factor limiting stand growth of the F_1 hybrid pine under the experimental conditions. Following correction of the P deficiency by application of BF including 60 kg P ha^{-1}, additional N fertilizer further improved the plantation development of the F_1 hybrid pine grown on the second-rotation site. Less than 14% of fertilizer ^{15}N applied at 25 kg N ha^{-1} as $(NH_4)_2SO_4$ or KNO_3 in the presence of BF was recovered in the stand biomass 14 months after fertilization, a further 30-37% in the soil, while 51-57% was apparently lost from the soil and plant ecosystem.

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Table 1: Soil chemical and physical properties in the F_1 hybrid pine plantation grown in subtropical Australia[a]

Soil depth (cm)	0-10	10-20	20-30	30-60	60-90	90-120	120-150	150-180
Chemical properties								
pH (1:5 H_2O)	5.6	5.6	5.7	5.6	5.5	5.5	5.8	5.7
Organic C (%)	2.03	1.00	1.78	0.48	0.26	0.29	0.13	0.18
Total N (%)	0.061	0.045	0.064	0.029	0.028	0.025	0.018	0.019
Total P (mg kg^{-1})	57	55	69	48	52	69	75	60
Total K (mg kg^{-1})	275	244	278	370	744	969	1186	1117
Available P (mg kg^{-1})	4.7	3.2	4.2	1.3	0.9	1.4	2.0	1.3
Available K (mg kg^{-1})	20	20	26	12	31	18	5	27
Cation exchange capacity (cmol kg^{-1})	8.1	7.0	9.1	7.1	9.8	5.6	13.7	10.0
Physical properties								
Electrical conductivity (dS m^{-1})	2.2	2.5	2.7	2.1	1.7	2.7	2.4	2.5
Clay (%)	14	16	14	22	38	40	42	40
Silt (%)	15	15	17	15	15	15	15	15
Coarse sand (%)	24	25	26	22	16	14	14	13
Fine sand (%)	47	44	43	41	31	31	29	32

[a] 0.1 *M* H_2SO_4 extracted available P and K.

Table 2: Heights (m) of the F_1 hybrid pine at 2, 5 and 12 months after fertilization of the 4-month-old stands

Fertilizer application[a]	Months after fertilization		
	2	5	12
Control without fertilizers	0.43 b[b]	0.58 c	1.18 c
Basal fertilizers (BF)	0.51 a	0.79 b	1.56 b
BF + 25 kg N ha^{-1} as NH_4^+-N	0.55 a	0.87 a	1.84 a
BF + 25 kg N ha^{-1} as NO_3^--N	0.53 a	0.85 a	1.85 a

[a] Basal fertilizers including 60 kg P ha^{-1}, 74 kg K ha^{-1}, 5 kg Cu ha^{-1}, 5 kg Zn ha^{-1} and 2.5 kg B ha^{-1}.
[b] Means within a column followed by the same letter are not different from each other at the 5% level of significance by DMRT.

Table 3: Above-ground biomass development of the F_1 hybrid pine 14 months after fertilization of the 4-month-old stands

Fertilizer application[a]	Dry matter production (kg ha^{-1})			
	Foliage	Branch	Stem	Total
Control without fertilizers	422 c[b]	159 b	282 c	863 c
Basal fertilizers (BF)	1091 b	394 a	882 b	2367 b
BF + 25 kg N ha^{-1} as NH_4^+-N	1581 a	609 a	1180 a	3370 a
BF + 25 kg N ha^{-1} as NO_3^--N	1497 a	556 a	1175 a	3228 a

[a] Basal fertilizers including 60 kg P ha^{-1}, 74 kg K ha^{-1}, 5 kg Cu ha^{-1}, 5 kg Zn ha^{-1} and 2.5 kg B ha^{-1}.
[b] Means within a column followed by the same letter are not different from each other at the 5% level of significance by DMRT.

