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NUTRIENT BALANCE STUDIES TO DETERMINE THE SUSTAINABILITY OF MANAGEMENT SYSTEMS OF NATURAL AND PLANTATION FORESTS IN COSTA RICA

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The Atlantic Zone Programme (CATIE-AUW-MAG) is the result of an agreement for technical cooperation between the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), the Agricultural University Wageningen (AUW). The Netherlands and the Ministerio de Agricultura y Ganadería (MAG) of Costa Rica. The Programme, that was started in April 1986, has a long-term objective multidisciplinary research aimed at rational use of the natural resources in the Atlantic Zone of Costa Rica with emphasis on the small landowner.

PREFACE

General description of the research programme on sustainable Landuse.

The research programme is based on the document "elaboration of the VF research programme in Costa Rica" prepared by the Working Group Costa Rica (WCR) in 1990. The document can be summarized as follows:
To develop a methodology to analyze ecologicaly sustainable and economically feasible land use, three hierarchical levels of analysis can be distinguished.

1. The Land Use System (LUS) analyses the relations between soil type and crops as well as technology and yield.
2. The Farm System (FS) analyses the decisions made at the farm household regarding the generation of income and on farm activities.
3. The Regional System (RS) analyses the agroecological and socio-economic boundary conditions and the incentives presented by development oriented activities.

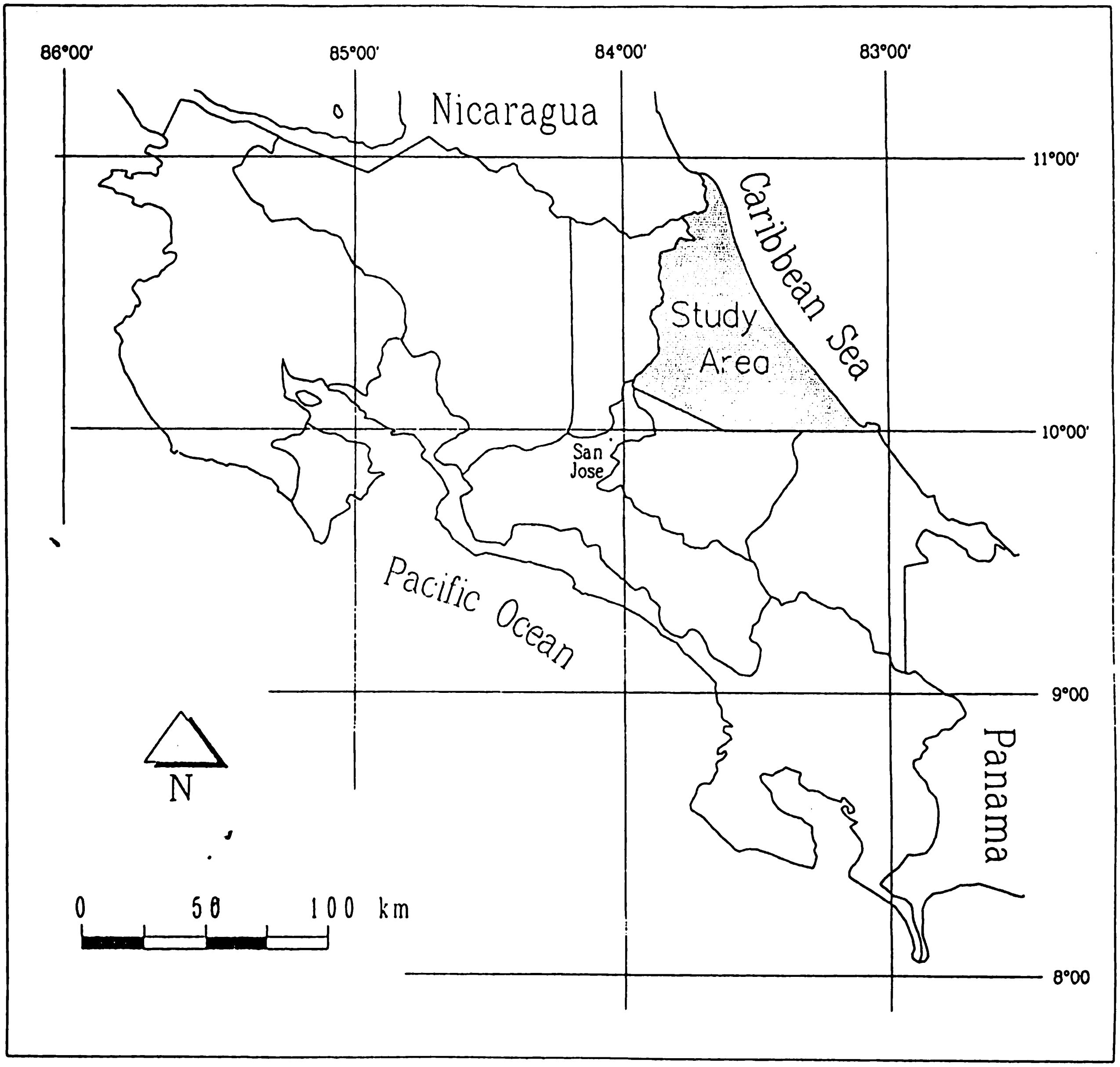
Ecological aspects of the analysis comprise comparison of the effects of different crops and production techniques on the soil as ecological resource. For this comparision the chemical and physical qualities of the soil are examined as well as the polution by agrochemicals. Evaluation of the groundwater condition is included in the ecological approach. Criterions for sustainability have a relative character. The question of what is in time a more sustainable land use will be answered on the three different levels for three major soil groups and nine important land use types.

Combinations of crops and soils

	Maiz	Yuca	Platano	Piña	Palmito	Pasto	Forestal
							I II III
Soil I	x	x	x		x	x	x
Soil II						x	x
Soil III	x			x	x	x	x

As landuse is realized in the socio-economic context of the farm or region, feasibility criterions at corresponding levels are to be taken in consideration. MGP models on farm scale and regional scale are developed to evaluate the different ecological criterions in economical terms or visa-versa.

Different scenarios will be tested in close cooperation with the counter parts.


86°00'
85°00'
84°00'
83°00'
Nicaragua
11°00'
Caribbean Sea
Study Area
10°00'
San Jose
Pacific Ocean
9°00'
Panama
N
0
50
100 km
8°00'

LIST OF CONTENTS

1. Introduction 3

2. Soils 3

3. Climate 5

4. Vegetation 10
    4.1. Tropical lowland rain forest 10
    4.2. Teak 12

5. Simulation of undisturbed forest 12

6. Simulation of natural forest under polycyclic management 14

7. Simulation of the growth of forest plantations 16

8. Yields 17

9. Nutrients 18
    9.1. Climax situation natural forest 19
    9.2. Natural forest under polycyclic management 20
    9.3. Plantation forest of teak 22

10. Discussion 25

11. Conclusions 26

12. References 27

APPENDIX I. INPUT FILES 29
    Appendix I.1 Average monthly and yearly climatic data 29
    Appendix I.2. Input file for the La Selva soil and 3 standard Costa Rican soil types 31
    Appendix I.3. Vegetation input file dry land forest 32

APPENDIX II. ORGANIC MATTER FLOWS 33
    Appendix II.1. Organic matter flows of managed natural forest 33
    Appendix II.2. Organic matter flows in a teak plantation 34

APPENDIX III. LIBERATION AND UPTAKE OF NUTRIENTS 35
    Appendix III.1. Liberation and uptake of nutrients in managed natural forest 35
    Appendix III.2. Liberation and uptake of nutrients in teak plantation 36

List of Tables

Table 1 - Average soil properties of 3 soil groups Atlantic Zone....4

Table 2 - Van Genuchten parameters for 2 soil groups Atlantic Zone....4

Table 3 - Moisture contents and hydraulic conductivities at different soil suctions of 3 representative soil types....5

Table 4 - Fragment of the input file for daily climatic data....9

Table 5 - Average yearly climatic data of Los Diamantes, Costa Rica for 1982-1986....10

Table 6 - Estimated maximum phytomass amounts of typical undisturbed dry land forest in the Atlantic Zone of Costa Rica (t/ha)....11

Table 7 - Phytomass amounts at the beginning and at the end of the simulation....13

Table 8 - Provisional concentrations (%) of plant components (a) and litter pools (b)....13

Table 9 - Yearly amounts of litter fall and nutrient contents of the litter (kg/ha.y) in undisturbed forest (climax situation)....14

Table 10 - Phytomass changes during exploitation and refinement....15

Table 11 - Development of phytomass (t/ha) in treated natural forest without (a) and with (b) second refinement at year 10....16

Table 12 - Development of phytomass (t/ha) in a forest plantation....17

Table 13 - Exploitation scheme of the forest plantation....18

Table 14 - Estimated yearly inputs of nutrients by the atmosphere and by mineral weathering....19

Table 15 - Decomposition (%) of different litter types with time....19

Table 16 - Nutrient flows in a natural forest ecosystem in a steady state (kg/ha.y)......................20

Table 17 - Summary of nutrient flows in managed natural forest (kg/ha.y)....................................22

Table 18 - Maximum cumulative surpluses and shortages of nutrients (kg/ha)...........................24

Table 19 - Summary of nutrient flows in the teak plantation (kg/ha.y).............................24

List of Figures

Figure 1 - θ-h relationships for three standard soil groups....................6

Figure 2 - K-h relationships for three standard soil groups....................7

Figure 3 - Relationship between short wave radiation and sunshine....................8

Figure 4 - Yearly litter production in treated natural forest....................20

Figure 5 - Increase in stem weight without refinement at year 10....................21

Figure 6 - Increase in stem weight with refinement at year 10....................21

Figure 7 - Yearly litter production in a teak plantation....................23

Figure 8 - Yearly increase in stem weight in a teak plantation....................23

ABSTRACT

Nutrient balance studies were performed for sites in the Atlantic Zone in Costa Rica with natural and plantation forests in use for wood production. Goal of the investigations was to determine the capacities of three soil types to produce timber in managed natural forests and in plantations and to determine the sustainability of these land uses from a nutrient point of view. To this end collected data on soil, climate, vegetation and hydrology were used in dynamic simulation of forest growth using the growth model for tropical forests TROPFOR. In the nutrient balances studies attention was given, next to nutrient cycling in the soil-vegetation system to inputs by atmospheric deposition and mineral weathering and to exports of nutrients with drainage water and solids.

In the simulations, the natural forests were managed and harvested in a polycyclic system with selective harvests every 24 years according the the CELOS Silvicultural System. The plantations were harvested in three thinnings in the years 8, 12 and 16 followed by clear felling in the year 24.

It was found that managed natural forest can give a sustainable yield on all three soil types. Stemwood harvests between 25 and 50 m^3/ha are possible, depending on stocking with valuable species. Plantation forest with a species such as teak (Tectona grandis) is not possible on soil type II, the poorly drained soil. On soil type III, the well drained soil of low fertility, teak can be grown but large nutrient shortages will occur, because of immobilization in increasing amounts of phytomass, especially when starting on a site with little phytomass such as agricultural land or grassland. A main problem is also the strong variation of nutrients in the soil, years with surpluses alternating with years of shortages. To avoid losses, high nutrient buffering capacities of the soils are necessary.

Calculated production levels of teak are 290 m^3/ha of stemwood, including thinnings, during a cycle of 24 years. To make this land use sustainable, large fertilizer additions are necessary on soil type III. On soil type I, the well drained soil of high fertility, mineral weathering is expected to be able to supply most of the nutrients, but further research is necessary.

1. Introduction

In the joint research programme of CATIE, the Ministery of Agriculture and Animal Husbandry of Costa Rica (MAG) and the Agricultural University of Wageningen, The Netherlands, executed in the Atlantic Zone of Costa Rica, the Land Utilization Types (LUT's) Bosque Natural (natural forest) and Plantationes (forest plantations) are studied, next to several agricultural LUT's. The forests in these LUT's are production forests, so natural forests in National Parks and Nature Reserves are not included. The forests in the LUT Bosque Natural (Natural Forests) produce hardwood by selective felling in a polycyclic production system, while the plantations are harvested in a monocyclic system (clear-cut and replanting).

A main objective of the research programme is to compare different land use scenarios, using linear programming. A good physical description of the different Land Utilization Types (LUT's) is necessary as a basis for calculations in which socio-economic, sustainability and political aspects are included.

Questions to be answered for the forestry LUT's are: What are the physical yields under different management systems and on different soils and how are the nutrient flows for each LUT.

In this study a simulation of forest growth and nutrient cycling will be performed for representative natural and plantation forests.

