ATLANTIC ZONE PROGRAMME

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Field Report No. 142

SIMULATION OF GROWTH OF MANAGED FORESTS IN THE ATLANTIC ZONE OF COSTA RICA AND ANALYSIS OF NUTRIENT CYCLING TO DETERMINE SURPLUSES AND SHORTAGES

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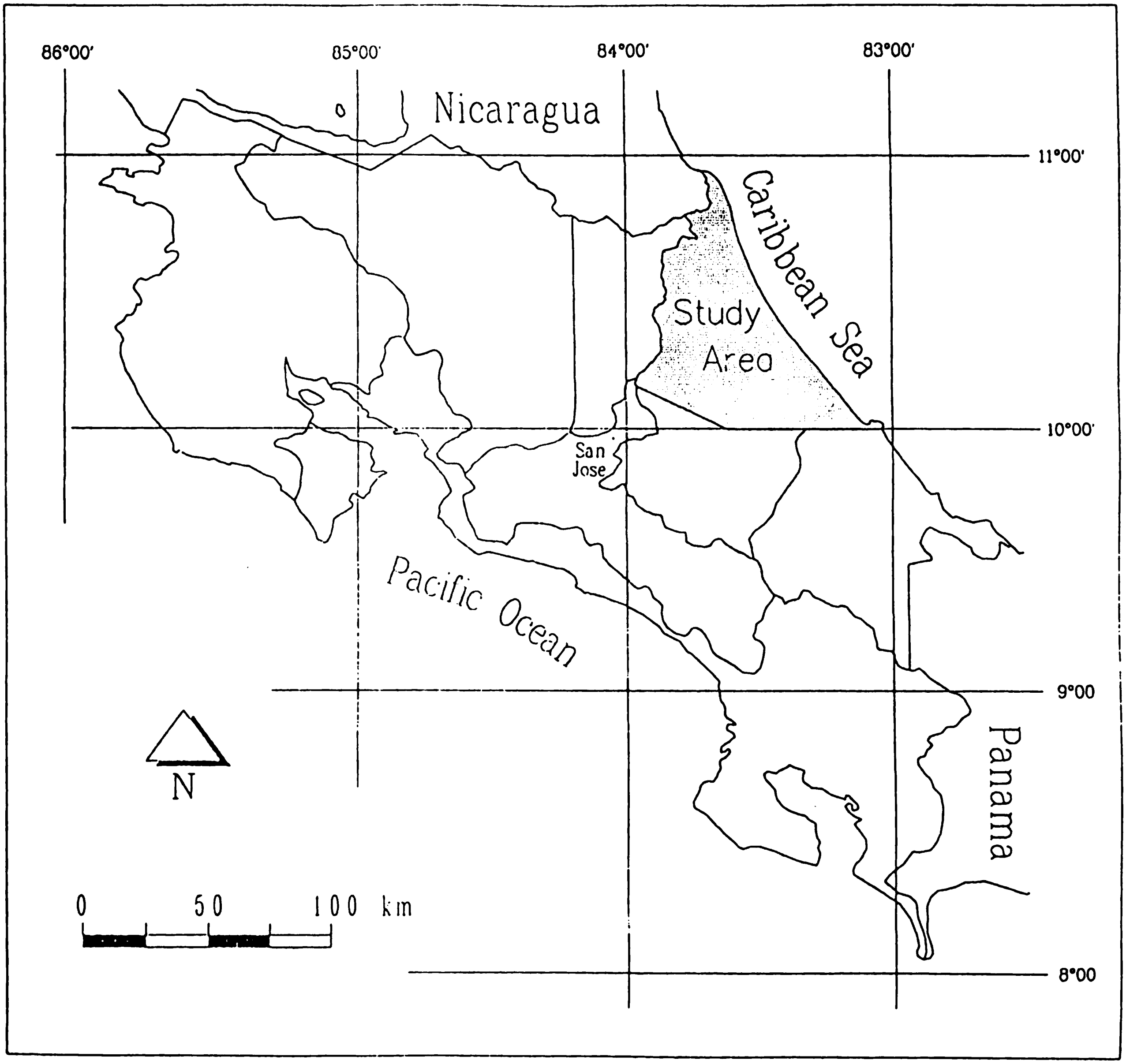
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PREFACE

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.

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.

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ABSTRACT

Growth of a managed natural forest and a forest plantation in the Atlantic Zone of Costa Rica were simulated with the TROPFOR programme and the resulting organic matter flows combined with concentrations of plant components to calculate nutrient flows. 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.

A climate file was constructed with 5 years of actual daily weather data: rainfall, short wave radiation, maximum and minimum temperature, vapour pressure and wind speed. Missing values of short wave radiation were calculated with the Ångström equation, that was adjusted for the Atlantic Zone conditions. A soil file was made with hydrological characteristics for 3 representative soil types occurring in the Atlantic Zone: a well drained young soil (fertile), a poorly drained soil and a well drained old soil of low fertility. A vegetation input file was made with growth characteristics for natural forest and for a teak plantation.

The climate, soil and vegetation files were used as input in the TROPFOR programme, that calculated for each day during 20 years the development of both vegetations: assimilation, maintenance respirations, formation of plant components and litter production and the influence of silvicultural activities on these processes. Simulated productions are the maximum productions that can be expected under current climatic and soil conditions when nutrient supply is not limiting.

Amounts of N, P, K, Ca and Mg needed for the simulated production per year and the amounts of the same elements that are liberated by litter decomposition per year were compared in nutrient balances. Also the inputs by the atmosphere and by weathering were included in these balances, especially to compare these inputs with the exports of nutrients with harvested stemwood.

It was found that the land utilization type (LUT) Managed Natural Forests with light harvests every 20 year can be sustainable on all three soil types from a nutrient point of view, both in the short and in the long run. The LUT Forest Plantation is not sustainable without input of nutrients. Large nutrient deficiencies develop during the first cycle caused by phytomass build-up. High nutrient buffering capacities are needed to take up surpluses and to supply shortages of nutrients caused by the phytomass fluctuations that are much larger in the plantation than in managed natural forest. Even on soils with extremely high nutrient buffering capacities problems will occur in the long run by the export of nutrients with stemwood.

1. PREFACE

In the joint research programme of the international research institute CATIE, the Ministry 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 Plantaciones Forestales (tree 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 in the study.

A main objective of the research programme is to compare different land use scenario's, using linear programming. A good physical description of the different Land Utilization Types (LUT's) is necessary as a basis for the production of these land use scenario's in which also 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.

This study is a first attempt to give answers to these questions. It is done within the project J050-916: "Water and element flows in tropical forest ecosystems" that is part of the VF-programme 94.34: "Sustainable land use in the tropics ". Cooperation in Costa Rica was especially with the AIO research project: "The integration of trees and forests in farming systems and land use planning on regional level in the Atlantic Zone of Costa Rica" by A.C.J. van Leeuwen.

Representative data have been collected on climate and soil of the area around Guapiles in the Atlantic Zone of Costa Rica. Data have also been collected on phytomass and growth of managed natural forest and plantations. Phytomass and growth data are very fragmentary. A complete picture was made with the help of dynamic simulation of forest growth using the model TROPFOR.

Growth of managed natural forest and plantations under optimal mineral nutrient supply was estimated in this way and the nutrient flows that would occur during this growth. Surpluses and shortages of nutrients are discussed with respect to the sustainability of both land uses.

Field work Costa Rica was done in July 1993 and February 1994. All people of the Atlantic Zone Programme are thanked for their support, the supply of data and the pleasant atmosphere, especially Rob Sevenhuysen, Arthur van Leeuwen, Fernando, Olga, Luis, Celia, Don Jansen, Jetse Stoorvogel, Andres Nieuwenhuyse, Margreet Hofstede, Janet Bessembinder. John Belt, Rob Schipper, Huib Hengsdijk, and Erik Schinkel.

2. INTRODUCTION

The Atlantic Zone is a low lying area in the North-east of Costa Rica formed by sedimentation of volcanic material from the Cordillera Central. Several sedimentation phases have occurred, older sediments of mainly Pleistocene age occupy higher positions in the landscape and have undergone strong weathering and soil formation under the prevailing very wet tropical climate. Younger Holocene sediments have undergone less, but a varying amount of weathering and soil formation, depending on age and position. This position is very important. Large flat low lying areas occur that are poorly drained and are overgrown with a swamp forest vegetation under natural conditions. They have undergone less and different soil formation than better drained areas of the same age.

The Atlantic Zone has been largely under dense tropical forest until recently. Population density was low because Costa Rica has other areas with good soil and a more pleasant climate such as the highland around San José. Occupation of the Atlantic Zone has mainly taken place after the Second World War. Main activities were wood extraction from natural forests and establishment of banana plantations. Migration into the area from other parts of Costa Rica and from Nicaragua became very important and pressure on the land increased. Logged over forest land not used for banana came under a multitude of uses: slow transition from forest to extensive grazing land and several agricultural and horticultural uses on the better soils near population centres.

The Atlantic Zone Programme, a cooperation between the international research institute CATIE, the Agricultural University of Wageningen in the Netherlands and the Ministry of Agriculture and Animal Husbandry in Costa Rica, started its work in 1986. Its objective was (and is) to make a multidisciplinary study of the Atlantic Zone aimed at a rational use of the natural resources.

The first years were mainly devoted to data collection and the execution of surveys on natural resources and socio-economic factors. Now, in the second phase, these data are applied in research on land use scenarios. Land and soil data were presented in maps and reports and also in a computerized geographic information system called SIESTA that permits easy storage, retrieval and processing of data and production of maps at any scale (Wielemaker and Vogel, eds, 1993). Also coupling with other (e.g. socio-economic) data bases is possible.

A number of agricultural and forestry land uses have been selected for study by the Programme in the second phase. For forestry they are: managed natural forest, forest plantations and agroforestry. For all land uses data on the following aspects have to be produced to be able to compare them in linear programming of land use scenario's: production, prices, costs, nutrients and sustainability. Sustainability is added to the economic aspects to safeguard the production in the far future. Degradational land uses often have a high production and may be economically very attractive for a short period.

This report deals with production and nutrient cycling of 2 of the 3 mentioned forestry land uses only. Agroforestry is not included as it is not well described in the Atlantic Zone and is therefore difficult to model. Agroforestry (combinations of trees with crops or grassland) in the Atlantic Zone may vary from pure grasslands with life fences of leguminous trees to transitions of natural forests to grasslands whereby the tree component decreases during the years by harvest and death. In Costa Rica the latter example is prevalent.