Table 4: Foliar nutrient concentration of the F_1 hybrid pine at 2, 5 and 8 months after fertilization of the 4-month-old stands

Fertilizer application[a]	Months after fertilization		
	2	5	8
	N (%)		
Control without fertilizers	0.97 c[b]	1.08 a	1.57 a
Basal fertilizers (BF)	1.25 b	0.98 a	1.18 a
BF + 25 kg N ha^{-1} as NH_4^+-N	1.51 a	1.02 a	1.21 a
BF + 25 kg N ha^{-1} as NO_3^--N	1.40 a	1.07 a	1.41 a
	P (%)		
Control without fertilizers	0.068 c	0.073 b	0.095 b
Basal fertilizers (BF)	0.156 a	0.121 a	0.127 a
BF + 25 kg N ha^{-1} as NH_4^+-N	0.116 b	0.119 a	0.125 a
BF + 25 kg N ha^{-1} as NO_3^--N	0.121 b	0.127 a	0.121 a
	K (%)		
Control without fertilizers	0.51 d	0.64 b	0.63 b
Basal fertilizers (BF)	0.96 b	0.83 a	0.81 a
BF + 25 kg N ha^{-1} as NH_4^+-N	0.81 c	0.95 a	0.93 a
BF + 25 kg N ha^{-1} as NO_3^--N	1.14 a	0.87 a	0.80 a

[a] Basal fertilizers including 60 kg P ha^{-1}, 74 kg K ha^{-1}, 5 kg Cu ha^{-1}, 5 kg Zn ha^{-1} and 2.5 kg B ha^{-1}.

[b] Means within a column followed by the same letter are not different from each other at the 5% level of significance by DMRT.

Table 5: Nutrient uptake and distribution in the F_1 hybrid pine 14 months after fertilization of the 4-month-old stands

Fertilizer application[a]	Nutrient distribution in plant tops (kg nutrient ha^{-1})				Recovery[b]
	Foliage	Branch	Stem	Total	(%)
	N				
Control without fertilizers	5.1 c[c]	0.45 b	0.78 c	6.3 c	-
Basal fertilizers (BF)	11.2 b	1.22 a	1.89 b	14.3 b	-
BF + 25 kg N ha^{-1} as NH_4^+-N	18.3 a	2.01 a	2.93 a	23.3 a	35.7 a
BF + 25 kg N ha^{-1} as NO_3^--N	18.0 a	1.67 a	2.92 a	22.6 a	33.1 a
	P				
Control without fertilizers	0.33 b	0.05 b	0.07 b	0.45 b	-
Basal fertilizers (BF)	0.99 a	0.21 a	0.29 a	1.49 a	1.73 a
BF + 25 kg N ha^{-1} as NH_4^+-N	1.33 a	0.25 a	0.33 a	1.90 a	2.42 a
BF + 25 kg N ha^{-1} as NO_3^--N	1.38 a	0.20 a	0.33 a	1.91 a	2.44 a
	K				
Control without fertilizers	2.3 b	0.52 b	0.67 b	3.4 b	-
Basal fertilizers (BF)	8.6 a	1.47 a	2.16 a	12.2 a	11.9 a
BF + 25 kg N ha^{-1} as NH_4^+-N	11.6 a	2.06 a	2.29 a	15.9 a	16.9 a
BF + 25 kg N ha^{-1} as NO_3^--N	10.0 a	1.96 a	2.54 a	14.5 a	14.9 a

[a] Basal fertilizers (BF) including 60 kg P ha^{-1}, 74 kg K ha^{-1}, 5 kg Cu ha^{-1}, 5 kg Zn ha^{-1} and 2.5 kg B ha^{-1}.
[b] Recovery of fertilizer N by plant tops is estimated by the difference method between N treatment and BF, P and K recoveries between BF (or N treatment) and control.
[c] Means within a column followed by the same letter are not different from each other at the 5% level of significance by DMRT.