2. Soils

In the Atlantic Zone Programme 3 typical soil types are discerned. They are:

I	well drained fertile soil	(Los Diamantes)
II	poorly drained soil (generally of high fertility)	(Santa Clara)
III	well drained soil of low fertility	(Silencio, Neguev, Cocori)

This classification is in fact a grouping of soil suitabilities, not of taxonomic groups. These 3 soil types are broad groups of soil, resulting from combining numerous soil series that have been described in soil reports by the CATIE/AUW/MAG project and by others. For each of the 3 soil types a representative set of soil properties is given in Tables 1 and 2 (Stoorvogel, pers. comm.). A representative for group I is soil series Los Diamantes (Eutric Hapludand), for soil type 2 Santa Clara (Andic Aquic Eutropept) and for soil type III Silencio (Andic Oxic Humitropept).

Table 1. Average soil properties of 3 soil groups Atlantic Zone

	Sand	silt	clay	bulk dens	porosity total	P Olsen	K exch	C org	pH H_2O	
I	40	40	20	0.93	0.72	16	10	28	6.0	
II	30	40	30	0.95	0.68	13	10	31	6.1	
III	20	15	65	1.01	0.63	8	4	24	4.7	low fertility

Table 2. Van Genuchten parameters for 2 soil groups Atlantic Zone

Soil depth	I 0-10 cm		I 30-40		III 0-10 cm		III 30-40 cm	
	a	b	a	b	a	b	a	b
α	0.0277	0.028	0.0701	0.0449	0.0404	0.0809	0.0187	0.0197
n	1.224	1.1791	1.2091	1.2252	1.191	1.3087	1.2666	1.2535
$\Theta(r)$	0.001	0.001	0.189	0.202	0.0177	0.2142	0.1649	0.2225
Ksat	20	14	12.4	12.4	12.197	17.39	22.16	22.16
τ	20.43	18.683	0.0001	0.0001	15.260	4.9111	19.452	19.452

Θ - h relations (pF-curves) and K - h relations (conductivities as function of soil suction) were calculated from these Van Genuchten parameters using the following equations:

$$K(h) = Ksat * \frac{(((1+(\alpha * h)^{n})^{m})-(\alpha * h)^{n-1})^{2}}{(1+(\alpha * h)^{n\ (m*(\tau+2))}}$$

$$\Theta(h) = \Theta r + \frac{(\Theta s - \Theta r)}{(1 + (\alpha * h)^{n})^{m}}$$

$$m = (1 - \frac{1}{n})$$

These calculated pF and K-h values were averaged given the following representative values for use in the simulation programme (Table 3).

Table 3. Moisture contents and hydraulic conductivities at different soil suctions of 3 representative soil types

Soil suction		Water content (% vol) Soil type			Conductivity (cm/d) Soil type		
(cm)	pF	I	II	III	I	II	III
0	-oo	0.72	0.68	0.63	352.80	352.80	443.44
1	0	0.72	0.68	0.63	85.91	85.91	151.16
5	0.7	0.71	0.67	0.62	28.73	28.73	56.83
10	1.0	0.69	0.65	0.60	11.96	11.96	25.23
50	1.7	0.61	0.57	0.54	0.39	0.39	0.37
100	2.0	0.56	0.53	0.49	0.07	0.07	0.01
200	2.3	0.50	0.48	0.45	0.01	0.01	3*10-4
500	2.7	0.44	0.41	0.39	2*10-3	2*10-3	2*10-6
1000	3.0	0.39	0.37	0.36	3*10-4	3*10-4	8*10-8
5000	3.7	0.31	0.30	0.29	6*10-6	6*10-6	1*10-12
16000	4.2	0.26	0.25	0.26	3*10-7	3*10-7	8*10-13

Table 3 clearly shows the differences between soil I and II at one hand and soil III at the other. Soils I and II are young Holocene soils of high fertility developed in alluvial sandy volcanic material. Soil III has the same origin but, being of Pleitocene age, has been subject to weathering for longer periods, occurring in higher positions on sloping terrain. Soil texture has become clayey by this weathering, porosity has decreased, but is still high and water contents at low suctions are lower than for I and II, reaching the same values near wilting point.

Soil III has a more developed structure than I and II, granular elements predominating. Because of this, saturated hydraulic conductivity and conductivities at low tensions are very high, surpassing those of the more sandy soil types I and II. At higher tensions, however, conductivities decrease faster because of the clayey tecture, reaching much lower levels than in the other 2 soil types. Fig. 1 shows the 3 pF-curves and Fig. 2 the two conductivity curves; conductivity of soil II is considered to be equal to that of soil I. The graphs are very regular because of their construction from the Van Genuchten parameters.

All these data have been introduced into the simulation model for forest growth TROPFOR, making it possible to simulate forest growth on 3 different soil types.

3. Climate

Climatic data are available for 7 meteo stations in the Atlantic Zone: Carmen (1973-1991), Cobal (1970-1976), Los Diamantes (1971-1991), Limon (1970-1990), Lola (1970-1990),

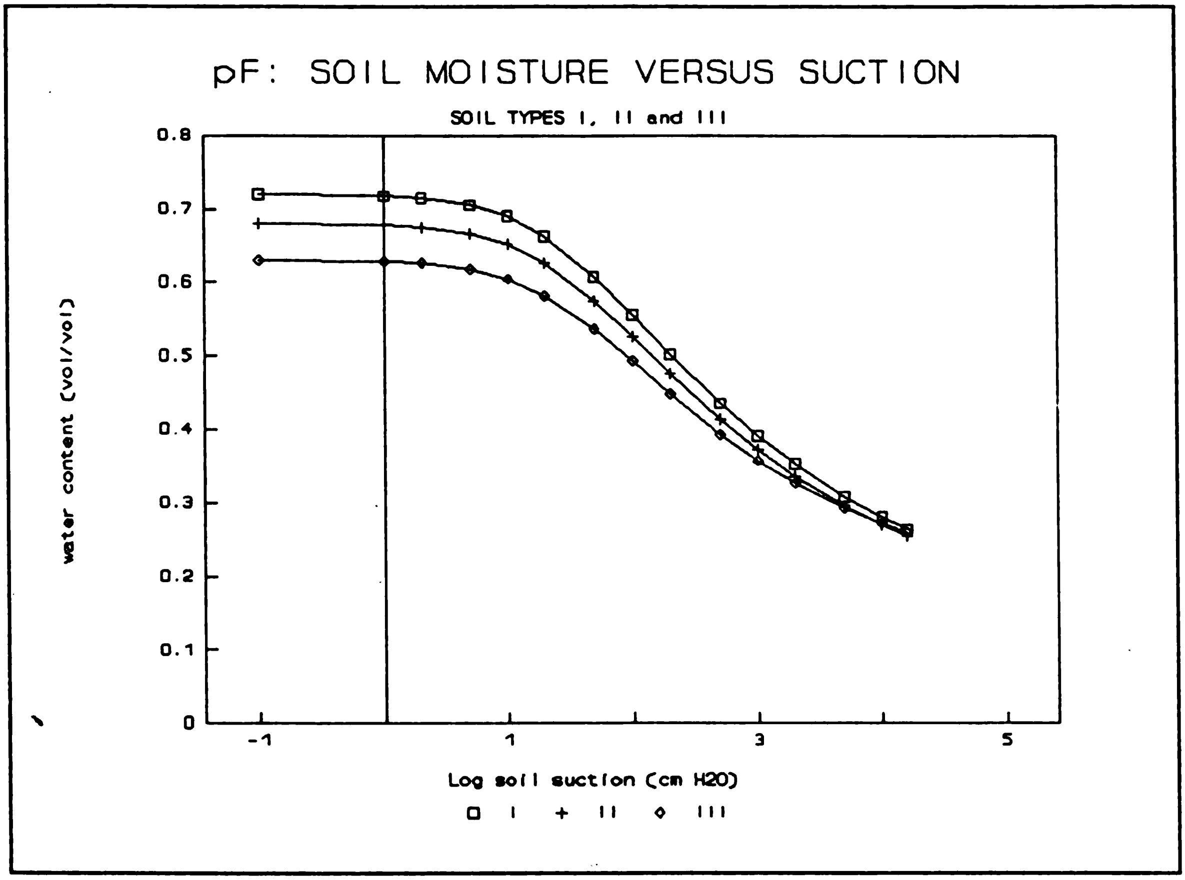


Figure 1. Θ-h relationships for three standard soil groups

Mola (1980-1991) and Rio Frio (1982-1991). These data have kindly been provided by the Instituto Meteorologico Nacional de Costa Rica and collected by D. Jansen (pers. comm).

The collected data are very divers. Sometimes only temperature or rainfall are given. Only a small part of the data is complete and then the following daily data are available: rainfall (mm), maximum and minimum temperature, short wave radiation (cal/cm^2.d or kJ/m^2.d), vapour pressure at 7, 13 and 18 hours in mbar, average wind speed in km/h and the number of sunshine hours.

The best data are available for meteo station Los Diamantes at Guapiles and it was decided to prepare a climate input file for TROPFOR using 5 years with good data in which both dry and wet years occur. The chosen period is 1982 - 1986. For this period temperature, vapour pressure and rainfall data are practically complete, daily sunshine hours are available for most of the period, but part of the short wave radiation and most of the wind data are lacking.

TROPFOR needs daily data of short wave radiation, maximum and minimum temperature, avarage vapour pressure and average wind speed, so part of the short wave radiation and most of the wind data had to be constructed.

For the calculation of the short wave radiation the Angstrom equation has been used. This equation calculates the short wave radiation from the number of sunshine hours per day, taking into account daylength, extra terrestrial radiation and local radiation conditions expressed in two variables A and B. The equation is as follows:

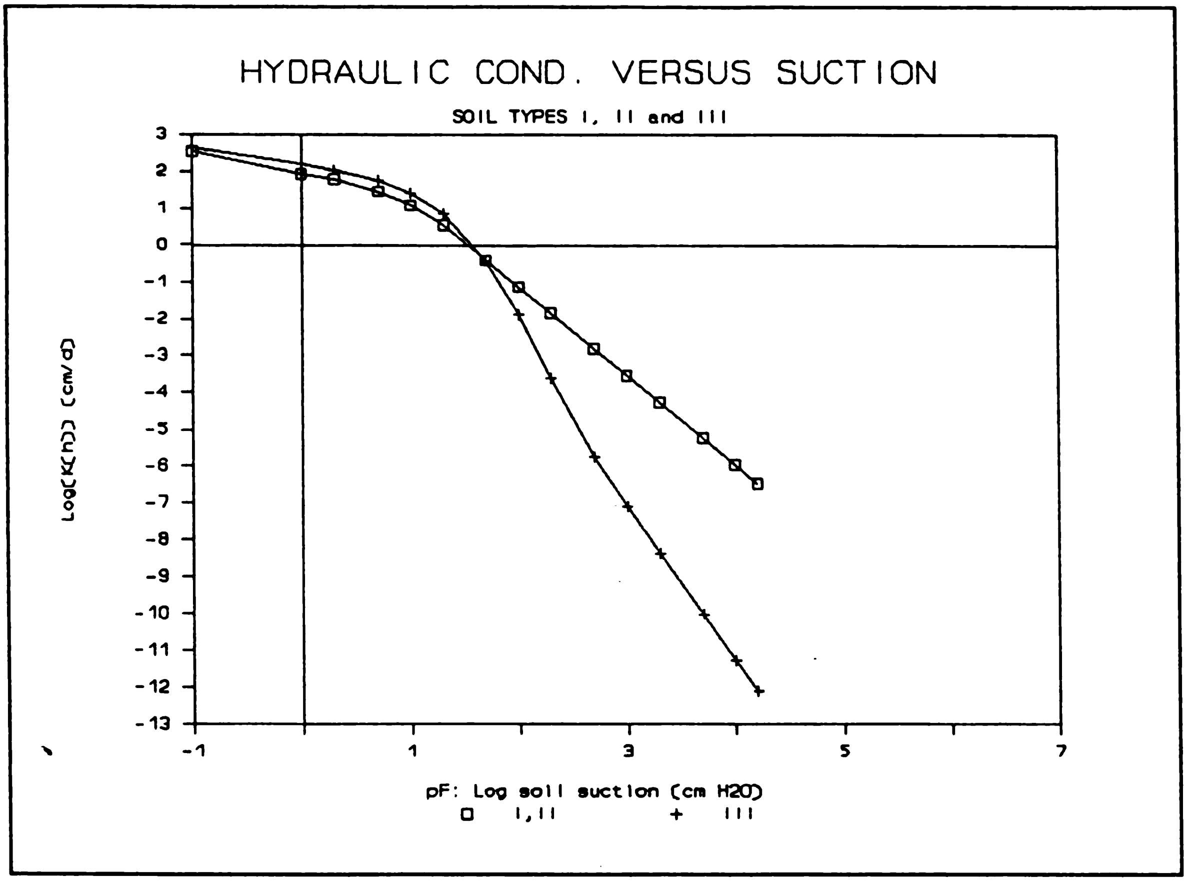


Figure 2. K-h relationships for three standard soil groups

$$Ri = Ra * (A + B*(n/N))$$

in which:

Ri = incoming short wave radiation ($MJ/m^2.d$)
Ra = extraterrestrial short wave radiation ($MJ/m^2.d$) or Angot-value
n = number of sunshine hours per day
N = maximum number of sunshine hours per day (daylength)
A and B are location specific constants

A and B can be calculated for a certain location when both sunshine hours and directly measured short wave radiation data are available. A and B values have been calculated for many locations. Van Keulen and Wolf (1986) give A and B values for many stations, for locations in dry tropical areas they generally give 0.25 and 0.45 for A and B respectively, for wet tropical areas generally 0.29 and 0.42. Poels (1987) used 0.28 and 0.42 for Suriname, determined by Lenselink and Van der Weerd (1973). For the Costa Rican situation A and B could be different, rainfall and humidity being very high here compared to most wet tropical stations.