Managed natural forest and forest plantations in this study are meant to be sustainable land uses. Up to now the natural forests in the Atlantic Zone like elsewhere in the tropics are generally exploited in a non-sustained way, clear cutting followed by agricultural land uses or selective exploitation with no regard for future harvests. In the LUT natural forest as it is studied here, it is assumed that the forest produces a sustained flow of wood and other forest products over a very long period, whereby the forest retains a high biomass and a high biological diversity. Wood is produced by selective felling in a polycyclic production system. The forest plantations are harvested in a monocyclic system (clear-cutting and replanting). Also this land use should be sustainable, i.e. yields of the different cycles should remain at a stable level.

The study consists of 2 parts: 1) determination of the production of managed natural forest and plantation and 2) determination of the nutrient flows that go with it. The production is simulated with the computer program TROPFOR (Poels and Bijker, 1993). To run the program 3 input files were made: a vegetation file with growth characteristics of natural forest and teak, a soil file with infiltration characteristics, Θ - h and K - h relationships for 3 representative soil types and a climate file with actual daily weather data (rainfall, radiation, temperature, air humidity and wind speed) for the years 1983-1987.

The program calculates the maximum production that can be reached under the prevailing climatic and soil conditions under optimum nutrient supply and by absence of pests and diseases. The calculated production is therefore higher than in practice, where often one or more limiting factors apply (nutrient shortage, herbivore attack, disease). However, with good management, it should be possible to approach the calculated production levels. Calculated maximum productions of both the natural forest and the plantation agree reasonably well with the (scarce) data in literature on this subject (e.g. Kira and Ogawa, 1971, UNESCO, 1978, Wolff van Wülfing, 1938 and Jordan, 1983). More information exists on litter fall in undisturbed forests that gives a good approximation of net production (see remarks in Chapter 6). Simulated amounts of litter fall agree reasonably well with data in literature (e.g. UNESCO, 1978 and Burghouts, 1993) especially of fine litter. For coarse woody litter fall it is difficult to acquire good average yearly values because of irregular production of this litter component, that often only takes place during calamities (storms, diseases). During an experiment of several years there may be no coarse litter fall at all at a certain spot. On such a spot the forest is not in a steady state during that period. The phytomass increases there till the next calamity. To establish the steady state a large number of observations over extended areas and during long periods is necessary.

Nutrient flows are calculated from production amounts and nutrient contents of plant components. Literature data on nutrient contents of plant components are very variable. It makes quite a difference whether a young leaf or an old leaf is taken for determination of the nutrient content. The chosen data represent rather the average of the whole component than the (very high) nutrient contents of the youngest parts. From the nutrient flows surpluses and shortages are calculated which are discussed with respect to nutrient buffering capacity, sustainability and fertilizing.

3. SOILS

During soil studies in the Atlantic Zone of Costa Rica 67 soil types were described (Wielemaker and Vogel, eds, 1993). They were grouped in 3 broad classes for the purpose of land evaluation on the basis of drainage and fertility (Table 3.1).

Table 3.1. Soil grouping used by the Atlantic Zone Programme

Group	Description	Representative soil type
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. The groups result from combining numerous soil types (series) that have been described in soil reports by the CATIE/AUW/MAG project and by others. A representative soil type for group I is soil series Los Diamantes (Eutric Hapludand in the American Soil Classification system), for soil type 2 Santa Clara (Andic Aquic Eutropept) and for soil type III Silencio (Andic Oxic Dystropept) or Neguev and Cocorí (Andic Humitropept). Two soil profiles of the Neguev series, described by E. Veldkamp were classified by ISRIC as Tropeptic Haplorthox (ISRIC, 1991). For the forestry LUT's soil group III is most important. These soils generally occur on elevated areas of older (Pleistocene) volcanic sediments, dissected into hills or plateaus, and are well drained, acid, clayey and strongly weathered.

For each of the 3 soil groups a representative set of soil properties is given in Tables 3.2 and 3.3 (Stoorvogel, pers. comm.). Table 3.2 gives general information on average soil properties in the root zone. Table 3.3 gives the Van Genuchten parameters (Van Genuchten, 1980), that are typical for each soil group. With these parameters water contents and conductivities at different soil suctions can be calculated. These relationships are needed in dynamic computer models to simulate the water balance of the soil.

Table 3.2. 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

Table 3.3. 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:

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

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

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

In which h is the soil suction expressed in cm water, Θ(h) is the volumetric soil water content as function of the soil suction, and K(h) is the hydraulic conductivity (cm/d) of the soil as function of the soil suction.

The soil suction h has the dimension of length, it is the suction that results in the soil when a water column of so many cm's hangs under the soil (e.g. a ground-water depth of so many cm's below the point under consideration) and when the soil moisture is in equilibrium with this water column. With such a water column only suctions smaller than 1000 cm can be made, corresponding with a ground-water depth of 10 m. Suctions may be much higher by further desiccation, but although in that case the suction can no longer be acquired by a water column, the suction is still expressed in cm H_2O.

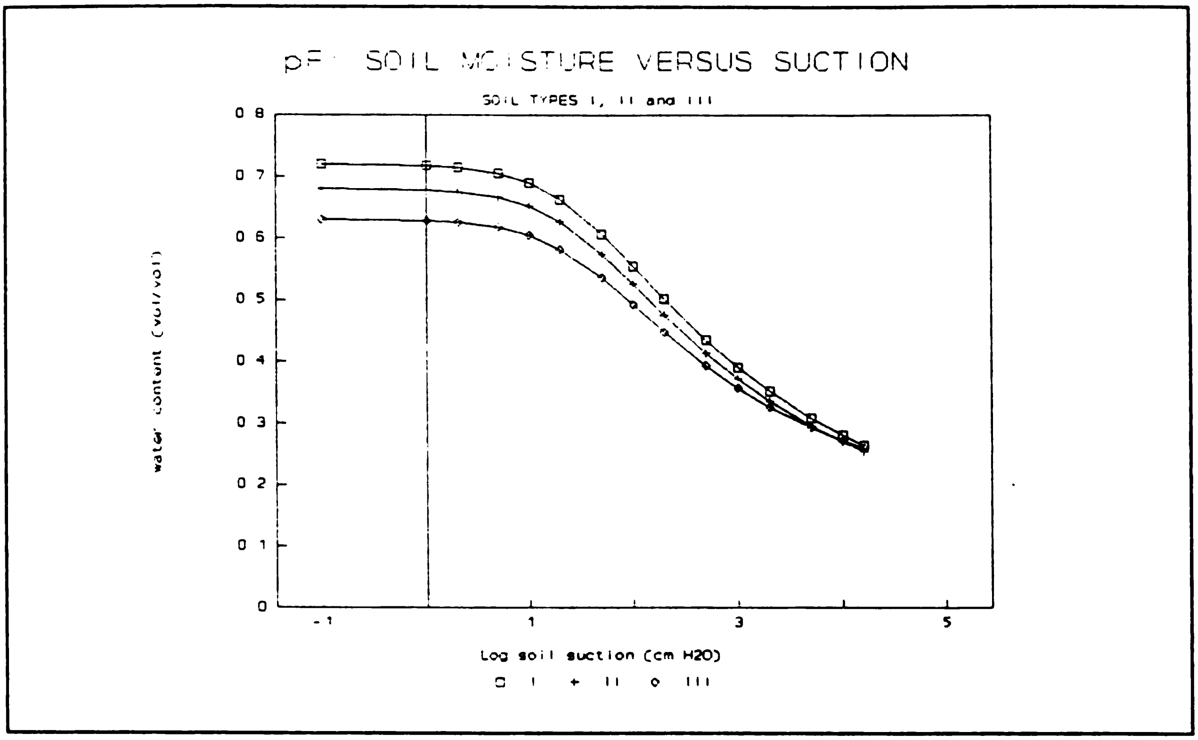

Figure 1. Θ-h relationships for three standard soil groups

The pF and K-h values calculated with these equations from the parameters of Table 3.3 were averaged and shown in Table 3.4 and Figs. 1 and 2. The graphs are very regular because of their construction from the Van Genuchten parameters. These average values will be considered representative for the different soil groups and used in the simulation program of forest growth.

Table 3.4. 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

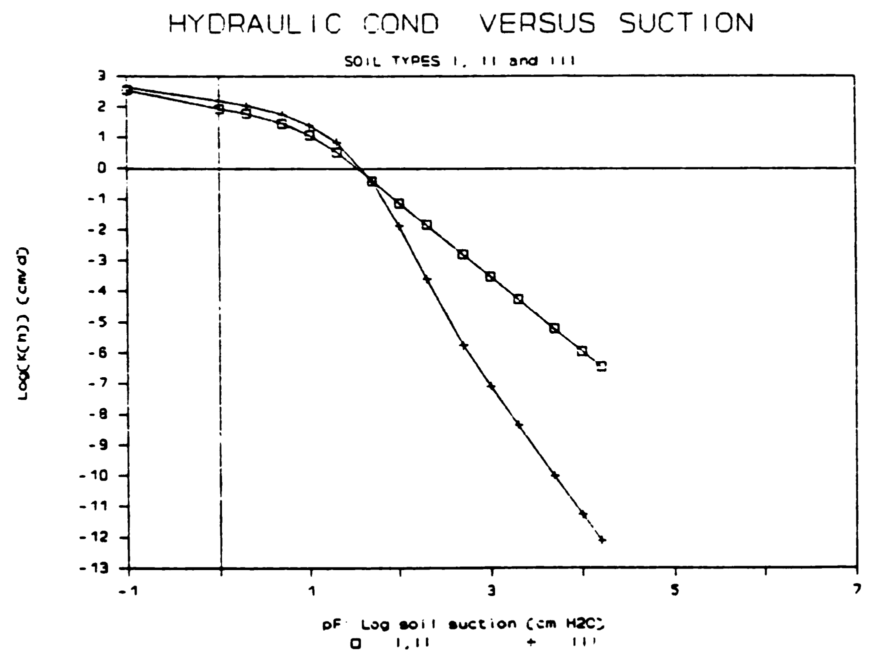

Figure 2. K-h relationships for three standard soil groups

The table and figures clearly show 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 Pleistocene 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 texture, reaching much lower levels than in the other 2 soil types.

4. CLIMATE

4.1. Preparation of a climate input file for computer simulation of forest growth

TROPFOR needs daily data of rainfall, short wave radiation, maximum and minimum temperature, average vapour pressure and average wind speed.

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), 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 C. Herrera-Reyes (pers. comm) for the Atlantic Zone Programme.

The collected data are very divers. Sometimes only temperature or rainfall data are available. 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 most extensive and complete data are available for meteo station Los Diamantes at Guapiles and it was decided to prepare a climate input file for TROPFOR of a period of 5 years in which both (relatively) dry and wet years occur. The chosen period was initially 1982 - 1986. Later it was shifted to 1983-1987. 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. Main problems for the preparation of the climate input file were therefore the calculation of short wave radiation and wind data.