Table 6: Distribution of fertilizer ^{15}N in the soil profile 14 months after fertilizer application

^{15}N application[a]	% of the added ^{15}N recovered in different soil depth (cm)							
	0-10	10-20	20-30	30-60	60-90	90-120	120-150	150-180
25 kg N ha^{-1} as NH_4^+-^{15}N	11.9 a[b]	4.8 a	3.0 a	1.2 a	7.2 a	1.4 a	ND[c]	ND
25 kg N ha^{-1} as NO_3^--^{15}N	6.3 a	3.7 a	2.6 a	3.3 a	18.5 a	2.7 a	ND	ND

[a] ^{15}N-labelled fertilizer was applied either as $(NH_4)_2SO_4$ or KNO_3.
[b] Means within a column followed by the same letter are not different from each other at the 5% level of significance by DMRT.
[c] Not detectable (ND).

Table 7: Fate of fertilizer ^{15}N in the soil and plant system 14 months after ^{15}N application

^{15}N application[a]	Recovery of fertilizer ^{15}N applied (%) in the soil and plant system						Deficit
	Foliage	Branch	Stem	Plant top	Root	Soil[b]	(%)
25 kg N ha^{-1} as NH_4^+-^{15}N	9.5 a[c]	0.84 a	1.32 a	11.6 (12.3) a[d]	1.57 a	29.5 a	56.6 a
25 kg N ha^{-1} as NO_3^--^{15}N	8.9 a	0.70 a	1.26 a	10.8 (11.1) a	1.34 a	37.1 a	50.5 a

[a] ^{15}N-labelled fertilizer was applied either as $(NH_4)_2SO_4$ or KNO_3.
[b] Total ^{15}N recovery in the 180 cm soil profile.
[c] Means within a column followed by the same letter are not different from each other at the 5% level of significance by DMRT.
[d] Figures in parentheses include ^{15}N recovery in the weeds.

BENEFICIAL USE OF NUTRIENT-SOLUBILIZING AND AGGREGATE STABILIZING MICROBES FOR FERTILIZER EFFICIENCY IN THE TROPICS

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ABSTRACT

A series of laboratory and greenhouse experiments has been conducted with special interest on the elaboration of the potential uses of selected root-inhabiting microbial isolates in promoting a better soil microenvironment. The isolates used were those revealing the abilities in root growth promotion, nitrogen fixation without symbiosis, phosphate solubilization, and/or soil aggregate stabilization. The first experiment included the use of *Agrobacterium tumifaciens* isolate LBA 4404 to induce nutrient uptake of coffee seedlings on a highly weathered tropical soil. Second experiment was aimed to determine the ability of *Azotobacter sp.*, *Aeromonas sp.*, and *Penicillium sp.* on soil aggregate stability. The results indicated that inoculation by *A. tumefaciens* strain LBA 4404 on coffee seedlings seems to provide a better nutrient uptake and possibly combined treatments with reduced fertilizer dosage could be applied. Availability of soil N, P, K was significantly increased by *Azotobacter sp.*, *Streptomyces sp.*, and *Aspergillus sp.* inoculation after 14 days incubation period. Inoculation of *Azotobacter sp.*, *Aeromonas sp.*, and *Penicillium sp.* on compost-enriched soil promoted a more stable soil aggregation.

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1. Introduction

Highly weathered soils under humid tropical conditions have been characterized by low organic matter contents, predominant low activity clays, and strongly acid in reaction. These in effect will depress the microbial activities which in turn disturb the nutrient cycle in the soil. Many have considered that this constraint could be overcome by applying most suitable microbes in the root zones known as a microbial inoculants or biofertilizers (DUNNIGAN, 1979, WEAVER, 1979, RAO, 1981). However, most the works were unintentionally missed the importance in providing condusive soil microenvironment.

The role of microbes in mediating mineral transformation and nutrient dissolution has been very well recognized (STOTZKY, 1989). Much attentions have been focused in the last two decades on the use of plant growth promoting rhizobacteria (LYNCH, 1983), non-symbiotic N-fixing bacteria (RAO, 1981), phosphate solubilizing microbes (KUCEY, 1983, ILLMER and SCHINNER, 1991, GOENADI *et al*, 1993, GOENADI and SARASWATI, 1993). The application of these inoculants has opened the possibility of increasing microbial activity at least within the rooting zone of the soil. However, study on microbially induced soil aggregation was rather very limited (LYNCH and BRAGG, 1985).