To determine the A and B values for Los Diamantes, all days with both measured short wave radiation and sunshine hours were singled out and a regression was performed between Ri/Ra and n/N to determine A and B. The result is shown in Fig. 3. A was found to be 0.24 and B 0.37 by a R^2 of 0.51 and 3690 observations. Hengsdijk (in press) did the same excercise for the nearby station of Copal. He found also an A value of 0.24, a B-value of 0.38 and a R^2 of 0.65 by 1382 observations.

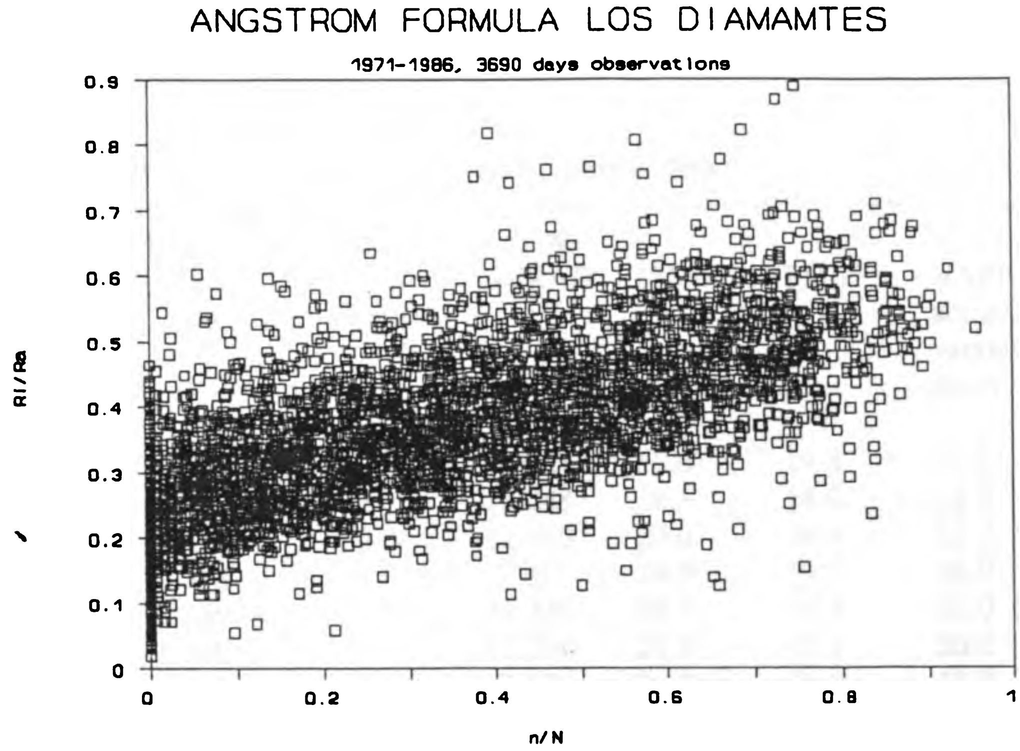


Figure 3. Relationship between short wave radiation and sunshine

It appears, therefore, that radiation levels here are relatively low, A and B being lower than for many other wet tropical regions.

Using the values 0.24 and 0.37 for A and B, missing values for short wave radiation were calculated for Diamantes for the years 1982 - 1986.

Wind data are very scarce in the Atlantic Zone. For Diamantes they exist only for part of the year 1986. For Copal, wind data are available for 1974-1976 and part of 1973. Wind speed is generally low and rather constant at around 1 m/s. To find systematic seasonal differences in wind speed, the data for Cobal were averaged per date to give an average wind year, which was considered to apply also for the nearby station of Los Diamantes.

The climate input file CLMDAYCR.DAT was constructed as input file for TROPFOR as follows: Daily data of Los Diamantes for 1982 - 1986 were taken. Short wave radiation was taken directly from measured values or calculated from sunshine hours with the Anstrom equation using 0.24 and 0.37 for A and B. For days with both sunshine hours and direct radiation measurement the average of the measured and the calculated value of the radiation was taken.

Vapour pressure for the model was the average of the 3 measured values at 7, 13 and 18 hours. Rainfall data were taken directly from the source files and for wind data the averages of Cobal were used, which were averaged again with the Los Diamantes data for the days for which these data existed. For illustration, part of the resulting CLMDAYCR.DAT file is given below in Table 4.

Table 4. Fragment of the input file for daily climatic data

CLMDAYCR.DAT: LOS DIAMANTES 82-86

DATE	DAY No	RAIN mm/d	AVRAD MJ/m2.d	TMAX	TMIN	VAPP act.av. vapour press	WIND m/s
1857 *)							
821221	355	20.5	7.420	21.0	19.8	17.9	0.95
821222	356	0	15.048	28.3	18.0	18.8	1.06
821223	357	0	11.940	29.0	19.4	21.2	0.96
821224	358	3.3	9.835	29.0	19.5	20.0	0.89
821225	359	16.2	11.346	28.5	19.5	21.0	0.88
821226	360	0.7	12.256	27.5	19.5	20.2	1.10
821227	361	11.7	7.436	26.0	19.5	18.9	1.20
821228	362	0.4	7.442	25.5	18.2	18.0	1.03
821229	363	0	10.469	27.5	18.0	16.9	1.07
821230	364	0	17.131	29.0	17.7	16.4	0.88
821231	365	0	17.450	28.6	17.0	16.4	0.98
830101	1	6.5	12.216	27.4	18.2	24.3	0.72
830102	2	0.4	8.387	28.2	20.0	25.8	0.99
830103	3	3.2	13.055	28.3	17.5	25.0	0.89
830104	4	7.2	11.146	28.2	21.0	26.5	0.75
830105	5	2.6	8.014	26.8	20.2	24.9	0.74
830106	6	4.2	14.024	28.5	20.5	25.4	0.97
830107	7	17.0	8.038	27.5	20.2	26.2	1.01

*) No of lines in file

DAY: Julian day
RAIN: rainfall
AVRAD: short wave radiation
TMAX: maximum temperature
TMIN: minimum temperature
VAPP: actual average vapour pressure
WIND: average windspeed

Yearly totals and averages of the CLMDAYCR.DAT file are given in Table 5. The years 1982 and 1983 are wet and 1985 and 1986 relatively dry. The average radiation level of 13 $MJ/m^2.d$ is low compared to that of Suriname (18.7 $MJ/m^2.d$) and also temperatures are lower.

Table 5. Average yearly climatic data of Los Diamantes, Costa Rica for 1982-1986

YEAR	RAIN mm/d	AVRAD $MJ/m^2.d$	TMAX °C	TMIN °C	VAPP mbar	WIND m/s
1982	4438	13.7	28.8	20.1	19.7	0.92
1983	4301	12.7	29.1	20.8	27.1	0.92
1984	4038	10.4	28.4	19.8	25.6	0.92
1985	3436	14.4	28.2	19.6	25.3	0.92
1986	3920	13.6	28.0	19.9	25.9	0.97
Average	4035	13.0	28.5	20.0	24.7	0.93
Aver. Surin.	2150	18.7	31.8	22.4	27.7	1.2

Vapour pressure data for 1982 are much lower than for the other years. This could be a systematic error. Therefore, for detailed work the year 1983 is chosen as representative for a wet year and not 1982. The year 1985 is chosen to represent a relatively dry year. A complete listing of the daily climatic data file is too lengthy to be presented here, but to give an idea of the variation during the years, the average data for all months are given in Appendix I.1. From this listing it appears that during all these 5 years no really dry period occurred. The lowest monthly rainfall was 52 mm in February 1986, but this month was preceeded and followed by months with more than 300 mm rainfall.

4. Vegetation

4.1. Tropical lowland rain forest

Vegetation characteristics of tropical lowland rain forest for use in TROPFOR are stored in the vegetation input file. Information on biomass and growth for this forest type is scarce. The following procedure is, therefore, adopted. The forest of Kabo Suriname is used as a base, adapted and changed in so far data for the Atlantic forests of Costa Rica are available.

Changes made mainly concern the differences in soil fertility, resulting in higher nutrient concentrations in the vegetation in La Selva and a relatively lower root biomass, and the wetter climate and more clayey soil (Soil III) in the Atlantic Zone resulting in a shallower rooting depth. The higher nutrient levels in the leaves result in higher maintenance respiration rates which influence the net production. The maintenance respiration rate for leaves was calculated with the equation of de Wit et al. (1978) in Mohren (1987):

$$MRR = 0.04 * protein + 0.08 * minerals$$

Average N-content of the leaves in Suriname is 1.33 % and in La Selva 1.5 % (Osinga, in press) resulting in protein levels of 8.25 and 9.3 % respectively. Assuming the mineral content of the leaves in La Selva to be equal to that in Suriname (4 %) the maintenance respiration rates of the leaves become 0.065 for the Surinam and 0.069 per day for the Costa Rican forest, meaning that 1 ton of leaves (dry weight) looses per day 69 kg to respiration. Maintenance respiration rates for roots have also been increased from 0.015 to 0.025 and that for the sapwood of branches and stems was kept at 0.0004 (no better data being available).

Also death rates are influenced by soil fertility. Generally death rates increase at higher fertility levels. Osinga (in press) found from literature (not specified) higher death rates than those of the Kabo forest. These have been introduced in the vegetation file for La Selva (Appendix I.3).

Phytomass amounts of the undisturbed forest had to be estimated as no complete data were available. Existing data are often limited to stemwood above a certain diameter and sometimes only stemwood of valuable species. On top of that, stem volumes are estimated lower than they are because of expected losses to occur during extraction and processing of the wood. Some data are given below. Kapp et al. (1992) give 128 m^3 commercial volume (DAB > 50 cm) stemwood in swampy forest; Schinkel (pers. comm.) gave data of basal areas of dry land and swamp forest near Rio Jimenez. Total basal areas of all trees with a DAB (diameter at breast height) above 10 cm was 28.4 and 21.4 m^2 per ha for dry land and swamp forest respectively. Other unpublished data given by Schinkel are 115 m^3 of stemwood in dry land forest in Cocori with a diameter of more than 40 cm. The total amount of stemwood, including ends and stumps, badly formed and defective stems and stems with small diameters may be two to three times this amount. Assuming a average dry wood density of 0.6 (Alfaro, 1993) the weights can be calculated.

From these scattered data it is estimated for the time being until better data come available that in undisturbed dry land forest the maximum stemwood amount is about 200 t/ha. From this, the other phytomass amounts are estimated (Table 6), using ratios from the Kabo forest of Suriname (Poels, 1987).

Table 6. Estimated maximum phytomass amounts of typical undisturbed dry land forest in the Atlantic Zone of Costa Rica (t/ha)

	Living	Heartwood	Total
Leaf	15	-	15
Branch	35	55	90
Stem	70	150	220
Root	30	50	80
	---	---	---
Total	150	255	405

Net assimilate production is divided over the plant components leaf, branch, stem, flower/seeds and roots, increasing their weight. At the same time weights decrease as living parts die to become litter.

Litter production proceeds as follows. There is a basic death rate with which living phytomass dies every day. For leaves accelerated death rates apply when there is drought stress, when the leaf area index (LAI) becomes too high and when leaves surpass there maximum age. All dead leaves go to the leaf litter compartment. For stems, branches and roots there are two dead compartments each: the heartwood and the litter compartment. Heartwood is the dead wood in living trees and wood litter is the remaining dead wood consisting of dead trees, whether still standing or lying and woody litter on and in the soil.

For these woody compartments, there is a basic death rate that tranforms living wood partly into heartwood and partly into litter. This death rate increases when maximum live weights (climax situation) have been reached. There are also maximum weights of heartwood. When these have been reached, increased rates of heartwood move to the woody litter compartments.

4.2. Teak

In the lower part of Appendix I.3 the vegetation parameters for teak grown in plantations are given. Important differences with the natural forest are development rates, initial weight and fractioning of assimilates over plant organs. Further adjustments can be made when more data become available.

5. Simulation of undisturbed forest

Growth of the undisturbed forest was simulated using the climatic data of Los Diamantes for a period of 8 years.

At the beginning of the simulation living phytomass was set at 147 t/ha and dead heartwood amounts at 255 t/ha dry weights (Table 7).