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

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

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 (day length)
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 other wet tropical stations.

To determine the A and B values for Los Diamantes, all days between 1971 and 1986 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 exercise for the nearby station of Cobal. 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.

It would appear, therefore, that different A and B values apply for the very wet climate of Guapiles than those given in literature. This could be possible, as of the examples given in literature, e.g. in Keulen and Wolf (1986), none of the wet tropical stations have

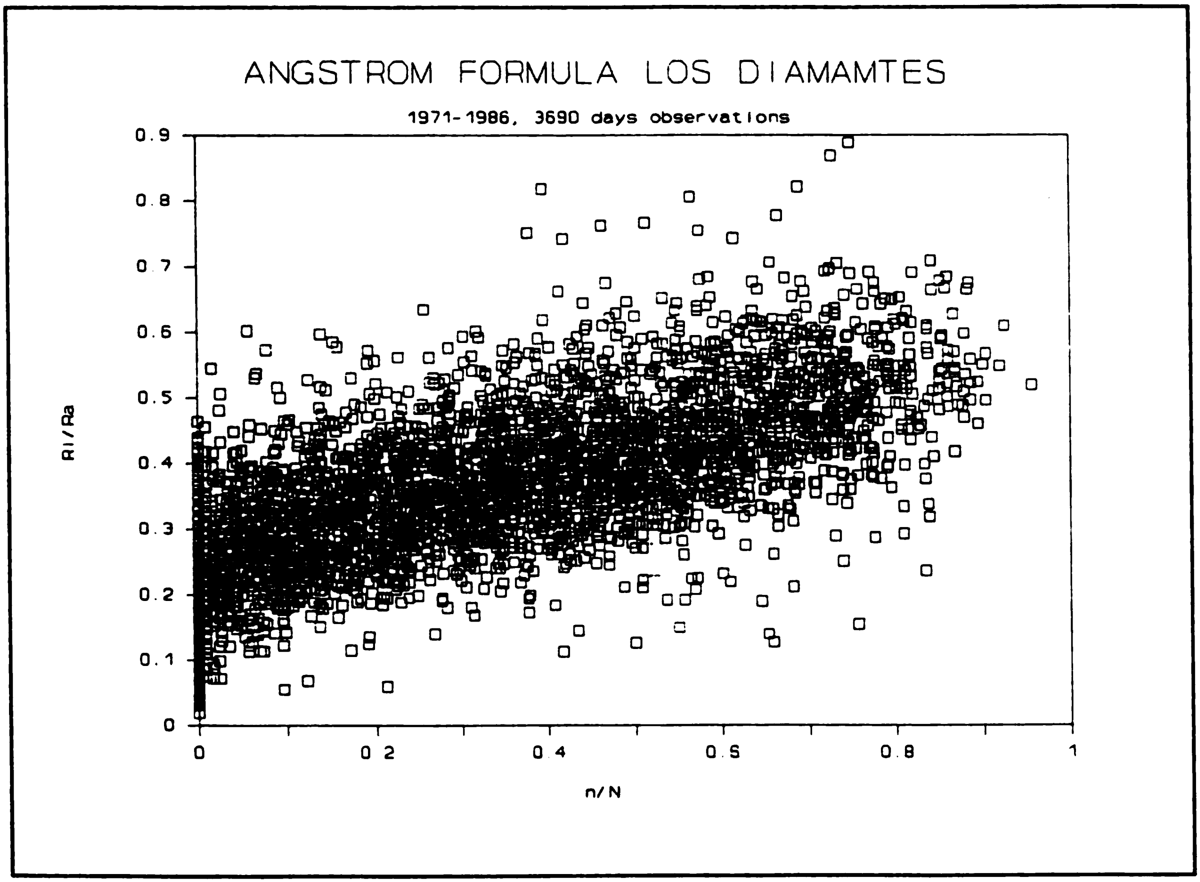

Figure 3. Relationship between short wave radiation and sunshine for the period 1971-1986

climates as wet as that of Guapiles. They generally have yearly rainfalls around 2000 mm with a more or less pronounced dry season. The lower A and B values in the Ångström equation for the Guapiles area compared to that of many other wet tropical regions could be caused by the higher air humidity and lower radiation levels in the Atlantic Zone.

With 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 from the daily sunshine hours.

Analyzing the resulting data, some doubts arose on the quality of the radiation data for the different years. When calculating A and B values for different periods discrepancies occurred that could not be explained. The calculated A and B values in the first phase for the different periods are given in Table 4.1, upper part. Low values for A and B are found for the years 1971-1982 and higher values for the period 1983-1986. This must be due to a systematic difference in the measurement method or elaboration of the direct radiation data.

Table 4.1. Average number of sunshine hours (n) and calculated A and B values of the Ångström equation for different periods for the Los Diamantes meteorological station

Period	No of observations	n	A	B	R^2
1971-1975	711	4.1	0.24	0.36	0.66
1976-1979	1068	4.1	0.24	0.33	0.56
1980-1982	733	4.0	0.20	0.39	0.53
1983-1986	1178	3.5	0.25	0.42	0.48
1971-1986 (whole period)	3690	3.9	0.24	0.37	0.51
1983	117	3.0	0.24	0.40	0.71
1984	346	3.4	0.27	0.47	0.68
1985	353	3.9	0.31	0.45	0.71
1986	362	3.5	0.29	0.46	0.71
1987	98	4.2	0.29	0.42	0.73
1983-1987 (whole period)	1276	3.6	0.283	0.459	0.69

The large differences in A and B values between 1983-86 and the earlier periods led to the conclusion that it was not right to use the average values of A and B for the whole period (0.24 and 0.37) for the period under study (1982-86). Additional factors such as the extremely low vapour pressure data for 1982 and the fact that corrected meteo data for 1983 and 84 came available with higher radiation levels, led to the conclusion that the Ångström equation was to be calculated again and that the study period should be shifted from 82-86 to 83-73.

It is now assumed that the radiation data for the beginning period (1971-1982) are too low resulting in these low A and B values and that the data for the period after 1982 are more reliable.

The newly calculated A and B values for 1983-1987 are given in the lower part of Table 4.1. They are considered more reliable to calculate the short wave radiation, not only because of more reliable radiation data but also because they were calculated from the same period for which they will be applied, eliminating changes in measurement and calculating techniques during the years. The regression between n/N and Ri/Ra for the period 83-87 is shown in Fig. 4. The relationship is better than that of Fig. 3 for the whole period. A and

B values are much higher than in earlier calculations over the period 1971-1986. This is caused by the higher radiation values of the later period and also by the lower number of sunshine hours that were determined with Campbell Stokes paper strips in the later period.

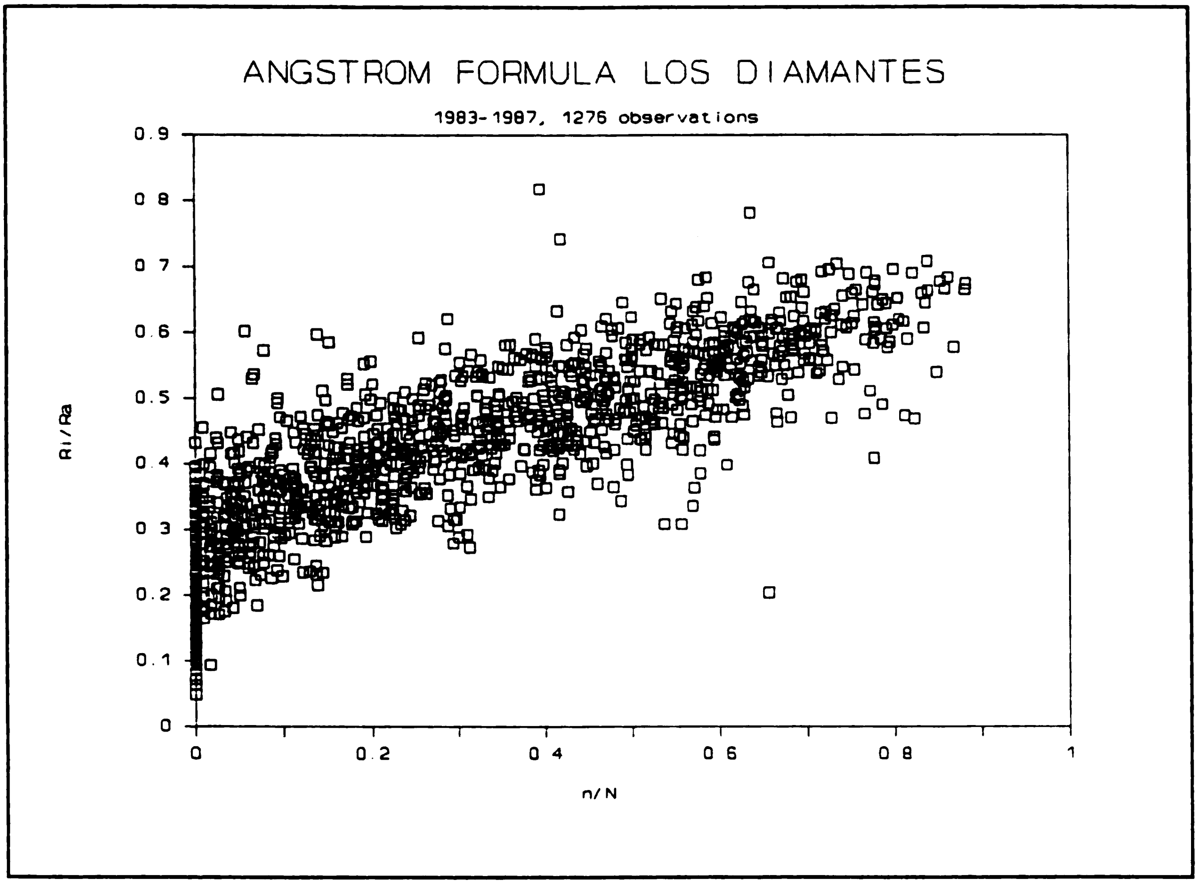

Figure 4. Relationship between short wave radiation and sunshine for the period 1983-1987

In the climate input file CLIMDIAM.DAT the directly measured radiation data were placed in sofar they were available, the missing values were calculated with the Ångström equation from the sunshine hours, the day length and the A and B values 0.283 and 0.459.

Maximum and minimum temperature data and sunshine duration data were practically complete for the whole period. For the missing data (less than 0.2 %) estimated values were introduced. The same applies for the vapour pressure data at 7, 13 and 18 hours every day. The averages of these 3 values were taken for CLIMDIAM.DAT.