It is obvious that the compatibility of microbial isolates to the soil microenvironment will to some extent be dependent upon the origin of the isolates and/or the carrier material used. TAHA *et al* (1968) mentioned that to assure the effective use of microbial inoculants the isolates should be obtained from the soils intended. Furthermore, GOENADI *et al* (1994) reported that selected carrier formula composed of clay mineral and peat was suitable for biofertilizer carrier materials.

This paper present the results of the following research objectives in determining (a) the effect of root promoting bacteria on the growth of coffee seedlings, (b) changes in nitrogen and phosphate availability of soil inoculated by non-symbiotic N-fixing and phosphate solubilizing bacteria, and induced stable aggregate stability incubated by selected fungal and bacterial isolates.

2. Materials and Methods

2.1. Microbial isolation

The root-promoting rhizobacterium used was *A. tumefaciens* strain LBA 4404 of the Cambia RF Kit. *Azotobacter sp.* as non-symbiotic N-fixing and aggregate-stabilizing bacteria was isolated from Gunung Kidul Ultisols, Central Java, whereas *Streptomyces sp.* and *Aspergillus sp.* as phosphate solubilizing bacterial and fungal isolates, respectively, were cultured from Jeneponto Alfisols, South Sulawesi. Soil aggregate-stabilizing microbes, i.e. *Aeromonas sp.* and *Penicillium sp.*, were isolated from Rajamandala Ultisols, West Java, and Jeneponto Alfisols, South Sulawesi, respectively. The isolation was conducted by diluting the soil extracts in a saline solution and then following a serial dilution was plated on selective agar media, i.e. yeast manitol agar for *A. tumefaciens*, Nfb for *Azotobacter sp.*, Pikovskaya for *Streptomyces sp.* and *Aspergillus sp.*, and Luria Bertani + flourescent brightener for *Aeromonas sp.* and *Penicillium sp.* Detailed isolation techniques were reported elsewhere (GOENADI *et al.*, 1995). The isolates used were those showing the highest relative activity.

2.2. Greenhouse Experiment

2.2.2. Effects of root-promoting bacteria on the nutrient uptake of coffee seedlings.

Soil-containing pots were inoculated each by a 10^{-2} l suspension of 1.5×10^{-2} and 3.0×10^{-2} l fresh culture in 10^{-1} l liquid YMA in which the sel population (log 10) reached 7.979 and 8.263/ml, respectively. These inoculation dosages were combined by five levels of standard fertilization for seedlings, i.e. 0 (without NPK fertilizers), and 25%, 50%, 75%, and 100% equal to standard dosage. The seedlings were arabican coffee obtained from Margosuko Plantation, East Java. Fertilizers were given every months, whereas watering by sterile distilled water was done daily. The experiment was set in a factorial design with three replicates. Nutrient uptake was determined by summation of multiplication of the content of each elements in plant parts to their corresponding dry weight. Supporting analysis was performed by scanning electron microscopy to visualize the interaction between selected inoculant and stable aggregate formed.

2.2.2. Induced nutrient solubilization and aggregate stabilization by phosphate-solubilizing and aggregate-stabilizing microbes

Single and mixed inoculants were used in this experiment. The isolates used were *Azotobacter sp.*, *Streptomyces sp.*, and *Aspergillus sp.* for nutrient solubilization, and *Azotobacter sp.*, *Aeromonas sp.*, and *Penicillium sp.* for aggregate stabilization experiments. Fresh culture in its corresponding liquid media was prepared three days before inoculation on a mechanical shaker. For the first experiment, 250 g of autoclaved Rajamandala Ultisols was placed into sterile polyethylene bags. Prior to inoculation, the soil was fertilized by urea, local rock phosphate, and muriate of potash to reach soil concentrations of 3 g kg^{-1} N, 300 mg kg^{-1} P, and 2 mg kg^{-1} of K_2O. Inoculation was conducted aseptically by inserting a 2 x 10^{-3} l of each culture suspension added by a sterile distilled water to make up the total volume of 10^{-2} l. Similar to the above, aggregation experiment was conducted in a polyethylene bag containing 2 kg of sterilized soil enriched by plant compost to reach an organic carbon content of 20 g kg^{-1}. All treatments were incubated at room temperature for 14 days. At the end of the first experiment analyses were performed including N-Kjeldahl, available P-Olsen, and total K_20-HCl, whereas aggregate stability was determined at the second experiment by employing wet-sieving microanalysis designed by KEMPERr and ROSENAU (1986).