Table 7. Phytomass amounts at the beginning and at the end of the simulation

	Leaf	branch	stem	root	flowers seeds	total
Before:						
Living	11.0	35.0	70.0	30.0	1.0	147.0
Heartwood	-	55.0	150.0	50.0	-	255.0
Litter	-	-	-	-	-	-
	----	----	-----	----	---	-----
	11.0	90.0	220.0	80.0	1.0	402.0
After:						
Living	11.2	34.9	69.5	29.9	1.2	146.7
Heartwood	-	54.8	149.1	49.6	-	253.5
Litter	79.6	42.4	83.5	58.6	1.9	266.0
	----	-----	-----	----	---	-----
	90.8	132.1	302.1	138.1	3.1	666.2

Gross assimilation during the 8 years was 891 t/ha, maintenance respiration 524 t/ha and conversion losses 103 t/ha, leaving 264 t/ha for dry matter increase or 33 t/ha.y. This dry matter passes through the living biomass, partly also through the heartwwood phase, ending up as litter.

No data are available on the nutrient content of freshly fallen litter in Costa Rica forests. These data are difficult to acquire, as concentrations of freshly fallen litter differ from those of the litter pool and also from the composition of the plant components. The reason is that nutrients are withdrawn from e.g. leaves and twigs before they drop, and that during decomposition on the forest floor concentrations change by oxidation of organic C and preferential withdrawals. In our calculation, the composition of freshly fallen litter is set equal to the composition of the plant components, as withdrawal does not change the amount of nutrients that becomes available to the vegetation. The difference is that the nutrients that are withdrawn from the litter before the drop become available faster to the vegetation than when they go through decomposition on the forest floor and also that they do not run the risk of being leached after liberation and before uptake. Table 8 gives the concentrations of the Kabo forest in Suriname, taken from Poels and Bijker, in press, adapted for the Costa Rican situation where possible.

Table 8. Provisional concentrations (%) of plant components (a) and litter pools (b)

	N		P		K		Ca		Mg	
	a	b	a	b	a	b	a	b	a	b
Leaves	1.50	1.80	0.077	0.050	0.99	0.20	0.52	0.40	0.164	0.120
Branches	0.38	0.56	0.032	0.022	0.35	0.12	0.72	0.61	0.064	0.079
Stems	0.29	0.52	0.018	0.018	0.25	0.10	0.61	0.63	0.049	0.077
Roots	0.80	0.96	0.056	0.028	0.38	0.13	0.43	0.47	0.077	0.077
Flowers, seeds	1.00	1.40	0.225	0.150	0.65	0.20	0.60	0.60	0.100	0.120

Amount of nutrients in the litter are calculated from the litter amounts and concentrations in the litter. In a steady state situation these amounts are liberated by decomposition as fast as they are formed (Table 9).

Table 9. Yearly amounts of litter fall and nutrient contents of the litter (kg/ha.y) in undisturbed forest (climax situation)

	Phytomass	N	P	K	Ca	Mg
Leaves	9950	149.2	7.66	98.5	51.7	16.3
Branches	5300	20.1	1.70	18.6	38.2	3.4
Stems	10430	30.2	1.88	26.1	63.6	5.1
Roots	7330	58.6	4.10	27.9	31.5	5.6
Flowers, seeds	240	2.4	0.54	1.6	1.4	0.2
Total	33250	260.5	15.88	172.7	184.4	30.6

6. Simulation of natural forest under polycyclic management

The following situation will be simulated. Un undisturbed forest is being logged for the first time. A light exploitation is carried out and care is taken to limit logging and extraction damage as much as possible by using inventory maps, planning extraction roads, employing direction felling and winching where possible and useful. For damage controlled exploitation methods, see Hèndrison, 1990.

During the exploitation 25 m^3/ha of stemwood is extracted (15 t) by which a total phytomass of 54 t/ha is killed. The exploitation is followed by a refinement. This is a treatment to increase the growth of small and medium sized valuable trees for future harvests by killing large trees of non-valuable species and defective trees of valuable species. Trees are not felled in refinement but killed while standing by girdling, with or without the use of herbicides. By such treatment growth of valuable trees may increase tenfold by the combined effect of improved light conditions and nutrient liberation from additional decomposing litter. In the simulated situation it is assumed that the refinement kills 40 % of the remaining phytomass (Table 10).

Table 10. Phytomass changes during exploitation and refinement

	Leaf	branch	stem	root	flowers seeds	total
Before:						
Living	11	35	70	30	1	147
Heartwood	-	55	150	50	-	255
TOTAL:	11	90	220	80	1	402
Killed by exploitation:						
Living	2	7	9	3	0.2	21.2
Heartwood	-	10	17	6	-	33
TOTAL:	2	17	26	9	0.2	54.2
Killed by refinement:						
Living	4	11	25	10	0.3	50.3
Heartwood	-	19	55	18	-	92
TOTAL:	4	30	80	28	0.3	142.3
After treatment:						
Living	5	17	36	17	0.5	75.5
Heartwood	-	26	78	26	-	130
TOTAL:	5	43	114	43	0.5	205.5

The situation after treatment is the starting point for the simulation of forest growth. Forest characteristics as given in Appendix I.3 (upper part) were introduced and the soil characteristics from Appendix I.2 (Costa Rica III, unfertile, well drained). This forest on this soil was subjected to the daily climatic data from Los Diamantes (Table 4). Growth was driven by solar radiation and the watersupply was calculated from the water balance. Table 11 gives the course of the phytomass build up during the years for 2 situations: without further interference and with a second refinement after 10 years. During the refinement in year 10 the biomass killed was as follows (t/ha): leaf 3.02, branch 43.44, stem 84.40, root 35.38 and flowers/seeds 0.57.

Table 11. Development of phytomass (t/ha) in treated natural forest without (a) and with (b) second refinement at year 10

	Leaf		branch		stem		root		flowers seeds		total	
Year	a	b	a	b	a	b	a	b	a	b	a	b
-1	11		90		220		80		1.2		402	
0	5		43		114		43		0.5		206	
1	12		51		129		50		0.7		242	
2	9		55		138		54		0.8		258	
3	12		62		150		61		0.9		286	
4	11		66		158		66		1.0		302	
5	10		69		165		69		1.0		314	
7	12		76		179		77		1.1		345	
10	8	5	86	43	198	114	78	43	1.1	0.5	372	206
11	12	12	90	51	207	129	80	50	1.1	0.7	390	242
15	8	10	89	69	219	165	79	69	1.1	1.0	397	314
20	12	8	90	86	218	198	80	78	1.2	1.1	401	372
24	12	12	90	90	218	220	80	79	1.2	1.1	401	402

It appears from Table 11 that a second refinement at year 10 is advisable when a large part of the phytomass consists of trees of non-valuable species or of low quality stems of valuable species (hollow, rotten, badly formed). At year 24 the difference in phytomass between both treatments has disappeared. Average stem size is higher in case a and there may be differences in exploitable stem volume. Regular refinements that keep the phytomass considerably below the maximum (climax) weights result in lower maintenance respiration and death rates. A negative aspects of these refinements is the irregular addition of litter to the forest floor causing irregular nutrient supply from decomposing organic matter and danger of nutrient leaching.

It is clear from Tables 10 and 11 that an extraction of 15 t/ha of stemwood once every 24 years is very modest and far below the production capacity of the forest. Only 6 % of the organic matter production is extracted, the remainder being available as litter to support the natural functions of the forest.

7. Simulation of the growth of forest plantations

Important differences between natural forest and forest plantations are age distribution and phytomass fluctuations combined with differences in nutrient supply from decomposing litter and variations in nutrient uptake.

The crop growth model does not take into account differences in botanical composition, but variations in assimilation speed, in maintenance respiration and death rates, and in assimilate distribution can be brought into the model.

Below, the result of a simulation of a teak plantation is given with planting of 1600 trees at the end of year 0, thinnings in the years 8, 12 and 16 and harvest in year 24. It should be stressed that results are very provisional, as nearly no growth data of teak were available, so calibration of the model was not possible. As soon as data become available, simulations may be improved. Table 12 gives the development of the phytomass.

Table 12. Development of phytomass (t/ha) in a forest plantation

	Leaf		branch		stem		root		flowers seeds		total	
Year	a	b	a	b	a	b	a	b	a	b	a	b
0	0.01		0		0.07		0.02		0		0.1	
1	2.5		0.5		2.4		2.6		0		8.1	
2	13		4.9		16		12		0.01		46	
3	15		10		33		23		0.04		80	
4	12		14		46		30		0.08		103	
5	10		17		58		35		0.13		121	
6	8		19		67		39		0.17		133	
7	12		23		79		44		0.26		158	
8	11	8	26	20	90	71	49	38	0.33	0.26	175	138
9	18		23		81		43		0.34		164	
10	8		25		90		46		0.40		169	
11	12		28		102		52		0.53		194	
12	11	8	31	22	112	79	56	39	0.64	0.45	211	148
13	18		24		90		44		0.58		176	
14	9		27		99		48		0.66		183	
15	12		30		112		53		0.80		208	
16	11	6	33	17	123	64	58	30	0.89	0.46	225	117
18	9		23		87		41		0.72		161	
20	11		30		112		52		0.94		207	372
22	8		33		127		57		0.92		227	
24	11		39		150		67		1.04		267	402

a: situation at end of the year
b: directly after thinning

8. Yields

The natural forest produces every 24 year 25 m^3 or 15 t/ha of high quality hardwood of large dimensions. Higher yields are possible when the natural forest contains a high percentage of marketable species as is the case in many Costa Rican forest such as those dominated by Carapa guianensis. In those cases harvests can be larger and refinements accordingly smaller. Therefore 2 yield levels natural forest are considered: 25 and 50 m^3/ha every 24 years. This is the net production which is exported from the forest.

The forest plantation produces every 24 years stemwood from 3 thinnings and from one final cut. Planting is done in former natural forest land, now under grassland. Plant density is 1600 trees/ha. Between year 1 and 8, this number decreases to 800 by natural mortality and thinnings without harvest. The three thinnings that are harvested are in the years 8, 12 and 16. Only stemwood is harvested and of the stemwood one third stays behind in the forest as stumps, upper part near branches and defected stems. Details of the exploitation are given in Table 13. It is assumed that the average lenght of the exported stems is 10 m, that the form factor is 0.7 and that the wood density is 0.6. The form factor (ff) gives the deviation between the average stem form and a cylinder as follows:

Stem volume = basal area * lenght * ff

Table 13. Exploitation scheme of the forest plantation

		Stemwood (t/ha)		number of	volume per	diameter of stems
Year	treatment	killed	exported	stems	stem (m)	(cm)
8	thinning	18.85	12.57	185	0.113	14
12	thinning	33.74	22.49	178	0.211	20
16	thinning	58.65	39.10	170	0.383	26
24	final cut	149.71	99.81	157	1.060	44
Total		260.95	173.97	690		

The number of stems of the thinnings and of the final cut is smaller than 200 because of the naturally occurring mortality of 1 % per year.

Average stem diameters of 44 cm are a bit small for a final cut. Planters like Huizinga (1993) claim a faster growth: 1.3 to 1.6 m^3 per tree at year 20 at the same tree density. This would mean that the stems (lenght (10 m) and form factor (0.7) being the same) have diameters of 49 to 54 cm. More growth data are needed, and especially over prolonged periods, as very fast initial growth is often followed by slower growth or even stagnation in later stages. Very optimistic prognoses often result from extrapolation of favourable growth during the first years.

9. Nutrients

The question is: do nutrient shortages occur in the short run (during the growth) or in the long run (after several exploitation cycles). This problem is rather complex. Nutrients come available to the vegetation from different sources: atmospheric deposition (wet and dry), biological Nitrogen fixation, weathering of minerals, decomposition of organic matter and runon of water and sediment. On the other hand there are losses: leaching, runoff and erosion, and export by harvest.

Atmospheric inputs and weathering inputs of elements are relatively small. It is assumed that these inputs are constant and equal for both vegetations. Amounts have been estimated (Table 14) using data from Poels (in press 2). Weathering inputs are for the Costa Rican well drained soils of low fertility. For the soils of high fertility the inputs are estimated to be threefold.

Table 14. Estimated yearly inputs of nutrients by the atmosphere and by mineral weathering

Element	N	P	K	Ca	Mg
Atmosphere	5	0.1	1	1	3
Weathering	0	0.2	7	7	3
Total	5	0.3	8	8	6

Decomposition of organic matter contributes the largest quantity of nutrients to the vegetation in a forest situation. The nutrients do not come available at the moment of litter fall but later, depending on the type of litter. The following decomposition times will be used: leaf 0.5, small woody litter 2 and coarse woody litter 5 years. Decay rates are therefore 2, 0.5 and 0.2 per year. To simplify the calculation, it is assumed that all fine woody litter is completely decomposed after 3 years and coarse woody litter after 10 years (Table 15). Given is the percentage of the litter that falls in year 0 that decomposes in a certain year, liberating the nutrients contained in the decomposed part.