Wind data are very scarce in the Atlantic Zone. For Diamantes they exist only for part of the year 1986. For Cobal, 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.

Summarizing the above information, the climate input file CLIMDIAM.DAT was constructed as input file for TROPFOR as follows: Daily data of Los Diamantes for 1983 - 1987 were taken. Rainfall data were taken directly from the source files. Short wave radiation was taken directly from measured values or (when missing) calculated from sunshine hours with the Ångström equation using 0.283 and 0.459 for A and B. Maximum and minimum temperatures were taken directly from the source files. Vapour pressure in the file is the average of the 3 measured values at 7, 13 and 18 hours. For wind data the averages of the Cobal station for 1974-76 were used. For the days for which wind data exist in the Los Diamantes file the Los Diamantes data were used.

4.2. The climate of Guapiles

The structure of the climate input file CLIMDIAM.DAT, prepared as documented in Chapter 3.1, is given in Table 4.2. A complete listing of this 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 and the average yearly data in Table 4.3.

Table 4.2. Fragment of the input file for daily climatic data CLIMDIAM.DAT

CLIMDIAM.DAT: NEW CLIMATE INPUT FILE FOR GUAPILES
PREPARED FROM DIA8387.WK1

Date	Julian day	Rain mm/d	Avrad MJ/m2.d	Tmax °C	Tmin °C	Vapp mbar	Wind m/s
1826 *)							
830101	1	6.5	14.689	27.4	18.2	24.27	0.72
830102	2	0.4	9.945	28.2	20.0	25.83	0.99
830103	3	3.2	15.724	28.3	17.5	25.00	0.89
830104	4	7.2	13.358	28.2	21.0	26.47	0.75
830105	5	2.6	9.480	26.8	20.2	24.90	0.74
830106	6	4.2	16.917	28.5	20.5	25.37	0.97
830107	7	17.0	9.508	27.5	20.2	26.20	1.01
830108	8	5.2	12.803	27.2	22.0	27.77	0.85
830109	9	1.0	13.581	27.5	21.3	26.67	0.91
830110	10	1.2	18.915	29.7	20.9	26.63	0.90
830111	11	4.7	14.260	28.0	22.0	27.27	0.82
830112	12	0.5	12.382	27.5	18.8	25.30	1.03
830113	13	100.8	8.975	23.5	18.5	23.73	1.09
830114	14	40.9	8.993	23.2	19.6	24.87	1.06
830115	15	59.3	9.012	22.7	20.0	24.07	0.92
830116	16	41.6	9.031	21.0	19.2	21.93	0.83
830117	17	0.3	9.051	23.9	18.7	23.20	0.94
830118	18	5.7	11.250	26.3	19.0	25.50	1.15
830119	19	0.0	11.532	28.2	20.2	25.30	1.03
830120	20	0.0	16.059	28.7	19.3	24.90	0.69
830121	21	0.0	20.605	30.2	18.7	26.47	0.88

*) No of lines in file
Rain: rainfall
Avrad: short wave radiation
Tmax: maximum temperature
Tmin: minimum temperature
Vapp: actual average vapour pressure
Wind: average wind speed

Table 4.3 shows that the years 1983 and 1987 are wet and 1985 and 1986 relatively dry. The average short wave radiation level of 15 MJ/m^2.d is low compared to that of Suriname (18.7 MJ/m^2.d) and also temperatures are slightly lower in Guapiles.

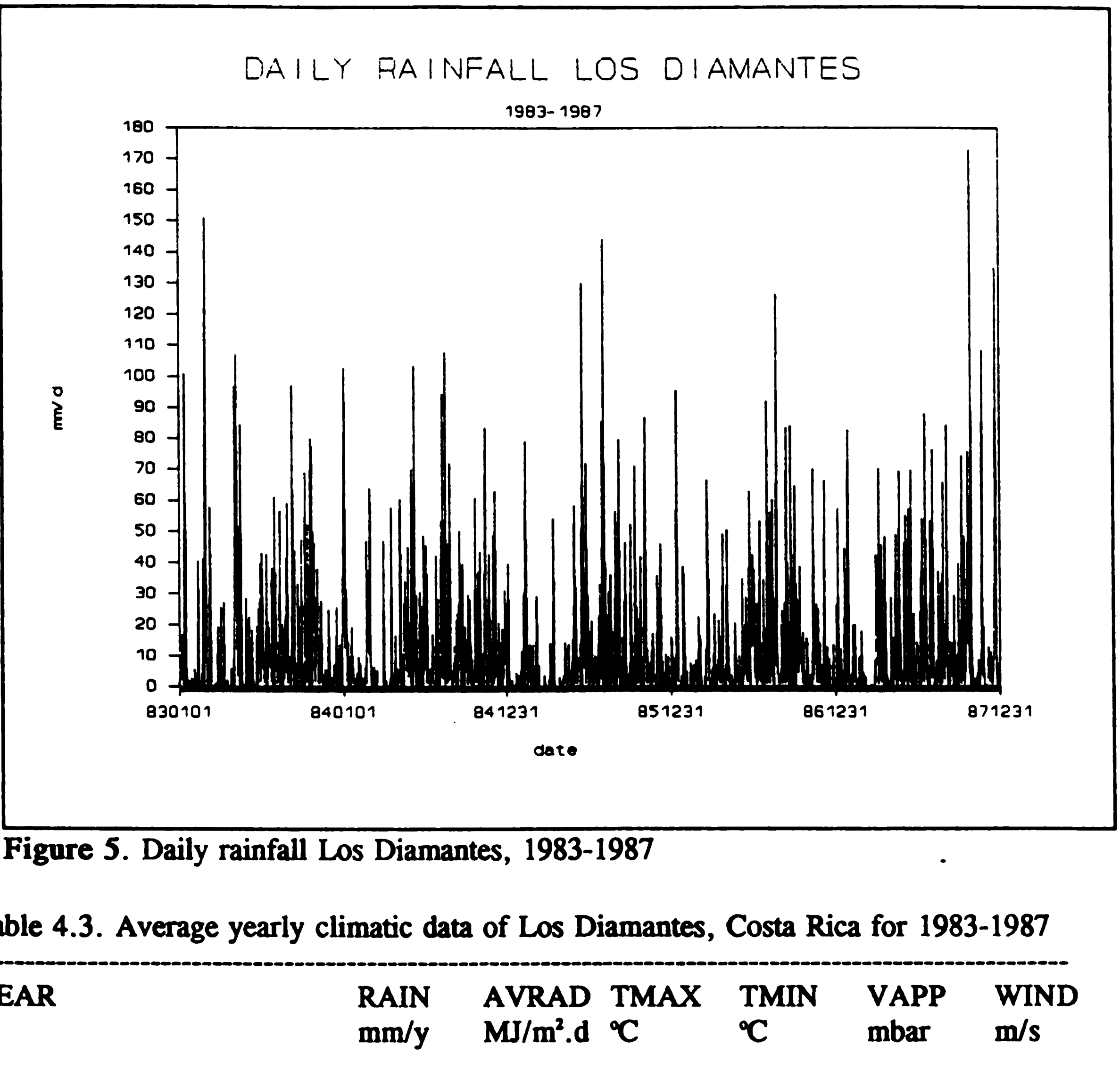

Figure 5. Daily rainfall Los Diamantes, 1983-1987

Table 4.3. Average yearly climatic data of Los Diamantes, Costa Rica for 1983-1987

YEAR	RAIN mm/y	AVRAD MJ/m².d	TMAX °C	TMIN °C	VAPP mbar	WIND m/s
1983	4301	14.6	29.1	20.8	27.2	0.9
1984	4038	14.5	28.4	19.8	25.6	0.9
1985	3436	16.2	28.2	19.6	25.3	0.9
1986	3920	15.0	28.0	19.9	25.9	1.0
1987	4244	14.5	28.5	20.8	26.7	0.9
AVERAGE	3988	15.0	28.4	20.2	26.1	0.9
Average Suriname	2150	18.7	31.8	22.4	27.7	1.2

For detailed work the year 1983 is chosen as representative for a wet year and 1985 to represent a relatively dry year.

Daily rainfall, short wave radiation, temperatures (max and min), average vapour pressure and wind speed are shown in Figs. 5-9. Fig. 5 shows that during these 5 years no really dry period occurred. There is a periodicity in rainfall, the first months of the year being

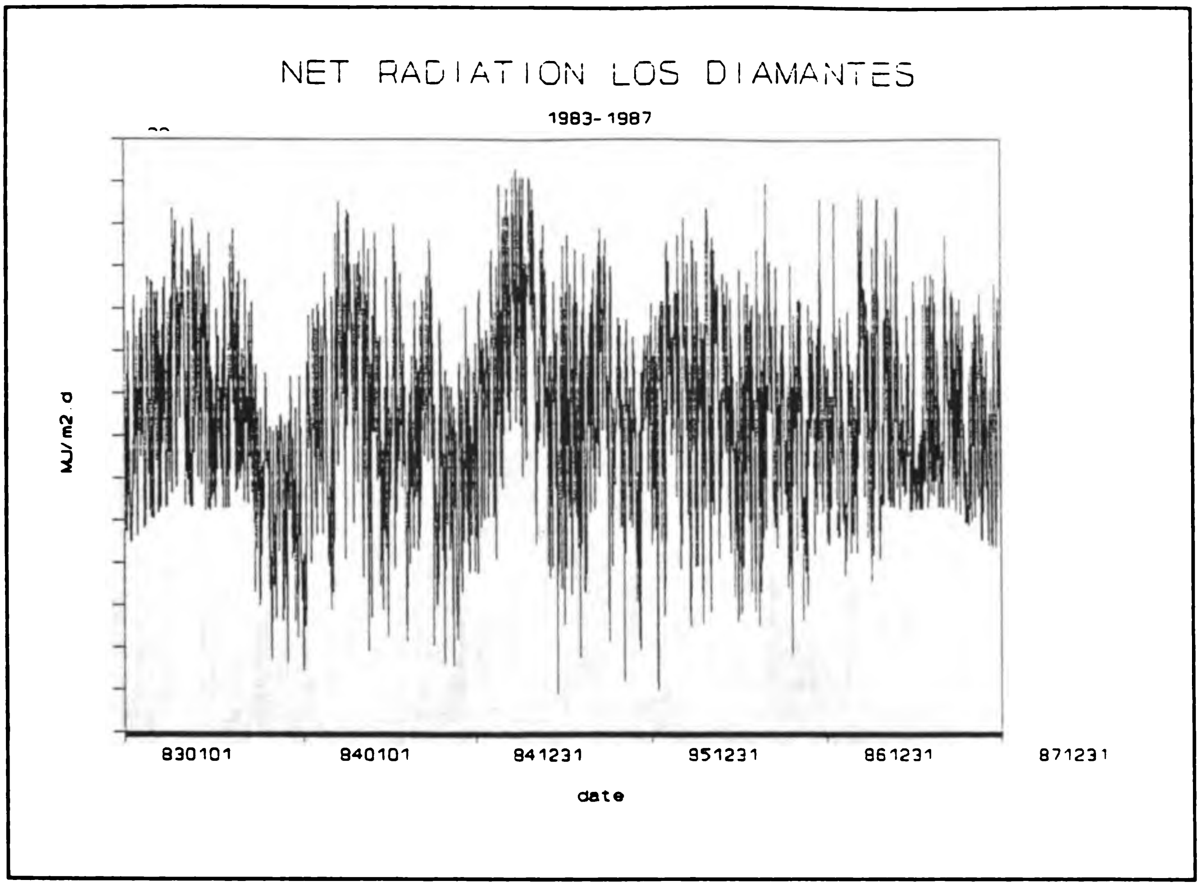

Figure 6. Daily short wave radiation Los Diamantes, 1983-1987

somewhat drier than the remainder of the year, but the number of consecutive days without rain is never large. The maximum rainfall in one day is 173 mm at the end of 1987, and in every of the 5 years under consideration the maximum rainfall in one day was higher than 100 mm. These rainfall amounts set large demands on the capacity of a drainage system in level land, e.g. when swamp forest is to be transformed to agricultural or plantation forest use. The lowest monthly rainfall was 52 mm in February 1986, but this month was preceded and followed by months with more than 300 mm rainfall (Appendix I).