3. Results and Discussion

3.1. Nutrient uptake by *A. temefaciens*-inoculated coffee seedlings

Data presented in Table 1 show that after three months period of inoculation, there is remarkable differences in the uptake of nutrients by the coffee seedlings. However, it is obvious that the application of the inoculant at the level of 3 x 10^{-2} l/pot tends to reduce the NPK absorption. Although statistically, analyzed by the Duncan Multiple Range Test, is not significantly different, the application of 1.5 x 10^{-2} l inoculant/pot tends to increase the nutrient uptake, particularly in the combined treatment with fertilization. The data also show that interaction between inoculation and fertilization resulted in an adverse effect on the nutrient absorption. Root growth data (not presented here) show a greater root biomass obtained from the inoculation treatment alone compared to those of combined treatments. These results provide to some extent evidence that the *A. tumefaciens* strain LBA 4404 is non pathogenic to the coffee seedlings opposing most

Table 1

reported in the literature that this organism may cause a so-called crown-galled disease (LYNCH, 1983). Nevertheless, the application of the isolate has a promising effect to reduce fertilizer use most probably by promoting a better root growth.

3.2. Nutrient solubility by *Azotobacter sp.*, *Streptomyces sp.*, and/or *Aspergillus sp.*

These microbes are believed to have a capability in providing catalytic agents for nutrient dissolution in soil (ALEXANDER, 1977, and SAHA *et al.*, 1991). A preliminary qualitative analysis show that the isolates produced certain amounts of urease, phosphatase, extracellular polysaccharides, and/or organic acids. Data showed in Table 2 indicate that inoculation treatments significantly yielded greater available NPK over the control. As a single inoculant each isolate used shows similar ability in providing higher nutrient availability. However, in terms of phosphate-solubilizing microbes, *Streptomyces sp.* and *Aspergillus sp.* seem to have a more effective dissolution of a relatively unsoluble rock phosphate applied to the soil. This evidence could be attributed to the fact that these two isolates also produced organic acids, such as citric, formic, and oxalic acids. Similar results have been reported by ILLMER and SCHINNER (1992) from selected phosphate solubilizing microbes isolated from Austrian forest soil. Surprisingly, the mixed inoculant treatments did not provide in general a more significant result. Nevertheless, the mixed culture consisting of *Streptomyces sp.* and *Aspergillus sp.* seems to be the best combination among the isolates tested. It is unclear from this study whether the mixed cultures affect nutrient solubilization synergitically or additively.

Table 2

3.2. Aggregate stabilization by *Azotobacter sp.*, *Aeromonas sp.*, and *Penicillium sp.*

LYNCH and BRAGG (1985) had made an extensive review on the aggregate formation and stabilization mediated by soil microorganisms. However, quantitative data on theeffect of microbial inoculant were nearly absent. Data presnted in Table 3 suggest a strong evidence that soil inoculation with *Azotobacter sp.*, *Aeromonas sp.*, and/or *Penicillium sp.* increased the stability of the aggregate formed. The most stable aggregate was obtained from the mixed culture application composed of the three isolates studied. The mechanisms in which the aggregates were stabilized in relation to the soil microorganisms are mostly attributed to the ability in producing extracellular polysaccharides. The ability of soil microorganisms to produce these substances may have a role in virulence or serve as protective mechanisms against predation or dessication (LYNCH and BRAGG, 1985). The viscosity of bacterial polysaccharides has been known of having close relationship with their aggregating effect. In contrast, the role of fungi in aggregate stabilization is partly caused by their mechanical attachment of the particles to hyphae (ASPIRAS *et al.*, 1971). This type of organisms may be effective stabilizer because the spread of hyphae between aggregates and into large pores distributes their associated binding agents through the soil (LYNCH and BRAGG, 1985). Supporting evidence obtained from scanning electron analysis is in agreement to this statement (Figure 1). The photographs shows the attachment of fungal mycellia on the microaggregate. However, many questions are still await further research, particularly in term of selecting the most effective treatment of the inoculant to the soils under field conditions.