Table 15. Decomposition (%) of different litter types with time

Year	0	1	2	3	4	5	6	7	8	9	10
Leaf	50	50									
Fine woody	10	50	25	15							
Coarse woody	0	21	17	14	12	10	8	6	5	4	3

Fine woody litter are twigs, branches, roots and seeds with diameters less than 3 cm. Coarse woody litter are stems, roots and branches thicker than 3 cm. To translate litter into these categories half of the root and branch litter and all of the flower/seed litter is considered to be fine woody litter and half of root and branch litter and all of the stem litter to be coarse woody litter.

9.1. Climax situation natural forest

This situation is relatively simple as the forest is in a steady state with litter decomposition speed equal to litter fall for all litter types. Yearly liberation of nutrient from decomposing litter are as given in Table 9. A summary of the nutrient flows for the climax situation is given in Table 16.

Table 16. Nutrient flows in a natural forest ecosystem in a steady state (kg/ha.y)

Element	N	P	K	Ca	Mg
Atmospheric input	5	0.1	1	1	3
Weathering input	0	0.2	7	7	3
Organic matter turnover	260	15.9	173	184	31
Export by leaching, erosion	5	0.3	8	8	6

9.2. Natural forest under polycyclic management

Organic matter turnover is influenced by harvesting and silvicultural treatments. Litter fall and decomposition are no longer in a steady state. For each year nutrient flows have to be calculated separately. Appendix II.1 gives the formation and the death of organic matter components as calculated with TROPFOR.

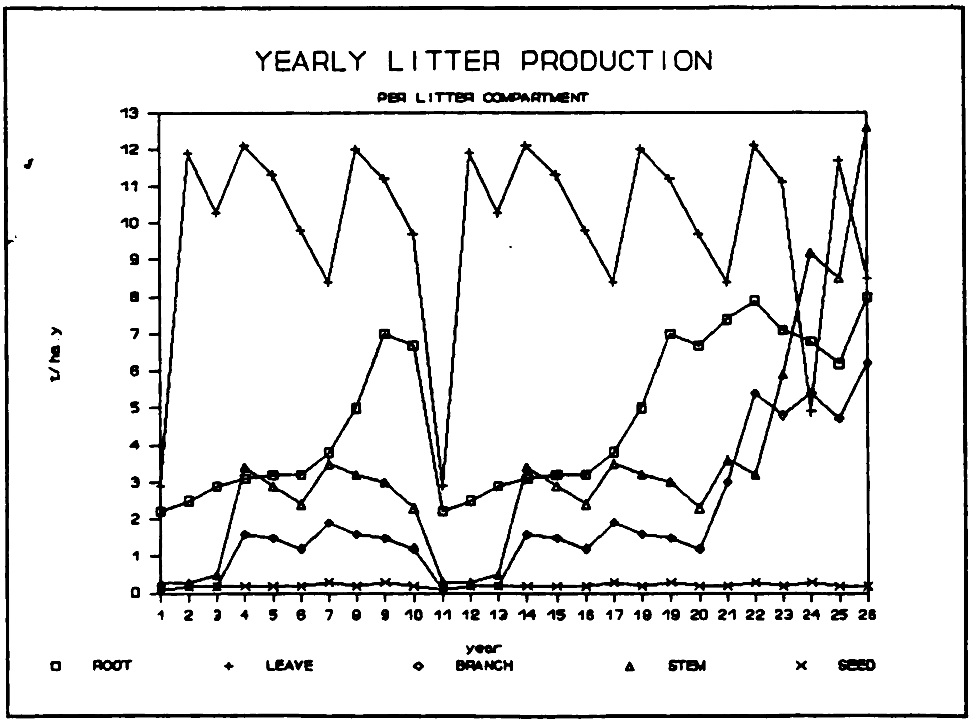


Fig. 4. Yearly litter production in treated natural forest

The yearly litter production data, not including litter from treatments, of Appendix II.1 are shown also in Fig. 4. After treatment in year 10, litter production drops sharply, favouring phytomass increase. After year 20, litter productions increase strongly because phytomass components are approaching climax amounts. When the second harvest takes place in year 24, litter production of year 25 becomes equal to that of year 11, making new room for dry matter increases.

That a refinement near year 10 is necessary is illustrated in Figs. 5 and 6. Without refinement, stemweight increases stop at year 15, as mortality becomes more or less equal to growth. With refinement at year 10, stem weight increases can be kept high till year 22. A second harvest at year 24 is to be preferred over a harvest at year 20 to increase the size of the stems to be harvested.

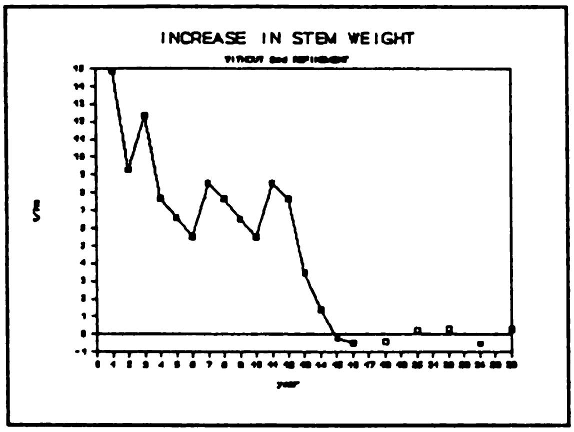


Figure 5. Increase in stem weight without refinement at year 10

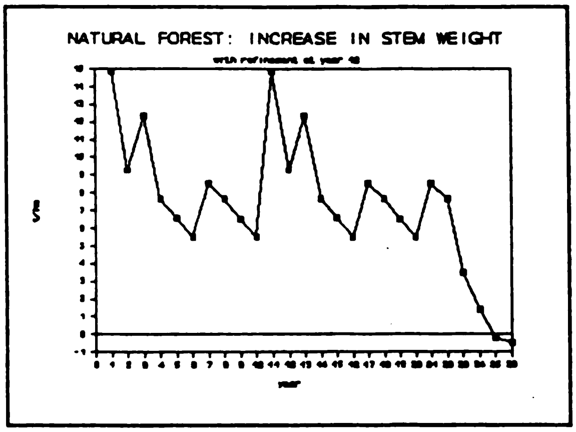


Figure 6. Increase in stem weight with refinement at year 10

Combining the data of Appendix II.1 with the concentrations of Table 8, nutrient balanses were constructed. They are given in Appendix III.1Uptake of a nutrient was calculated straightforward by multiplying amounts of plant components formed with their concentrations. Liberation of nutrients from decomposing litter was calculated step wise. First, the litter was grouped in leaf, fine woody and coarse woody. Then, for each group per year, the amount was calculated that decomposes and these amounts were multiplied with the concentrations and added per year.

During the years preeceeding the treatment, liberation and uptake are in balance (climax situation). In year zero, harvesting and refinement takes place, producing much litter of which decompositions reaches a peak in year 1. In that year 476 kg N, 32 kg P, 323 kg K, 475 kg Ca and 60 kg Mg are liberated from decomposing organic matter. After subtraction of uptake there is a surplus of 178 kg N, 13 kg P, 123 kg K, 234 kg Ca and 24 kg Mg reaching the soil buffer.

Liberation peaks are at the years 1, 11 and 25 for all elements and liberated amounts decrease slowly till the next treatment. Uptake varies per year because of the influence of the weather, favourable years (3, 7, 13, 17 and 21) with higher insolation having more production and nutrient uptake than other years. When these favourable years are long after treatment (years 7, 17 and 21) and, therefore, at low litter levels, nutrient shortages occur that will be claimed from the soil buffer. These maximum shortages in one year are: 123 kg N, 8 kg P, 87 kg K, 125 kg Ca and 16 kg Mg/ha in year 21.

Both nutrient surpluses and shortages in the soil have negative effects. Surpluses such as in year 1 may result in increased leaching and losses from the ecosystem and shortages result in decreased growth. The quality of the soil, i.c. the buffer capacity is important in this respect. Surpluses and shortages in this managed natural forest are relatively small.

A surplus of, for instance, 123 kg K can easily be taken up by the soil, giving an average increase of K-adsorbed from 4 to 4.05 cmol/kg in the layer 0-50 cm. For a surplus of 234 kg Ca/ha, the adsorbed amount of Ca only has to increase with 0.19 cmol(+)/kg of soil. Leaching losses are considered to be very low, as are the maximum shortages in year 21.

Table 17. Summary of nutrient flows in managed natural forest (kg/ha.y)

Element	N	P	K	Ca	Mg
Atmospheric input	5	0.1	1	1	3
Weathering input	0	0.2	7	7	3
Average O.M. turnover:					
- release	271	17	179	194	32
- uptake	268	16	177	191	32
Export with harvest:					
- 25 m^3/24 y	1.8	0.1	1.6	3.8	0.3
- 50 m^3/24 y	3.6	0.2	3.1	7.6	0.6
Maximum yearly surplus	178	13	123	234	24
Maximum yearly shortage	123	8	87	125	16
Export with leaching, erosion	5	0.3	8	8	6

9.3. Plantation forest of teak

Simulated organic matter flows in a teak plantation are given in Appendix II.2. Compared with the organic matter flows under managed forest amounts are lower and variation larger. There are more treatments and there is more extraction of wood. The results of these treatments (three thinnings and one final cut) are presented in the second line of the years 8, 12, 16 and 24.

The yearly litter production for each compartment (not including litter from treatments) is given in Fig. 7. Leaf litter production is at about the same level as in natural forest, strongly influenced by thinning, but not as strong as shown in the figure, where the sharp peaks are caused by imperfect simulation. The peak leaf litter levels of the years 10, 14, 18, 22 and 34 should be leveled of with the preceding years. Litter production of roots, stems and branches is smaller than in natural forest because of low phytomass levels.

Increases in stemweight (Fig. 8) are higher than in managed natural forest, mainly because of the lower phytomass and corresponding lower maintenance respiration rates and death (litter production) rates.

Nutrient balances are given in Appendix III.2. In the first year a soil input is given, calculated with the QUEFTS method (Janssen et al, 1990) to give the starting amount of nutrients for the plantation that the soil can supply. The amounts have been calculated from soil analysis data as given in Table 1 for N, P and K. For Ca and Mg amounts have been estimated. These available soil nutrients for the first year are (kg/ha): N 72, P 6, K 102, Ca 200 and Mg 50.

During the whole growing period, large shortages (liberation - uptake) occur, in sharp contrast to the managed forest (Table 18). Main cause for these shortages are the lack of phytomass at the beginning of the plantation and the fast phytomass increase during the growth.