Radiation levels (Fig. 6) oscillate around 15 MJ/m^2.d, lowest values occurring around November and highest around March. In some years no clear trends are visible. Because of the difficulties in establishing the Ångström equation, comparisons were made with other tropical stations to see whether the given radiations levels lie within acceptable limits. Van Keulen and Wolf (1986) gave short wave radiation levels for several tropical lowland stations. They varied between 17.5 (Abidjan, Ivory Coast) and 20 MJ/m^2.d (Mombasa). Poels (1987) gives for Zanderij, Suriname 18.7 MJ/m^2.d. For Altamira, Costa Rica, in the Northern plain where a pronounced dry season occurs and the average yearly rainfall is 3000 mm, Poels (1994b) calculated an average value of 16.2 MJ/m^2.d. Guapiles, having no dry season and the highest rainfall of all studied stations, is expected to have the lowest short wave radiation level of all. Therefore, the average value of 15.0 MJ/m^2.d for the period 1983-1987 could well be correct.

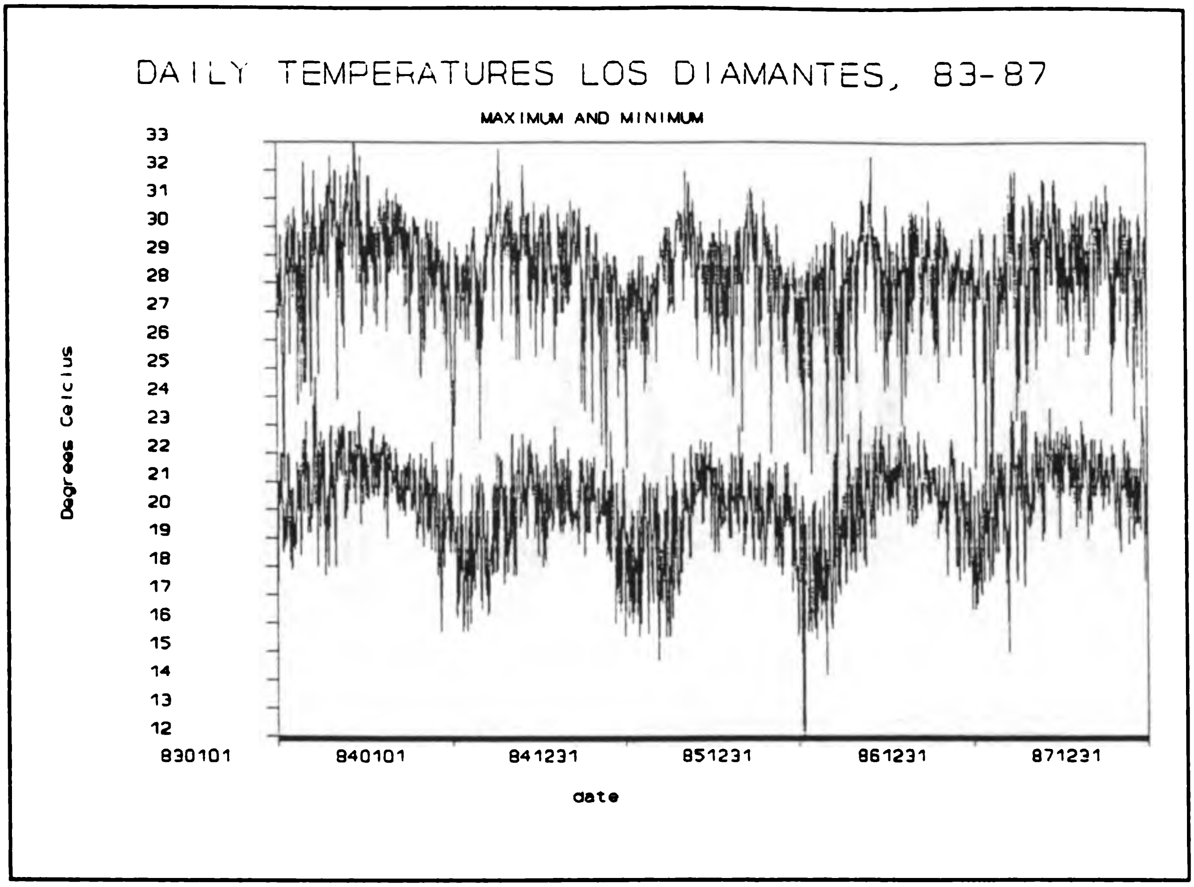

Figure 7. Daily maximum and minimum temperatures, Los Diamantes, 1983-1987

There is a weak positive correlation of radiation with temperature (Fig. 7), but the temperature changes follow the radiation changes with some delay as can be expected. A seasonal trend is also seen in vapour pressure and wind speed (Figs. 8 and 9). Higher temperatures give higher vapour pressures as then the capacity of the air to take up water is larger and there is nearly always enough water available. Therefore, relative humidities are rather constant, average daily values varying between 80 and 90 %, and daytime values between 70 (around March) and 80 % (around August). The relative humidities (not shown here) may be calculated as the quotient between VAPP (vapour pressure) and SVAPP (saturated vapour pressure) respectively at the average daily and the average daytime temperature.

Average daily wind speeds are highest during the first months of the year, but they are nearly always low, around 1 m/s (Fig. 9). It is well known that daytime wind speeds are higher, wind speeds increasing during the day and dropping in the evening, but no exact data exist on daytime wind speeds. For the time being it is assumed that the daytime wind speed, which is of importance for the calculation of water use by a vegetation, is 1.6 times the average daily wind speed, following the experience in Suriname (Poels, 1987). In the year 1986 wind speeds seem to oscillate stronger that during the other years. The reason is that during 1986 wind data exist for Los Diamantes. For the other years values of Cobal have been used whereby data over more years were averaged resulting in a smoothing effect.

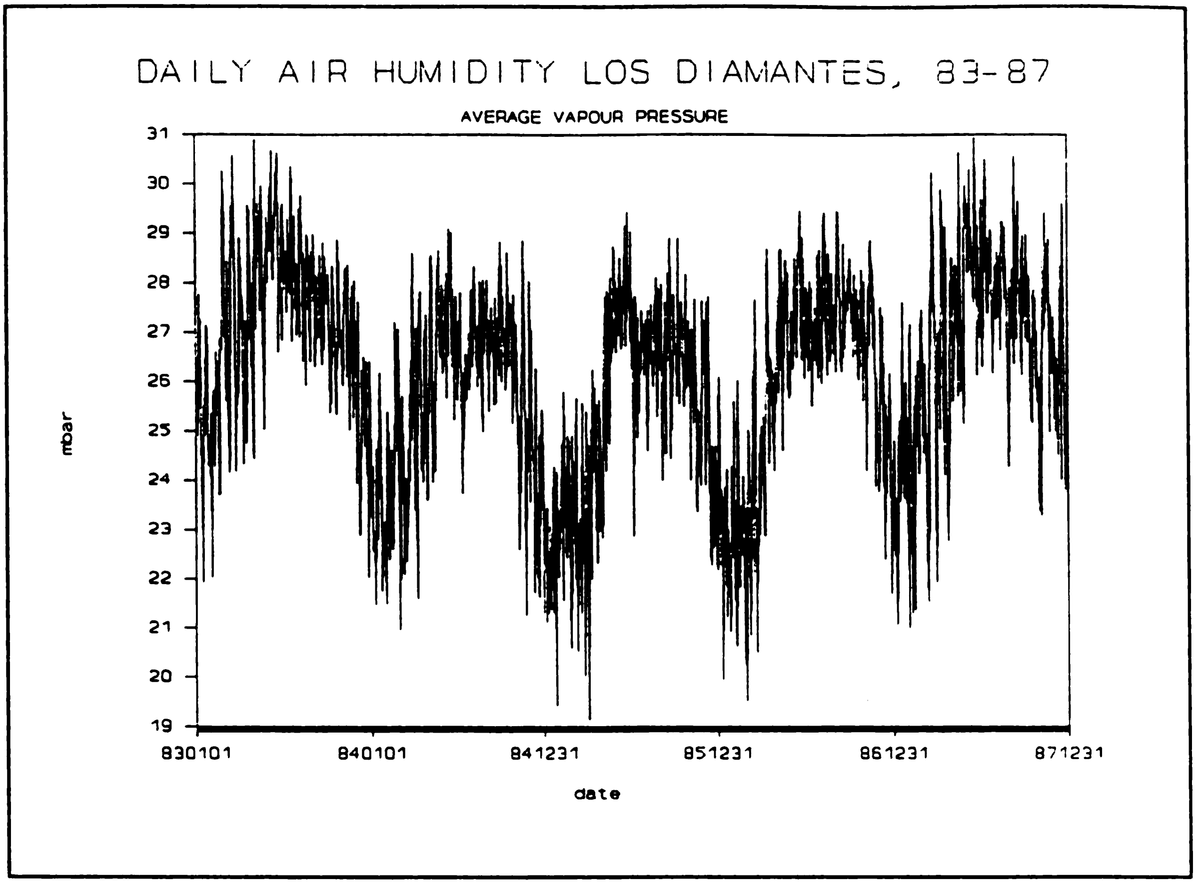

Figure 8. Average daily vapour pressures Los Diamantes, 1983-1987

5. VEGETATION

5.1. Tropical lowland rain forest

Vegetation characteristics of tropical lowland rain forest for use in TROPFOR are stored in the vegetation input file CROP41.DAT (Appendix III). 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, being higher in the Atlantic Zone of Costa Rica than in Suriname. As a consequence, nutrient concentrations in the forest vegetation are higher and root biomass relatively lower. The wetter climate and the more clayey soil (Soil III) in the Atlantic Zone result 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):