Table 3

Figure 1

4. Conclusions

The inoculation by *A. tumefaciens* strain LBA 4404 on coffee seedlings tends to provide a better nutrient uptake. This will possibly reduce fertilizer dosage when applied in combination with conventional fertilizers. Availability of soil N, P, K was significantly increased by *Azotobacter sp.*, *Streptomyces sp.*, and *Aspergillus sp.* at 14 days postinoculation. At the same incubation period, inoculation with *Azotobacter sp.*, *Aeromonas sp.*, and *Penicillium sp.* on compost-enriched soil promoted a more stable soil aggregation.

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Table 1: Effect of *A. tumefaciens* strain LBA 4404 inoculation on nutrient uptake by a three-month old coffee seedling grown on Sang Hyang Damar Ultisol.

Treatments	N-Kjeldahl	P-Olsen	HCl-K
	------------------	$(g\ pot^{-1})$	----------------
Without inoculant			
25 % dosage NPK	107 ab	7.5 a	123 ab
50 % dosage NPK	96 ab	6.2 a	129 ab
75 % dosage NPK	164 b	9.9 a	179 b
100 % dosage NPK	95 ab	5.5 a	105 ab
1.5×10^{-2} l inoculant/pot			
25 % dosage NPK	139 ab	8.7 a	155 ab
50 % dosage NPK	141 ab	7.9 a	138 ab
75 % dosage NPK	119 ab	6.6 a	151 ab
100 % dosage NPK	62 a	3.9 a	71 a
3.0×10^{-2} l inoculant/pot			
25 % dosage NPK	90 ab	7.2 a	110 ab
50 % dosage NPK	85 ab	5.7 a	99 ab
75 % dosage NPK	90 ab	5.5 a	114 ab
100 % dosage NPK	88 ab	5.4 a	85 ab

Note 1): Figures in the same column followed by the same letter(s) are not significantly different according to Duncan MRT ($P<0.05$).

Table 2: Effect of *Azotobacter sp.*, *Streptomyces sp.*, and *Aspergillus sp.* on NPK availability of Rajamandala Ultisols after 14 days of incubation period.

Type of Isolates	N-Kjeldahl ($g\ kg^{-1}$)	P-Olsen ($mg\ kg^{-1}$)	HCl-K ($g\ kg^{-1}$)
Control	1.0 a_1	37 a	20 a
Azotobacter sp. (A)	30.0 c	47 b	26 ab
Streptomyces sp. (B)	25.0 bc	52 bc	24 ab
Aspergillus sp. (C)	28.0 c	61 c	22 ab
A + B	25.0 bc	44 b	31 b
A + C	22.0 b	37 a	23.0 ab
B + C	30.0 c	46 a	28.0 ab
A + B + C	27.0 c	31 a	26.0 ab

Note 1): Figures in the same column followed by the same letter(s) are not significantly different according to Duncan MRT ($P<0.05$).

Table 3: Effect of *Azotobacter sp.*, *Aeromonas sp.*, and *Penicillium sp.* on aggregate stability of Rajamandala Ultisols after 14 days of incubation period.

Types of isolates	% Aggregate Stability
Control	68 a_1
Azotobacter sp. (A)	70 a
Aeromonas sp. (B)	78 ab
Penicillium sp. (C)	77 ab
A + B	78 ab
A + C	81 ab
B + C	75 ab
A + B + C	86 b

Note 1): Figures in the same column followed by the same letter(s) are not significantly different according to Duncan MRT (P<0.05).