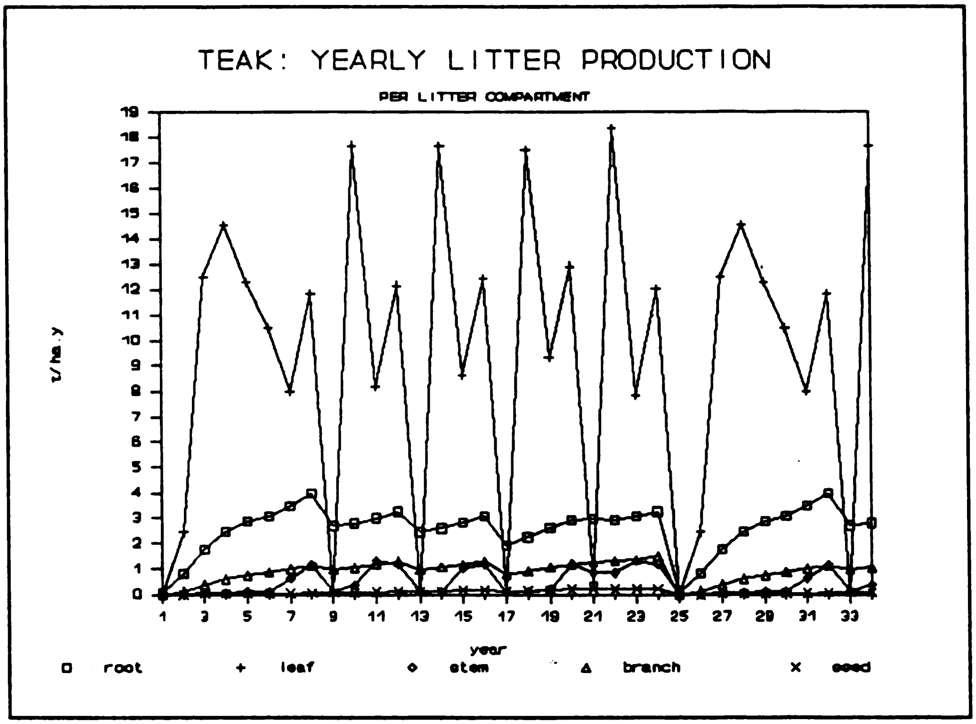


Figure 7. Yearly litter production in a teak plantation

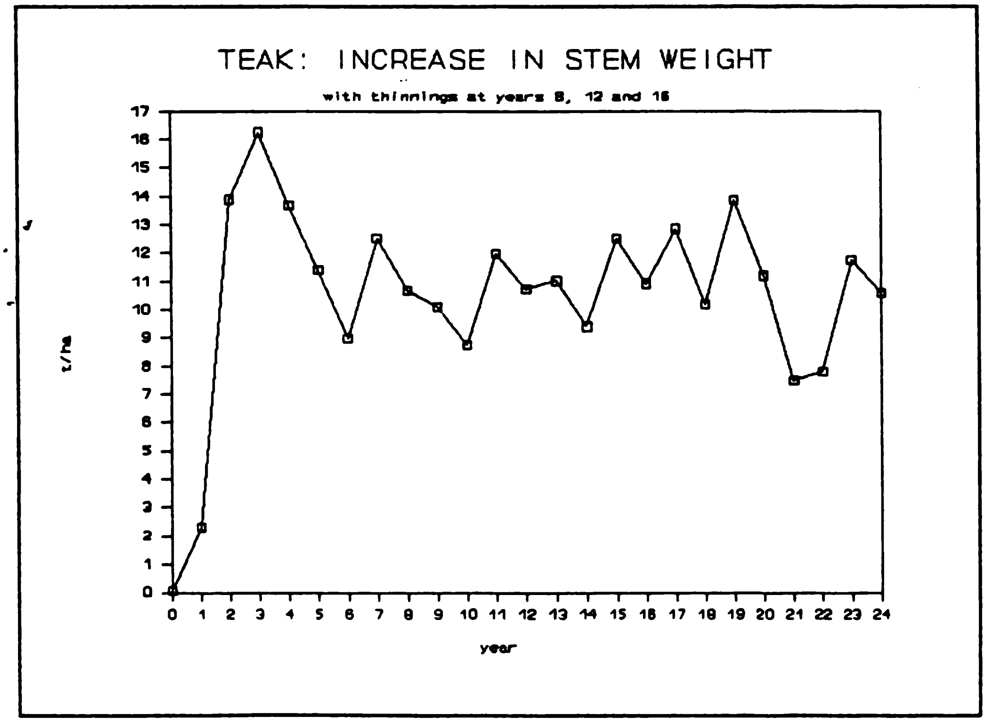


Figure 8. Yearly increase in stem weight in a teak plantation

Table 18. Maximum cumulative surpluses and shortages of nutrients (kg/ha)

	N	P	K	Ca	Mg
Managed natural forest					
Surpluses	443	32	319	614	61
Shortages	371	27	260	499	50
Teak plantation					
Surpluses	4	2	60	158	42
Shortages	1546	102	1028	1872	166

In managed natural forests, surpluses build up with some interruptions till year 12. From year 13 on, shortages start to occur that continue for most nutrients till the year 23 (see also App.III.1). The surpluses are larger than the shortages that come afterwards. That means that there are always enough nutrients provided that the buffer capacity of the soil is large enough.

For teak the situation is completely different. Surpluses only occur in year 1, when the soil provides the nutrients according to QUEFTS and uptake is still small. During the whole growing period there are shortages. Maximum cumulative shortages are reached in the year 23 for all nutrients except Ca, where the maximum is reached in year 24. This is because Ca mainly occurs in the wood, that decomposes slower than leaf litter.

Table 19. Summary of nutrient flows in the teak plantation (kg/ha.y)

Element	N	P	K	Ca	Mg
Atmospheric input	5	0.1	1	1	3
Weathering input	0	0.2	7	7	3
Average O.M. turnover:					
- release	204	12	133	108	24
- uptake	267	16	175	186	31
Export with harvest	21.0	1.3	18.1	44.2	3.6
Maximum yearly surplus	33	2	60	158	42
Maximum yearly shortage	311	19	203	224	36
Export with leaching, erosion	5	0.3	8	8	6

Yearly flows are given in Table 19. Average nutrient uptakes are higher than release from organic matter decomposition for all elements, indicating the shortages in the short run. Shortages in the long run appear from the line: export with harvest. Yearly exports are much higher than in managed natural forest (Table 17) and also higher than atmospheric and weathering inputs combined.

10. Discussion

Large differences exist between managed natural forest and a forest plantation, even if in both cases the cutting cycle is 24 years. In case of the natural forest, only few big stems of high quality trees are harvested, while in the case of a plantation of e.g. teak, a complete cut is executed at the end of the cycle, with all stemwood removed, including stemwood of thinnings.

The starting situation is better in managed natural forest with a high phytomass containing a large quantity of nutrients. During treatment the phytomass amount decreases somewhat, giving a surplus of nutrients. Also in the long run this land use is sustainable from a nutrient point of view, even on the well drained soils of low fertility, where the yearly input of nutrients from the atmosphere and from weathering is larger than the export of nutrients with harvested stemwood. Even a double harvesting level of 50 m3/ha per cycle (30 t of stemwood) seems possible, but in that case nutrient supply becomes more tight in the long run and concentrations of the drainage water will have to decrease somewhat.

Growing of teak or another tree species in an intensively managed plantation is a completely different matter. When starting from grassland or agricultural land, which is often the case, large nutrient shortages will develop during development of the trees because of immobilization of nutrients in phytomass. Average yearly shortages during the first cycle are: N 63, P 4, K 42, Ca 78 and Mg 7 kg/ha. During the first years these shortages are much larger (Table 19, Appendix III.2). Improvement of the nutrient situation will occur in the second cycle, because of decomposition of harvest refuse, if this litter is evenly divided over the area and not burned (Appendix III.2, nutrient balanses, years 25 -34).

Export of nutrient with harvested stemwood is much larger than in managed natural forest. In the long run, after several cycles, shortages will occur. This land use is not sustainable, from a nutrient point of view, on the well drained soils of low fertility without fertilizer addition. The average yearly export by harvested stemwood is significantly larger than the inputs by the atmosphere and by weathering. On fertile soils, that have an estimated yearly nutrient release by weathering that is at least three times that of the low fertility soils, this land use is considered sustainable, but more weathering research is necessary to make better estimates.

The yields considered here were calculated assuming no nutrient limitation. Whether limitations occur depends on the fertility and buffer capacity of the soil, on the biological nitrogen fixation and on fertilizing. Soil fertility is expressed by the initial available nutrients calculated with QUEFTS and by the yearly release from weathering. Necessary soil buffers are much larger in the teak plantation than in managed natural forest (Tables 17, 18 and 19). Maximum yearly and cumulative surpluses are limited for both forests. Not much increase in drainage water concentrations are expected. Nutrient shortages are very limited in managed natural forest, but very large in the teak plantation, especially the cumulative shortages (Table 18). The buffer capacity of the soil should be large enough to supply during the first cycle 17 mgr/kg P, 0.44 cmol(+) of K, 0.39 cmol(+) of Ca and 0.06 cmol(+) of Mg per kg of soil for the whole soil till a depth of 50 cm. For the fertile soil this seems possible, but for the low fertility soil (III, Table 1) this seems too much, especially when rooting is not very intensive throughout the whole soil depth of 50 cm. More research in the nutrient supplying capacity of the soils is needed.

11. Conclusions

The land utilization type (LUT): Bosque natural is a sustainable land use from a nutrient point of view on well drained soils of low fertility in the Atlantic Zone of Costa Rica, provided that harvests are kept low and executed with care to limit harvesting damage. Additional advantages of this land use type are high ecological value and the good soil protection.

The LUT Plantaciones: the growing of teak or other tree species in plantations produces higher amounts of stemwood (Table 13), but export of nutrients with the harvested stemwood is also much larger, making the land use not sustainable from a nutrient point of view on the well drained soils of low fertility in the long run without fertilizer input. In the short run even larger nutrient shortages occur due to immobilization of nutrients in the increasing phytomass. For a good growth, supplementary fertilizing with 50 kg P, 200 kg K and 300 kg Ca per ha in the second year seems advisable for the first cycle.

Also large N-shortages occur in the teak plantation during the first years, but artificial fertilizing with N could be prohibitively expensive. Teak itself is not able to fix atmospheric N biologically, but some N comes in with free living N-fixing bacteria, with N-fixing bacteria living in symbiosis with undergrowth species and with atmospheric deposition. Soil humus decomposition can supply part of the shortage and the remainder of the shortage will cause a temporary growth reduction.

Calculations were executed for one soil type only, Soil type III: the well drained soils of low fertility. The provisional adaptation for Soil type I (well drained fertile soil) is that nutrient release from mineral weathering is considered to be three times that of Soil type III. For the poorly drained soil (Soil type II) much more adaptations are necessary. It is well known that teak cannot grow in poorly drained soil. After artificial drainage it is possible to grow teak, but the drainage demands of teak are higher than of e.g. bananas. Artificial drainage for teak could be, therefore, probihitively expensive. Drainage research for teak is outside the scope of this study, but it can be said that with sufficient drainage yields of teak on Soil type II may approach those of Soil type I.

Natural forest on Soil type II is adapted to periods of waterlogging. Some species like Carapa guianensis are often more abundant in swamp forests than in dry land forests. However, adaptation to swampy conditions has its price. It costs additional energy to supply oxygen to the roots, reducing the growing speed. Moreover, mortality in swamps is higher as trees are more prone to windworp. To simulate forest grow in swamps much more data are necessary. At this time, it is only possible to estimate a reduction factor for the average productivity in swamps, compared to that on well drained soils. And it should be realized that all swamps are different, with different degrees of water logging and different growth reductions. Till better data become available it is estimated that the production level in swamps is 30 % lower than on well drained land with the same soil fertility.

For the linear programming of land use options in the Atlantic Zone by "Projecto de cooperacion CATIE/UAW/MAG in Guapiles to following results are presented:

Managed natural forest gives once per 24 years a yield of 25 m^3 of stemwood per ha that contains 44 kg N, 2.7 kg P, 38 kg K, 92 kg Ca and 7.4 kg Mg. In well stocked forests on all three soil types a double yield of 50 t/ha is possible, when refinement treatments are reduced accordingly. No or few nutrient limitations are expected for this type of land use on good soils of soil types I, II and III with sufficient nutrient buffering capacities.

Plantations of teak are possible on soil types I and III. The calculated production level amounts to 174 t/ha or 290 m3/ha per 24 years (Table 13). The exported stemwood contains 504 kg N, 31.3 kg P, 435 kg K, 1061 kg Ca and 85 kg Mg. This is much more than the inputs by atmosphere and mineral weathering in well drained soils of low fertility. Fertilizing is needed to make this land use sustainable from a nutrient point of view, not only to compensate for nutrient export with the wood but also for the phytomass build up during the first cycle and to compensate for leaching and erosion losses that result from the strong phytomass fluctuations that are unavoidable with this type of land use. On soil type I less nutrient problems will occur. A weathering speed of 3 times that of Soil type III (Table 14) would be enough to supply the necessary K and Mg, for Ca and P still shortages would occur in the long run.

Better estimates of yields and nutrient flows can be made as soon as more data become available. The development of simulation and calculation procedures was the main goal of this study.

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APPENDIX I. INPUT FILES

Appendix I.1 Average monthly and yearly climatic data Los Diamantes, Costa Rica (82-86)