$$MRR = 0.04 * \text{protein} + 0.08 * \text{minerals}$$

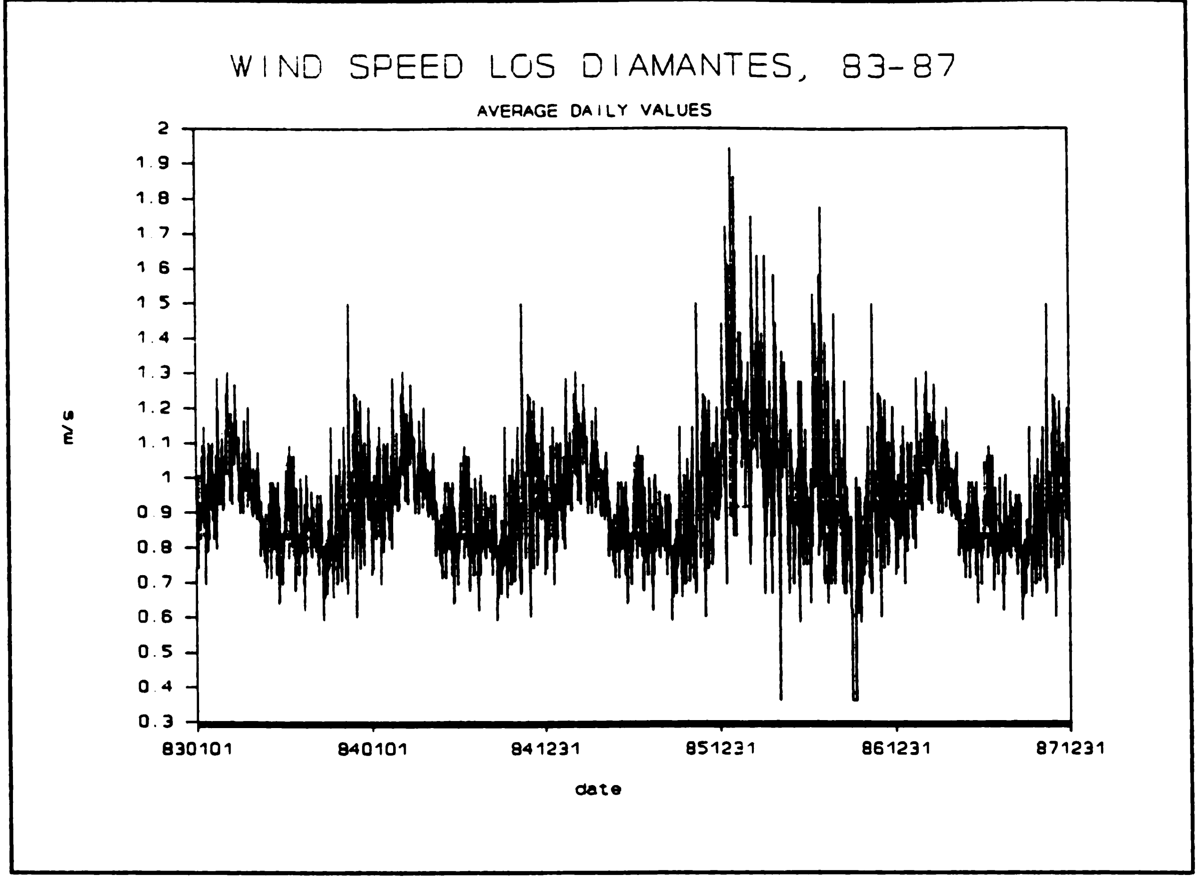

Figure 9. Average wind speeds Cobal (83, 84, 85 and 87) and Los Diamantes (1986)

Average N-content of the leaves in Suriname is 1.33 % and in La Selva 1.5 % (Osinga, 1993) 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.

Also death rates of plant components are influenced by soil fertility. Generally death rates increase at higher fertility levels. Osinga (1993) found from literature (Breitsprecher & Bethel, 1990) higher death rates than those of the Kabo forest. This is understandable as with higher growth rates climax amounts are reached sooner and a higher biomass increases the vulnerability for wind throw.

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 losses that are expected to occur during extraction and processing of the wood. Some data are given below. Kapp et al. (1992) give 128 m^3 commercial volume (DBH >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 DBH (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 Cocorí 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 an average dry wood density of $0.6\ t/m^3$ (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 220 t/ha. From this, the other phytomass amounts are estimated (Table 5.1), using ratios from the Kabo forest of Suriname (Poels, 1987).

These maximum amounts were introduced into the model to simulate the climax concept of the forest. This concept means that there exists a maximum forest biomass typical for each situation, depending on the forces of building/production and decay/consumption. This maximum forest biomass is influenced positively by a favourable climate, a fertile soil, absence of hurricanes, a stable soil structure and good drainage (good foothold), a low herbivory pressure and possibly some other factors.

As the living biomass increases, also maintenance respiration becomes larger. The difference between production and consumption of assimilates becomes smaller, resulting in a ever slower grow rate. On top of that, mortality increases when trees become very large. Very large trees are more prone to be blown down, at a certain moment vitality decreases and the trees may become hollow or attacked by pests and diseases. To simulate this effect, increased mortality rates have been introduced into the model that become active when the maximum or climax weight of a biomass component has been reached.

Table 5.1. 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
Flowers, seeds	1	-	1
Root	30	50	80
	---	---	---
Total	151	255	406

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 (the effect of self shadowing) and when leaves surpass their 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 litter (of stem, branch and root) 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 transforms 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 (Table 5.1). When these have been reached, increased rates of heartwood move to the woody litter compartments.

Transpiration is calculated with the Penman/Monteith equation (Monteith, 1973). For managed natural forest a zero plane displacement of 30 m and a roughness length of 5 m are assumed. The bulk canopy resistance to water vapour export or the combined resistance of the stomata to transport of water to the surface of the leaves was set at 115 s/m (Poels and Bijker, 1993) for the condition of a dry canopy and a soil well supplied with water (pF < 3.5).

5.2. Forest plantation

Different species may be used to be grown in forest plantations, both local and exotic. In Costa Rica the most important species is teak (Tectona grandis), which is an exotic tree originating from South-East Asia (Birma, Thailand, India, Indonesia). This tree is chosen to be representative for the forest plantation in this simulation exercise, not only because it is the most important species but also because it is the only species for which some data are available on growth and nutrient composition.

Teak originates from tropical lowland areas with a pronounced dry season. It may therefore better be suited for the somewhat drier areas of Costa Rica. The climate of Guapiles is continuously wet in most years. The advantage is a longer growing season with possibly a higher production compared to areas that experience a dry season. However, it is said that teak could suffer from pests and diseases in a continuously wet climate and produce a lower quality (less dense) wood. The future will learn, teak planting in the Guapiles region has started only a few years ago.

It may therefore be possible that for the Guapiles region other species are more adapted and that for teak planting areas in Northern and Western Costa Rica are more suited. For the simulation we have chosen for teak because of reasons mentioned before and we assume that other species have the same growth characteristics, until data become available that prove otherwise.

In the Costa Rican situation plantations of teak and other species are generally planted in man-made grasslands for extensive cattle grazing that followed the natural forest. Deforestation has slowed down lately because of limited forest left and government restrictions. The remaining natural forest is partly protected and partly destined for sustained management. Conversion of natural forest to plantations is generally not allowed. Because of this situation we consider the forest plantation only after grassland. After forest the nutritional situation of the plantation would be much more favourable because of the nutrients in the natural forest phytomass that become available after destruction of the forest.

In Appendix III, second part, 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. More assimilates go to roots and less to branches during the development phase. Initial phytomass is set at 360 kg/ha (weight of the stumps). A main difference with the natural forest is also the higher maintenance respiration rate of the leaves, 0.077 versus 0.069, caused by a higher N-content (1.8 % versus 1.5 %, Hase, 1981). The build-up of leaf biomass is restricted during the first 5 years to simulate the situation of slowly increasing canopy cover. After that period, canopy cover is considered to be 100 %.

For the calculation of transpiration with the Penman/Monteith equation (Monteith, 1973) a zero plane displacement of 10 m, a roughness length of 0.5 m and a bulk canopy resistance of 115 s/m are assumed for the teak plantation.

6. SIMULATION OF UNDISTURBED FOREST

Growth of the undisturbed forest was simulated for period of 10 years, using the climatic data of Los Diamantes for the period 1983-1987 twice as input file. At the beginning of the simulation living phytomass and heartwood amounts were set at near climax amounts and the flows that occurred during the simulation were recorded.

These flows consisted of assimilation, of maintenance respiration losses (Mres) which are considerable because of the extremely high living phytomass and of transfers of living and heartwood components to the litter compartments (Table 6.1).

Table 6.1. Phytomass amounts and flows in undisturbed natural forest during a simulation period of 10 years (t/ha)

	Amounts at start	Net assimilation	Mres	Litt	Amounts at end
Leaf	11.0			65.0	11.5
Branch				66.8	
sapw.	35.0				34.9
heartw.	55.0				54.6
Stem				91.6	
sapw.	70.0				69.5
heartw.	150.0				148.8
Flowers, seed	1.0			2.3	1.1
Roots				100.0	
sapw.	30.0				29.7
heartw.	50.0				49.9
Total	402.0	820.9	497.2	325.7	400.0

Gross assimilation during the 10 years was 1140.2 t/ha, this was converted to 820.9 t/ha plant components by which 319.3 t conversion losses or growth respiration losses occurred (28 %). Maintenance respiration losses are 497.2 t/ha leaving 323.7 t/ha for dry matter increase or 32.4 t/ha.y. This dry matter passes through the living biomass, partly also through the heartwood phase, ending up as litter.

The calculated production is the production that can be expected in the Guapiles area on deep well drained soils when nutrients are not limiting. Also water was not limiting during the period 1983-1987, that was used as climatic input. As a result of these very favourable conditions the simulated production is very high but in line with data from literature (see also Chapter 2). UNESCO (1978) reports of net primary productions of around 30 t/ha.y for selected rain forests in Zaire and Thailand, of leaf litter fall of 5-8 t/ha.y and of total fine litter of around 12 t/ha.y. According to Jordan (1983) net primary production of tropical rain forests vary from 10-35 t/ha.y.