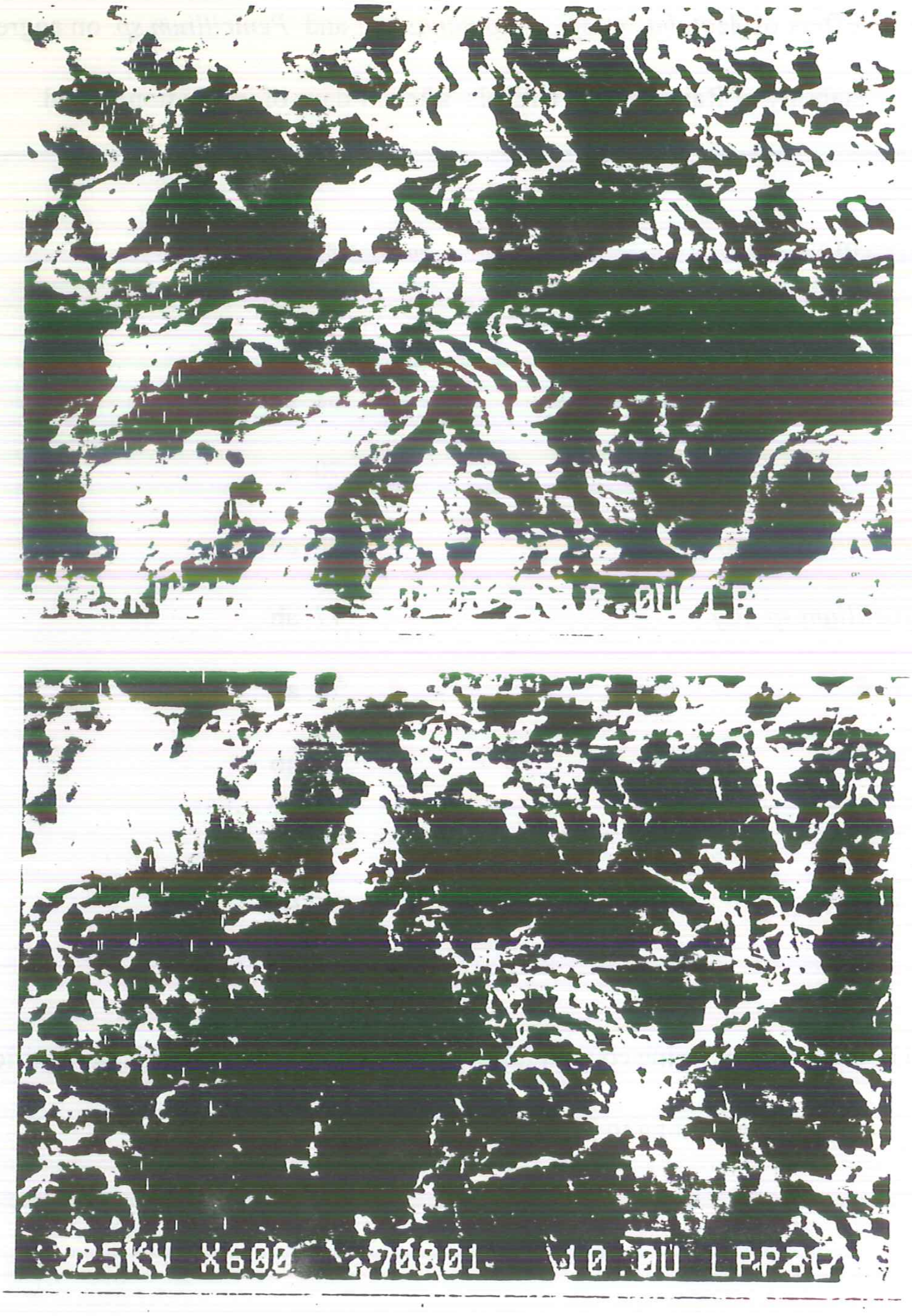

Figure 1: The SEM photographs of *Penicillium sp.* isolate used in this investigation (top) and the 'wraping-mechanism' of mycellia on the surface of soil aggregate (below).