MONTH	RAIN mm/m	AVRAD MJ/m2.d	TMAX oC	TMIN oC	TMPA oC	TMPD oC	SVAP1 mbar	SVAP2 mbar	SVAP3 mbar	VAPP mbar	R.H.1 %	R.H.2 %	R.H.3 %	WIND m/s
8201	79	14.2	28.6	18.9	23.8	26.2	29.5	34.0	21.9	18.3	0.62	0.54	0.83	0.93
8202	71	15.4	29.0	18.3	23.7	26.3	29.3	34.3	21.1	17.8	0.61	0.52	0.85	0.99
8203	104	15.4	28.8	19.0	23.9	26.3	29.7	34.3	21.9	17.9	0.60	0.52	0.81	1.11
8204	139	14.6	29.1	19.8	24.4	26.7	30.7	35.2	23.2	19.0	0.62	0.54	0.82	1.00
8205	383	13.8	30.3	20.9	25.6	27.9	32.9	37.7	24.7	20.8	0.63	0.55	0.84	0.89
8206	434	13.1	29.8	21.2	25.5	27.7	32.7	37.1	25.3	21.2	0.65	0.57	0.84	0.84
8207	875	11.3	28.2	21.2	24.7	26.5	31.2	34.6	25.2	20.8	0.67	0.60	0.83	0.90
8208	574	14.1	28.8	21.3	25.1	26.9	31.9	35.6	25.4	21.0	0.66	0.59	0.83	0.84
8209	355	16.6	29.2	20.8	25.0	27.1	31.8	36.0	24.6	20.6	0.65	0.57	0.83	0.81
8210	798	12.0	28.3	20.5	24.4	26.4	30.7	34.5	24.2	19.8	0.65	0.57	0.82	0.83
8211	381	12.2	27.8	20.0	23.9	25.8	29.7	33.4	23.4	19.5	0.66	0.58	0.83	0.96
8212	291	11.3	27.8	19.5	23.7	25.7	29.3	33.1	22.7	19.4	0.66	0.59	0.85	0.99
8301	308	11.2	27.4	19.8	23.6	25.5	29.2	32.8	23.2	25.4	0.87	0.77	1.09	0.93
8302	305	13.0	28.5	20.3	24.4	26.5	30.7	34.7	23.9	25.9	0.84	0.75	1.08	0.99
8303	357	12.8	28.9	21.4	25.1	27.0	32.0	35.7	25.5	27.1	0.85	0.76	1.07	1.11
8304	95	15.4	30.2	20.8	25.5	27.8	32.7	37.5	24.6	27.1	0.83	0.72	1.10	1.00
8305	662	13.8	29.7	21.6	25.6	27.6	32.9	37.1	25.8	28.2	0.86	0.76	1.09	0.89
8306	196	14.4	30.6	21.6	26.1	28.4	33.9	38.7	25.9	29.1	0.86	0.75	1.12	0.84
8307	384	12.6	29.1	21.6	25.4	27.3	32.4	36.3	25.8	28.5	0.88	0.79	1.11	0.90
8308	462	13.4	29.6	21.4	25.5	27.5	32.7	36.9	25.6	28.0	0.86	0.76	1.10	0.84
8309	367	13.6	29.7	20.9	25.3	27.5	32.3	36.8	24.8	27.6	0.85	0.75	1.11	0.81
8310	694	11.3	28.7	20.7	24.7	26.7	31.2	35.1	24.4	27.0	0.87	0.77	1.11	0.83
8311	277	10.7	28.5	20.5	24.5	26.5	30.8	34.7	24.1	26.9	0.87	0.78	1.12	0.96
8312	194	10.7	28.0	19.3	23.7	25.8	29.3	33.4	22.5	25.0	0.85	0.75	1.11	0.99
8401	399	9.3	26.7	18.3	22.5	24.6	27.2	30.9	21.0	23.3	0.86	0.76	1.11	0.93
8402	330	9.8	28.1	18.7	23.4	25.7	28.8	33.2	21.6	24.2	0.84	0.73	1.12	0.99
8403	91	12.4	28.7	18.6	23.6	26.1	29.2	33.9	21.4	24.3	0.83	0.72	1.14	1.11
8404	91	13.3	30.0	19.8	24.9	27.4	31.5	36.7	23.1	25.3	0.80	0.69	1.10	1.00
8405	426	11.2	29.0	20.4	24.7	26.8	31.2	35.4	24.0	26.7	0.86	0.75	1.11	0.89
8406	456	10.0	29.1	20.9	25.0	27.1	31.8	35.9	24.7	27.2	0.86	0.76	1.10	0.84
8407	277	11.0	29.0	20.1	24.5	26.8	30.9	35.2	23.6	26.2	0.85	0.74	1.11	0.90
8408	594	9.4	28.5	20.6	24.5	26.5	30.9	34.7	24.4	27.0	0.87	0.78	1.11	0.84
8409	303	11.5	29.2	20.2	24.7	27.0	31.2	35.7	23.7	26.8	0.86	0.75	1.13	0.81
8410	346	9.2	27.8	20.6	24.2	26.0	30.3	33.7	24.4	27.0	0.89	0.80	1.11	0.83
8411	372	8.6	27.0	20.0	23.5	25.3	29.0	32.2	23.4	25.3	0.87	0.79	1.08	0.96
8412	353	9.2	27.5	19.3	23.4	25.5	28.8	32.6	22.4	24.2	0.84	0.74	1.08	0.99
8501	96	13.7	27.0	17.8	22.4	24.7	27.1	31.2	20.3	22.3	0.82	0.72	1.10	0.93
8502	311	15.2	27.1	18.9	23.0	25.0	28.1	31.8	21.9	23.4	0.83	0.74	1.07	0.99
8503	80	17.9	28.2	18.2	23.2	25.7	28.5	33.1	20.9	23.1	0.81	0.70	1.10	1.11
8504	113	18.6	29.2	18.6	23.9	26.6	29.7	34.8	21.4	23.9	0.81	0.69	1.12	1.00
8505	163	15.4	29.8	20.2	25.0	27.4	31.8	36.6	23.8	26.4	0.83	0.72	1.11	0.89
8506	629	11.9	28.4	21.2	24.8	26.6	31.4	34.9	25.2	27.7	0.88	0.79	1.10	0.84
8507	283	13.3	28.0	20.4	24.2	26.1	30.2	33.8	24.0	26.5	0.88	0.78	1.10	0.90
8508	539	13.3	27.9	20.4	24.1	26.0	30.1	33.7	23.9	26.6	0.88	0.79	1.11	0.84
8509	290	15.8	29.2	20.2	24.7	27.0	31.2	35.7	23.7	26.4	0.85	0.74	1.12	0.81
8510	359	13.4	28.6	20.0	24.3	26.5	30.5	34.7	23.4	26.8	0.88	0.77	1.14	0.83
8511	346	12.4	27.9	19.7	23.8	25.9	29.6	33.4	23.0	25.7	0.87	0.77	1.12	0.96
8512	228	12.3	27.3	19.3	23.3	25.3	28.7	32.3	22.4	24.7	0.86	0.76	1.10	0.99
8601	367	12.4	26.2	17.6	21.9	24.0	26.3	29.9	20.1	23.0	0.87	0.77	1.14	1.05
8602	52	16.0	27.8	17.6	22.7	25.2	27.6	32.1	20.1	22.9	0.83	0.71	1.14	1.11
8603	312	14.0	26.8	18.7	22.8	24.8	27.7	31.3	21.7	23.6	0.85	0.75	1.09	1.15
8604	227	14.0	27.8	19.7	23.8	25.8	29.5	33.2	23.0	25.5	0.87	0.77	1.11	1.04
8605	202	14.9	29.1	20.5	24.8	27.0	31.4	35.6	24.1	26.9	0.86	0.76	1.12	0.96
8606	479	12.4	28.7	21.2	25.0	26.9	31.7	35.4	25.2	27.6	0.87	0.78	1.09	0.88
8607	436	13.1	27.7	21.1	24.4	26.1	30.6	33.8	25.1	27.1	0.88	0.80	1.08	0.98
8608	527	13.0	28.2	21.3	24.7	26.5	31.2	34.6	25.3	27.6	0.88	0.80	1.09	0.89
8609	552	13.9	28.7	21.1	24.9	26.8	31.5	35.2	25.0	27.5	0.87	0.78	1.10	0.86
8610	373	13.0	28.3	20.6	24.5	26.4	30.7	34.5	24.3	27.2	0.89	0.79	1.12	0.75
8611	229	13.3	28.4	20.5	24.5	26.4	30.7	34.6	24.1	26.8	0.87	0.77	1.11	0.96
8612	164	13.5	28.2	19.4	23.8	26.0	29.5	33.7	22.5	24.7	0.84	0.73	1.10	0.99
TOTALS	20177	778	1710	1203	1456	1583	1826	2070	1412	1483	49	43	63	56
AVER.	336.3	13.0	28.5	20.0	24.3	26.4	30.4	34.5	23.5	24.7	0.81	0.72	1.05	0.93
MONTH	RAIN mm/m	AVRAD MJ/m2.d	TMAX oC	TMIN oC	TMPA oC	TMPD oC	SVAP1 mbar	SVAP2 mbar	SVAP3 mbar	VAPP mbar	R.H.1 %	R.H.2 %	R.H.3 %	WIND m/s

PER YEAR:

YEAR	RAIN mm/y	AVRAD MJ/m2.d	TMAX oC	TMIN oC	TMPA oC	TMPD oC	SVAP1 mbar	SVAP2 mbar	SVAP3 mbar	VAPP mbar	R.H.1 %	R.H.2 %	R.H.3 %	WIND m/s
1982	4483	13.7	28.8	20.1	24.5	26.6	30.8	35.0	23.6	19.7	0.64	0.56	0.83	0.92
1983	4301	12.7	29.1	20.8	25.0	27.0	31.7	35.8	24.7	27.1	0.86	0.76	1.10	0.92
1984	4038	10.4	28.4	19.8	24.1	26.2	30.1	34.2	23.1	25.6	0.85	0.75	1.11	0.92
1985	3436	14.4	28.2	19.6	23.9	26.1	29.7	33.8	22.8	25.3	0.85	0.75	1.11	0.92
1986	3920	13.6	28.0	19.9	24.0	26.0	29.9	33.7	23.4	25.9	0.87	0.77	1.11	0.97
TOTAL	20177	65	142	100	121	132	152	172	118	124	4	4	5	5
AVER.	4035	13.0	28.5	20.0	24.3	26.4	30.4	34.5	23.5	24.7	0.81	0.72	1.05	0.93

Explanation:

MONTH 8612: December 1986
RAIN: rainfall
AVRAD: short wave radiation
TMAX: daily maximum temperature
TMIN: daily minumum temperature
TMPA: daily mean temperature
TMPD: daytime mean temperature
SVAP1: saturated vapour pressure at daily mean temperature
SVAP2: saturated vapour pressure at daytime mean temperature
SVAP3: saturated vapour pressure at minimum temperature
VAPP: actual average vapour pressure
R.H.1: average daily relative air humidity (VAPP/SVAP1)
R.H.2: average daytime relative air humidity (VAPP/SVAP2)
R.H.3: relative air humidity at minimum temperature (VAPP/SVAP3)
WIND: average daily wind speed

Appendix 1.2. Input file for the La Selva soil and 3 standard Costa Rican soil types

```
La Selva soil, Costa Rica
          18        16
          316.0     316.0     316.0
          -1.000    0.670     1.000     0.660     1.500     0.640     2.000     0.600     3.000     0.400
           4.000    0.320     4.200     0.310     5.000     0.280     7.000     0.000
          -.--
          0.000      2.500    1.000      2.400    1.500      2.050    2.000     0.800     2.500     -1.500
          3.000     -2.650    4.000     -3.725    4.200     -3.900
          -.--
Costa Rica I (fertile, well drained)
          30        30
          353.      353.      353.
          -1.000     0.720    0.000     0.718     0.300     0.715     0.700     0.706     1.000     0.690
           1.300     0.663    1.700     0.607     2.000     0.555     2.300     0.502     2.700     0.436
           3.000     0.391    3.300     0.353     3.700     0.309     4.204     0.264     7.000     0.000
          -1.000     2.548    0.000     1.934     0.300     1.777     0.700     1.458     1.000     1.078
           1.300     0.525    1.700    -0.410     2.000    -1.131     2.300    -1.842     2.700    -2.796
           3.000    -3.525    3.300    -4.258     3.700    -5.229     4.000    -5.963     4.204    -6.462
Costa Rica II (fert, poorly drained)
          30        30
          353.      353.      353.
          -1.000     0.680    0.000     0.678     0.300     0.675     0.700     0.667     1.000     0.652
           1.300     0.627    1.700     0.575     2.000     0.526     2.300     0.476     2.700     0.414
           3.000     0.373    3.300     0.337     3.700     0.296     4.204     0.270     7.000     0.000
          -1.000     2.548    0.000     1.934     0.300     1.777     0.700     1.458     1.000     1.078
           1.300     0.525    1.700    -0.410     2.000    -1.131     2.300    -1.842     2.700    -2.796
           3.000    -3.525    3.300    -4.258     3.700    -5.229     4.000    -5.963     4.204    -6.462
Costa Rica III (unfertile, well drained)
          30        30
          443.      443.      443.
          -1.000     0.630    0.000     0.628     0.300     0.626     0.700     0.618     1.000     0.605
           1.300     0.582    1.700     0.536     2.000     0.493     2.300     0.448     2.700     0.393
           3.000     0.358    3.300     0.327     3.700     0.293     4.204     0.260     7.000     0.000
          -1.000     2.647    0.000     2.179     0.300     2.041     0.700     1.755     1.000     1.402
           1.300     0.841    1.700    -0.427     2.000    -1.870     2.300    -3.598     2.700    -5.742
           3.000    -7.084    3.300    -8.353     3.700   -10.007     4.000   -11.254     4.204   -12.099
```