7. SIMULATION OF NATURAL FOREST UNDER POLYCYCLIC MANAGEMENT

Natural forest under polycyclic management is meant to be a sustainable land use in which the natural forest is altered as little as possible. In this land use system light harvests of high quality stemwood take place every 20 - 30 years. Small additional interferences are carried out to direct part of the growing capacity of the forest in a desired direction. The phytomass is are lower and phytomass fluctuations larger than in the undisturbed situation, but phytomass and nutrient stocks do not decrease in the long run.

The following situation will be simulated. An 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, for instance by using inventory maps, planning extraction roads, and employing direction felling and winching where possible and useful. For damage controlled exploitation methods, see Hendrison, 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 silvicultural treatment. 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 this treatment but killed 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 treatment kills approximately 40 % of the remaining phytomass (Table 7.1).

After 10 years a second treatment is carried out to speed up the growth of the desirable trees again, as the growing speed is declining by a high phytomass. Hereby also approximately 40 % of the phytomass will be killed. After 20 years a new harvest should be possible. Two harvest levels are considered, the normal yield of 25 m^3 and a double yield of 50 m^3, which might be possible in good forests with a high percentage of valuable trees. In Costa Rica such forests occur, like those dominated by Carapa guianensis. The mentioned yields should be sustainable, i.e. repeatable every 20 years without deterioration of the forest.

Also in very rich forests harvest levels should be limited to the mentioned 25 to 50 m^3/ha avoid too much damage to the remaining stand. The 2 levels of exploitation and treatnent are given in Table 7.1. When the harvest (exploitation) level is higher, the following treatment is slighter lighter.

Table 7.1. Phytomass changes as a result of initial exploitation and silvicultural treatment

	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 1:						
Living	2.0	7	9	3	0.2	21.2
Heartwood	-	10	17	6	-	33.0
Total:	2.0	17	26	9	0.2	54.2
Killed by exploitation 2:						
Living	4.0	14	18	6	0.4	42.4
Heartwood	-	20	34	12	-	66.0
Total:	4.0	34	52	18	0.4	108.4
Killed by silvicultural treatment 1:						
Living	3.6	11	24	11	0.3	49.9
Heartwood	-	18	55	18	-	91
Total:	3.6	29	79	29	0.3	140.9
Killed by silvicultural treatment 2:						
Living	2.8	8	21	10	0.2	42.0
Heartwood	-	14	46	15	-	75
Total:	2.8	22	67	25	0.2	117.0
After treatment 1:						
Living	5.4	17	37	16	0.5	75.9
Heartwood	-	27	78	26	-	131.0
Total:	5.4	44	115	42	0.5	206.9
After treatment 2:						
Living	4.2	13	31	14	0.4	62.6
Heartwood	-	21	70	23	-	114.0
Total:	4.2	34	101	37	0.4	176.6

The situation after treatment is the starting point for the simulation of forest growth. Forest characteristics as given in Appendix III (first part) were introduced and the soil characteristics from Appendix II (Costa Rica III, low fertility, well drained). This forest on this soil was subjected to the daily climatic data from Los Diamantes (Table 4.2). Growth was driven by solar radiation and the water supply was calculated from the water balance. Table 7.2 gives the course of the phytomass build up during the years for silvicultural treatment 1 with low exploitation level (25 m^3/ha).

Table 7.2. Development of phytomass (t/ha) in treated natural forest after light exploitation (25 m^3) and silvicultural treatment in year 0 and 10

Year	Leaf	branch	stem	root	flowers seeds	total
-1	11.0	90	220	80	1	402
0	5.4	44	115	42	0.5	207
1	11.4	51	126	54	0.7	243
2	11.5	57	136	61	0.8	266
3	11.5	63	147	67	1.0	290
4	11.5	67	156	72	1.0	308
5	11.5	69	163	77	1.0	322
6	11.3	72	171	79	1.0	334
7	11.5	74	179	80	1.0	346
8	11.5	77	188	80	1.1	358
9	11.5	80	196	79	1.1	368
10 a	11.5	82	204	80	1.1	379
10 b	6.9	49	122	48	0.6	226
11	11.4	56	133	58	0.8	259
12	11.5	61	143	66	0.9	282
13	11.6	66	153	71	1.0	303
14	11.6	69	161	77	1.0	320
15	11.5	72	169	80	1.0	334
16	11.4	74	178	79	1.0	343
17	11.5	77	185	79	1.0	354
18	11.6	80	194	80	1.1	367
19	11.6	82	202	79	1.1	376
20	11.5	85	210	80	1.1	388

A second silvicultural treatment in or near year 10 is necessary to make new room for phytomass, i.c. stemwood increases. When all large trees are of commercial species and have a good form, this treatment is not necessary as the large trees always get most of the increment. Generally this is not the case. A large part of the phytomass often consists of trees of non-valuable species or of low quality stems of valuable species (hollow, rotten, badly formed). In such a situation the value of the stand can be improved by the treatment.

Regular silvicultural treatments that keep the phytomass considerably below the maximum (climax) weights result in lower maintenance respiration and death rates. A negative aspects of heavy silvicultural treatments is the irregular addition of litter to the forest floor causing irregular nutrient supply from decomposing organic matter and danger of nutrient leaching. Regular and small interferences are therefore better.

With a double exploitation level of 50 m^3 stemwood per ha in year 0 followed by silvicultural treatment the development of phytomass is slightly different. In Table 7.3 the amounts are given for some of the years showing that after 20 years amounts of stemwood are approaching those of the light exploitation. There may, however, be differences in the stem sizes, stem quality and species composition between both cases.

Table 7.3. Development of phytomass (t/ha) in treated natural forest after strong exploitation (50 m^3) and silvicultural treatment in year 0 and 10

Year	Leaf	branch	stem	root	flowers seeds	total
-1	11.0	90	220	80	1	402
0	4.2	34	101	37	0.4	177
1	11.4	41	113	49	0.6	215
2	11.5	47	123	58	0.8	240
3	11.6	54	134	64	0.9	264
10 a	11.5	75	192	80	1.1	360
10 b	6.9	45	115	48	0.6	216
11	11.4	51	126	59	0.8	248
12	11.5	57	136	66	0.9	271
13	11.6	62	146	71	1.0	292
20	11.5	81	203	80	1.1	377

With both exploitation levels sufficient regrowth takes place during 20 years in the simulation to make a new exploitation possible. The phytomass is returned to near climax amounts, but stem sizes are smaller and the proportion of sapwood is larger.

An extraction of 15 or 30 t/ha of stemwood once every 20 years is very modest and far below the production capacity of the forest. Only 2-4 % of the organic matter production is extracted, the remainder being available as litter to support the natural functions of the forest.

8. SIMULATION OF THE GROWTH OF TREE PLANTATIONS

Important differences between natural forest and tree plantations are in botanical composition, in age distribution and in phytomass fluctuations. The crop growth model does not take into account differences in botanical composition. The plantation also consists of leaves, branches, stems, seeds and roots. Differences introduced into the plantation compared to the natural forest are in starting amount of phytomass, leaf thickness, in maintenance respiration, the division of assimilates over the plant components, aerodynamic roughness and lower initial LAI values.

Table 8.1 clearly shows the differences between managed natural forest and plantation with respect to intensity of treatment.

Table 8.1. Phytomass killed and exported (stems only) by treatments in natural and plantation forests (kg/ha)

	Leaf	branch	stem		root	flowers seeds	total
			killed	exported			
Managed natural forest							
Light exploitation							
year 0	5600	46000	105000	15000	38000	500	195100
year 10	4600	32910	81560	-	31860	430	151360
year 20	4600	34008	83904	15000	31844	428	154784
Strong exploitation							
year 0	6800	56000	119000	30000	43000	600	225400
year 10	4600	30040	76820	-	31890	430	143780
year 20	4600	32284	81052	30000	31868	428	150232
Teak plantation							
year 0	0	0	0	0	0	0	0
year 5	1360	4840	19380	14540	10330	40	35950
year 10	1590	7830	33670	25250	14660	150	57900
year 15	1590	9440	44170	33130	17920	240	73360
year 20	6360	42090	207960	155970	79450	1010	336870

The land use Plantation Forest has a much stronger impact on the ecosystem than managed natural forest. There are more treatments, exports of stemwood and with it of nutrients are much larger (229 versus 15 or 30 t/ha per 20 years) as are the fluctuations in phytomass and litter additions to the soil. These large fluctuations increase the risk of nutrient losses by leaching and even by erosion and surface runoff in the period of cutting and planting (Chapter 9).

The simulated development of the phytomass in a teak plantation is given in Table 8.2.

Table 8.2. Development of phytomass (t/ha) in a tree plantation. Amounts at end of the year

Year	Leaf	branch	stem	root	flowers seeds	total
0	0.1	0	0.1	0.2	0	0.4
1	1.4	1	9	11	0	22
2	2.5	6	25	21	0.01	54
3	3.5	11	44	30	0.05	89
4	4.5	15	62	37	0.10	119
5a	5.4	19	77	41	0.17	143
5b	4.1	14	58	31	0.13	107
6	6.3	19	75	39	0.23	139
7	6.4	22	90	45	0.32	164
8	6.4	26	105	50	0.42	188
9	6.4	29	120	54	0.51	210
10a	6.4	31	135	59	0.60	232
10b	4.8	23	101	44	0.45	173
11	6.3	27	118	52	0.59	204
12	6.4	30	132	58	0.72	227
13	6.4	33	147	63	0.84	250
14	6.4	35	162	67	0.92	271
15a	6.4	38	177	72	0.96	294
15b	4.8	28	132	54	0.72	219
16	6.3	31	149	62	0.83	249
17	6.4	34	164	67	0.91	272
18	6.4	37	179	72	0.97	295
19	6.4	40	194	77	1.00	318
20	6.4	42	208	79	1.01	336

a: situation just before thinning

b: directly after thinning. To simplify the calculations, thinnings take place on the last day of the year

The tree plantation produces every 20 year stemwood from 3 thinnings and from one final cut. Initial plant density is 1600 trees/ha at the end of year 0. Between year 1 and 5, this number decreases to 1560 by natural mortality. The three thinnings take place in the years 5, 10 and 15 and the final cut is in year 20. Only stemwood is harvested and of the stemwood one fourth remains behind in the forest as stumps, upper part near branches and defected stems. Increases in stem weight are higher than in managed natural forest, mainly because of the lower phytomass and corresponding lower maintenance respiration rates and death (litter production) rates.