Appendix I.3. Vegetation input file dry land forest

```
Tropical Rain Forest Costa Rica
CROPT   DSL     AIRDUC  SPAN    TBASE   RDMCR   DLO     DLC     EFF     CFET    DEPNR
3       0       0       366.    10.     999.0   1.0     0.      0.40    1.00    4.0
TDWI    RDI     DVRC1   DVRC2   RRI     KDIF    CVL     CVO     CVR     CVS
140000. 50.     0.0005  0.0005  1.2     0.800   0.720   0.730   0.720   0.720
SPA     SSA     Q10     RML     RMO     RMR     RMS     PERDL   PERRT   PERST
0.0000  0.0000  2.0     .0069   .0011   .0025   .0004   0.050   .0006   .00006
NMINSO  NMINVE  NMAXSO  NMAXVE          PMINSO  PMINVE  PMAXSO          PMAXVE
 0.0050 0.0040  0.0150  0.0088          0.0015  0.0003  0.0030          .00054
KMINSO  KMINVE  KMAXSO  KMAXVE          YZERO   NFIX
0.0045  0.0030  0.0085  0.0060          200.    0.40
L1      L2      L3      L4      L5      L6      L7      L8      L9      L10
4       6       6       6       4       8       4       12      4       6
        FRTB fraction to root
        0.00    0.22    2.00    0.22
        FLTB fraction to leaf
        0.00    0.21    0.20    0.35    2.00    0.35
        FSTB fraction to stem
        0.00    0.51    0.20    0.42    2.00    0.42
        FOTB fraction to storage organs
        0.00    0.01    0.20    0.01    2.00    0.01
        SLATB specific leaf area
        0.00    0.0008  2.00    0.0008
        DVRETB reduction dev. rate by temp
        0.00    0.00    10.0    0.00    30.00   1.00    45.00   1.00
        AMAXTB maximum leaf CO2 assimilation
        0.00    30.00   2.00    30.00
        TMPFTB (2 lines) reduction leaf assimil. by low temp.
        0.00    0.00    8.00    0.00    15.00   0.70    23.00   1.00
        40.00   1.00    50.00   0.00
        TMNFTB reduct. gross assimil. by low min. temp
        0.00    0.00    3.00    1.00
        FBTB fraction to branches
        0.00    0.27    0.20    0.22    2.00    0.22

Teak Plantation Costa Rica
CROPT   DSL     AIRDUC  SPAN    TBASE   RDMCR   DLO     DLC     EFF     CFET    DEPNR
3       0       0       366.    10.     999.0   1.0     0.      0.40    1.00    4.0
TDWI    RDI     DVRC1   DVRC2   RRI     KDIF    CVL     CVO     CVR     CVS
100.    50.     0.0003  0.0003  1.2     0.800   0.720   0.730   0.720   0.720
SPA     SSA     Q10     RML     RMO     RMR     RMS     PERDL   PERRT   PERST
0.0000  0.0000  2.0     .0069   .0011   .0025   .0004   0.050   .0006   .00006
NMINSO  NMINVE  NMAXSO  NMAXVE          PMINSO  PMINVE  PMAXSO          PMAXVE
 0.0050 0.0040  0.0150  0.0088          0.0015  0.0003  0.0030          .00054
KMINSO  KMINVE  KMAXSO  KMAXVE          YZERO   NFIX
0.0045  0.0030  0.0085  0.0060          200.    0.40
L1      L2      L3      L4      L5      L6      L7      L8      L9      L10
4       6       6       6       4       8       4       12      4       6
        FRTB fraction to root
        0.00    0.50    0.10    0.25    1.00    0.22    2.00    0.22
        FLTB fraction to leaf
        0.00    0.21    0.20    0.35    2.00    0.35
        FSTB fraction to stem
        0.00    0.51    0.20    0.42    2.00    0.42
        FOTB fraction to storage organs
        0.00    0.01    0.20    0.01    2.00    0.01
        SLATB specific leaf area
        0.00    0.0008  2.00    0.0008
        DVRETB reduction dev. rate by temp
        0.00    0.00    10.0    0.00    30.00   1.00    45.00   1.00
        AMAXTB maximum leaf CO2 assimilation
        0.00    30.00   2.00    30.00
        TMPFTB (2 lines) reduction leaf assimil. by low temp.
        0.00    0.00    8.00    0.00    15.00   0.70    23.00   1.00
        40.00   1.00    50.00   0.00
        TMNFTB reduct. gross assimil. by low min. temp
        0.00    0.00    3.00    1.00
        FBTB fraction to branches
        0.00    0.27    0.20    0.22    2.00    0.22
```

For: explanation of codes, see Appendix IV

APPENDIX II. ORGANIC MATTER FLOWS IN MANAGED NATURAL FOREST AND IN TEAK PLANTATION

Appendix II.1. Organic matter flows of managed natural forest

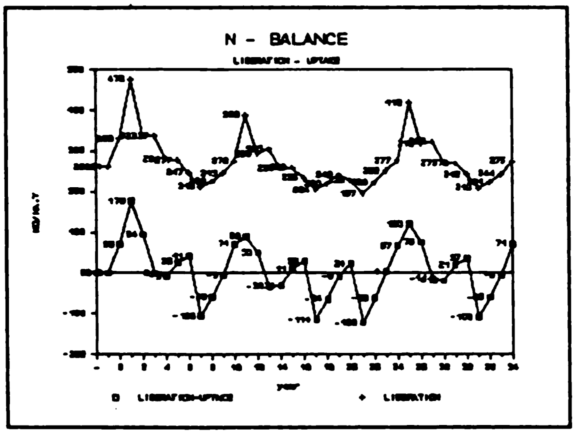
Year	Formation of plant components					Formation of litter				
	root	leaf	stem	br.	seed	root	leaf	stem	br.	seed
0	7330	9950	10430	5300	240	7330	9950	10430	5300	240
harvest and refinement						37000	6000	91000	47000	500
1	9330	9830	15170	7710	300	2200	2900	300	100	100
2	6770	9290	9570	4960	270	2500	11900	300	200	200
3	9290	13120	12840	6530	340	2900	10300	500	200	200
4	7980	11320	11050	5670	280	3100	12100	3400	1600	200
5	6870	9740	9460	4910	220	3200	11300	2900	1500	200
6	5660	8030	7900	4050	180	3200	9800	2400	1200	200
7	8750	12440	12030	6220	380	3800	8400	3500	1900	300
8	7880	11100	10880	5470	240	5000	12000	3200	1600	200
9	6800	9780	9520	4880	300	7000	11200	3000	1500	300
10	5650	7970	7780	4040	160	6700	9700	2300	1200	200
refinement						35380	3020	84400	43440	570
11	9330	9830	15170	7710	300	2200	2900	300	100	100
12	6770	9290	9570	4960	270	2500	11900	300	200	200
13	9290	13120	12840	6530	340	2900	10300	500	200	200
14	7980	11320	11050	5670	280	3100	12100	3400	1600	200
15	6870	9740	9460	4910	220	3200	11300	2900	1500	200
16	5660	8030	7900	4050	180	3200	9800	2400	1200	200
17	8750	12440	12030	6220	380	3800	8400	3500	1900	300
18	7880	11100	10880	5470	240	5000	12000	3200	1600	200
19	6800	9780	9520	4880	300	7000	11200	3000	1500	300
20	5650	7970	7780	4040	160	6700	9700	2300	1200	200
21	8840	12450	12130	6320	270	7400	8400	3600	3000	200
22	7780	11200	10880	5420	320	7900	12100	3200	5400	300
23	6910	9680	9410	4870	190	7100	11100	5900	4800	200
24	6570	6920	10600	5370	280	6800	4900	9200	5400	300
harvest and refinement						36280	6770	90520	46820	630
1	9330	9830	15170	7710	300	2200	2900	300	100	100
2	6770	9290	9570	4960	270	2500	11900	300	200	200
3	9290	13120	12840	6530	340	2900	10300	500	200	200
etc.										

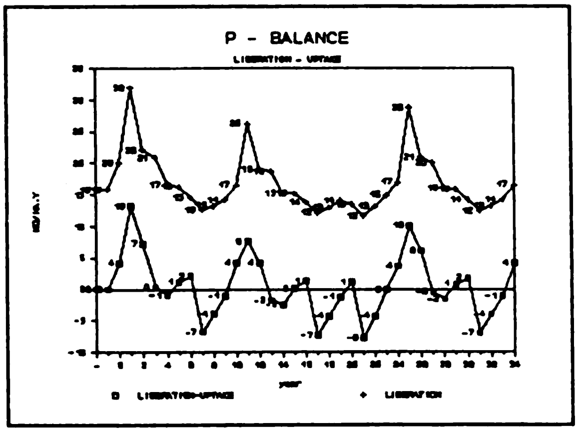
Appendix II.2. Organic matter flows in a teak plantation

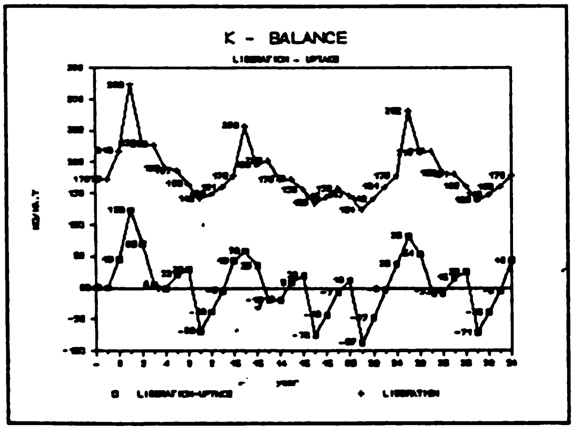
Year	formation of plant components					formation of litter				
	root	leaf	stem	br.	seed	root	leaf	stem	br.	seed
0	0	0	0	0	0	0	0	0	0	0
1	2690	2490	2310	520	0	60	0	0	0	0
2	10600	12520	13900	4570	10	830	2460	20	150	0
3	11900	14520	16310	5440	40	1780	12490	60	390	10
4	9910	12280	13760	4610	50	2470	14530	80	610	10
5	8220	10300	11510	3860	70	2880	12280	110	760	20
6	6390	8160	9100	3050	80	3070	10480	130	890	40
7	9150	11800	13150	4430	130	3480	8010	640	1000	40
8	8160	10690	11880	4010	140	3980	11830	1190	1120	70
thinning						10190	2240	6280	5370	70
9	6930	9220	10230	3450	150	2710	0	130	980	70
10	6110	8230	9110	3090	140	2800	17660	360	1060	80
11	8800	12030	13310	4520	230	3000	8180	1330	1170	100
12	7790	10830	11930	4060	240	3240	12160	1200	1290	130
thinning						16850	3230	11250	9250	190
13	7170	10110	11140	3790	250	2450	0	120	990	120
14	6130	8690	9550	3260	210	2600	17630	140	1090	130
15	8700	12320	13550	4620	310	2840	8640	1050	1190	170
16	7750	11020	12120	4130	270	3090	12450	1200	1320	180
thinning						27800	5240	19550	15690	430
17	8290	11770	12940	4410	290	1930	0	90	800	120
18	6610	9380	10310	3520	240	2250	17460	120	920	150
19	9030	12780	14070	4800	320	2610	9340	210	1070	180
20	7940	11260	12390	4210	280	2930	12900	1200	1200	200
21	5360	7600	8360	2850	190	2990	460	850	1270	210
22	5550	7870	8670	2950	200	2920	18330	850	1310	200
23	8400	11910	13090	4470	290	3060	7830	1330	1390	210
24	7560	10720	11800	4020	270	3250	12020	1200	1500	230
final cut						67100	10660	49900	38860	1040
1	2690	2490	2310	520	0	60	0	0	0	0
2	10600	12520	13900	4570	10	830	2460	20	150	0
3	11900	14520	16310	5440	40	1780	12490	60	390	10

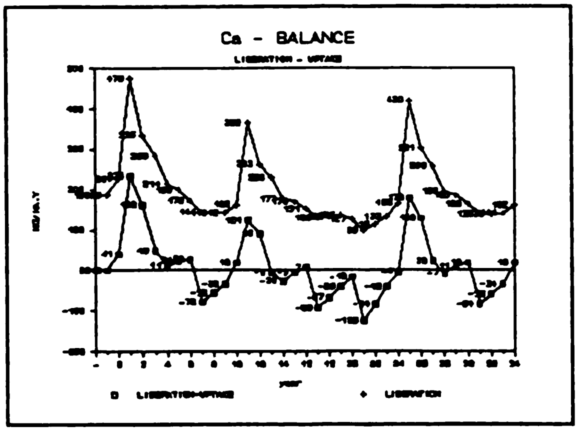
APPENDIX III. LIBERATION AND UPTAKE OF NUTRIENTS

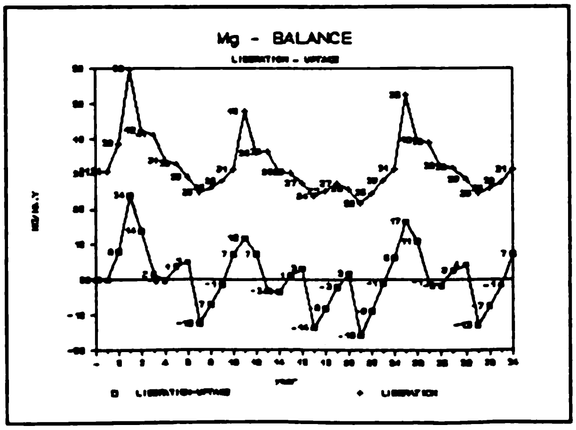
Appendix III.1. Liberation and uptake of nutrients in managed natural forest











Appendix III.2. Liberation and uptake of nutrients in teak plantation