Details of the exploitation are given in Table 8.3. The average length of the harvested stems increases from 4 to 10 m during the growing period. It is assumed that the form factor is 0.7 and that the wood density is 0.6 t/m^3 which is reasonable for teak. The form factor (ff) gives the deviation between the average stem form and a cylinder as follows:

$$\text{Stem volume} = \text{basal area} * \text{length} * \text{ff}$$

Table 8.3. Exploitation scheme of the tree plantation

Year	Stemwood (t/ha) killed	Stemwood (t/ha) exported	number of stems	stem length (m)	volume per stem (m^3)	diameter of stems (cm)
5	19.37	14.53	624	4	0.039	13.3
10	33.65	25.24	308	5	0.137	22.3
15	44.14	33.10	203	7	0.272	26.6
20	207.84	155.88	401	10	0.648	34.3
Total	305.00	228.75				

The mortality of the trees is 0.5 % during the first 5 years and 0.25 % per year afterwards. During the first thinning 40 % of the trees are removed and during the following thinnings 33 % of the trees. Some selection during thinning takes place. Therefore, 40 or 33 % of the trees contain only 25 % of the stem weight.

Phytomass fluctuations will be used in Chapter 9 to calculate the nutrient flows.

9. NUTRIENTS

9.1. Introduction

For a good growth of a vegetation, supply of nutrients is necessary at the right time, in the right amounts and in the right ratios between the elements. In the growing of agricultural crops, nutrient demand is high during development of the vegetation in spring and summer and low to zero during ripening and in the winter period.

Both nutrient surpluses and shortages in the soil have negative effects. Surpluses may result in increased leaching and losses from the ecosystem. Shortages result in decreased growth. The quality of the soil, or rather the nutrient buffering capacity is important in this respect.

The supply of nutrients is often not in tune with demand. Supply occurs by weathering of minerals, atmospheric deposition, decomposition of organic matter, biological N fixation, fertilizing and by run-on of water and sediments. During crop development there is often a shortage that can be overcome by fertilizing. During ripening and in the winter season supply of nutrients continues, but there is no demand. Nutrients accumulate in the soil. When the nutrient uptake capacity of the soil is large enough, there is no problem. Does the accumulation exceed the buffering capacity, then the nutrients are not held by the soil and are prone to leaching.

This buffering capacity is not only valuable for prevention of nutrient losses, it is as valuable for the supply of nutrients in periods with higher demand than supply. As mentioned, the spring period may be such a time, not only because of the large demand, but also because of the small supply from decomposing organic matter due to the still low temperatures. The concept of nutrient buffering capacity as given here is a simplification of reality. Nutrient buffering differs per element and transitions between nutrient holding and release when the buffer becomes full is gradual.

In natural tropical forests, supply and demand of nutrients are more evenly spread throughout the year. Especially in evergreen forests demand is more or less constant as growth continues throughout the year. Also supply is much more constant than in the temperate areas because of a constant high temperature that stimulates organic matter decomposition. However, rainfall is normally not evenly spread over the year, there is generally a dry season or a drier season for a few months. The dry season becomes more pronounced going from evergreen forests towards deciduous forests and with it the imbalance in nutrient supply. Upon drying of the litter and topsoil layer, organic matter decomposition slows down, and with it the liberation of nutrients (= mineralization) resulting from this decomposition. On top of that, nutrient input with wet deposition also slows down and even nutrient liberation from mineral weathering may decrease in very dry periods.

One can imagine that in the beginning of the dry season when litter and topsoil are already dry and the subsoil still contains enough water for continued growth of the vegetation there is a shortage of nutrients when the soil buffer does not contain enough of it.

In the same way, nutrient surpluses may occur in the beginning of the wet season when accumulated litter starts to decompose, giving a nutrient flush much higher than the average supply from decomposing organic matter.

From the foregoing the following two statements are made:

1. Supply and demand of nutrients are never completely synchronous and the more the vegetation deviates from an evergreen tropical forest the more a-synchronous the relationship between supply and demand becomes.
2. The soil quality: 'nutrient buffering capacity' is more important the more a-synchronous nutrient supply and demand are.

In this nutrient balance study we do not calculate variations of nutrient supply and demand within years but between years. Perennial crops and forests may have years with more nutrient demand than supply and vice versa. In the following, nutrient surpluses and shortages will be calculated on a yearly basis for two types of tropical forest under management: natural forest under selective cutting and a forest plantation with a clear cut regime. For both forests a cycle of 20 years is assumed.

Nutrient shortages may occur in the short run (during the growth) or in the long run (after several exploitation cycles). This problem is rather complex. As mentioned, nutrients become available to the vegetation from different sources: atmosphere, N fixation, weathering, decomposition and run-on. On the other hand there are losses: leaching, runoff and erosion, and export by harvest. In first instance we will calculate the nutrient flows occurring during one cycle of 20 years and see what the surpluses and shortages are during the cycle. Thereafter, we will consider the size of the nutrients exported by harvests to judge the nutrient decline in the long run.

Inputs by the atmosphere and by weathering are relatively small. It is assumed that these inputs are constant and equal for both vegetations: natural forest and plantation. The assumed atmospheric input is low (Table 9.3). Other authors (Jordan, 1985 and Hase, 1981) give higher figures. These higher figures may include some recirculation of nutrients (Poels, 1994a).

Amounts by weathering have been estimated (Table 9.3) using data from Poels (1994a). Weathering inputs are for the Costa Rican well drained soils of low fertility (Chapter 3). For the soils of high fertility the inputs are estimated to be threefold.

Decomposition of organic matter contributes the largest quantity of nutrients to the vegetation in a forest situation. These nutrients do not become available at the moment of litter fall but later, during decomposition of the litter. The speed of decomposition depends on the type of litter (e.g. size, composition and density). Generally, decomposition proceeds faster when litter is finer and richer. The following mean residence times of litter will be used: leaf litter 1.1 year, fine woody litter (< 3 cm diameter) 2 years and coarse woody litter (> 3 cm) 5 years. This corresponds with the following decay rates under steady state conditions: 0.91, 0.5 and 0.2 per year respectively. 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.

The given decomposition times correspond more or less with data in literature. In reality litter decomposition is very complex and can not be described with simple constant decay rates for the different litter types. Decomposition rates vary between species, with the seasons and the age of the litter. However for the calculation of yearly nutrient flows over a long period of

20 years the proposed simplification can be justified.

Potassium release from tree litter. In tree litter, potassium is mainly present in the cell solution. This in contrast to phosphorous and nitrogen that are structurally bound to the organic carbon. Consequently a large fraction of potassium will be released immediately after leaf litter fall. This fraction is assumed to be 0.5. The remaining fraction releases upon breakdown of the cell walls and is assumed to be proportionally to the decomposition of the leaf litter.

Nitrogen release from tree litter. During decomposition, plant litter with a relatively high C/N ratio is partially converted into microbial biomass with a much lower C/N ratio. During this conversion N is immobilized for some time and released later upon death and decomposition of the microbes. This delay in availability of N depending on C/N ratio of the substratum is not considered here as it does not change the total amount mineralized. For these long term studies this delay is less important. Nitrogen is released from the tree litter and enters the soil buffer proportionally to N-content and decomposition rate of the litter.

P, Ca and Mg release from tree litter. Release of these elements will be calculated in the same way as the release of Nitrogen: proportionally to the decomposition.

Nutrient concentrations of different litter compartments have to be known to calculate amounts of nutrients liberated by litter decomposition. In the same way, concentrations of plant components have to be known to calculate amounts of nutrients needed for growth (formation of plant components). Few 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 by roots.

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. Because of these considerations it is assumed that plant components and (fresh) litter components derived from them have the same composition. These compositions are given in Table 9.1. They are the concentrations of the Kabo forest in Suriname, taken from Poels and Bijker, 1993, adapted for the Costa Rican situation where possible (e.g. Osinga, 1993).

Table 9.1. Provisional nutrient concentrations (%) of plant components of natural forest in the Atlantic Zone of Costa Rica

	N	P	K	Ca	Mg
Leaves	1.50	0.077	0.99	0.52	0.164
Branches	0.38	0.032	0.35	0.72	0.064
Stems	0.29	0.018	0.25	0.61	0.049
Roots	0.80	0.056	0.38	0.43	0.077
Flowers, seeds	1.00	0.225	0.65	0.60	0.100

9.2. Natural forest in steady state (climax)

Calculation of nutrient fluxes for this situation is relatively simple. Amounts of nutrients in litter fall are calculated from the amounts of litter fall per year (Table 6.1) and concentrations in the litter. In a steady state situation nutrient amounts liberated by decomposition per year equal the amounts in the litter fall for all litter types (Table 9.2).

Table 9.2. 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	6502	97.5	5.01	64.4	33.8	10.7
Branches	6681	25.4	2.14	23.4	48.1	4.3
Stems	9161	26.6	1.65	22.9	55.9	4.5
Roots	9995	80.0	5.60	38.0	43.0	7.7
Flowers, seeds	233	2.3	0.52	1.5	1.4	0.2
Total	32572	231.8	14.92	150.2	182.2	27.4

Combining these data with nutrient inputs from the atmosphere and from weathering gives a summary of the nutrient flows for the climax situation (Table 9.3).

Table 9.3. Nutrient flows in a natural forest ecosystem in a steady state (kg/ha.y) on well drained soils of low fertility

Element	N	P	K	Ca	Mg
Atmosph. Jordan, 85	13	1.2	11	13	5
Atmosph. Hase, 81	8	0.5	6	7	2
Atmosph. Costa Rica, assumed	5	0.1	1	1	3
Weathering input	0	0.2	7	7	3
Organic matter turnover	232	14.9	150	182	27
Export by leaching, erosion	5	0.3	8	8	6

The given export by leaching and erosion is for a truly steady state in which weathering and denudation are exactly in balance and the soil depth constant. A large amount of nutrients cycles around in the organic matter cycle: uptake, incorporation, litter fall, decomposition and uptake again. The unavoidable losses from this cycle are fully compensated by atmospheric deposition and weathering inputs.

9.3. Calculation of nutrient flows in managed forests

Combining the data of organic matter flows (Tables 9.4, 9.5 and 9.8) with the concentrations of nutrients in tree components (Table 9.1), nutrient balances were constructed. Need of nutrients (= uptake in situation of sufficiency) was calculated straightforward by multiplying amounts of plant components formed per year with their concentrations.

Release of nutrients from decomposing litter was calculated with the help of the data on formation of litter (= litter fall = supply). First, the litter was grouped in leaf, fine woody and coarse woody litter for which different decomposition times apply (Chapter 9.1). From litter amounts at the end of the preceding year, from litter additions and from decomposition rates the standing stocks for each litter group were calculated and the amounts that decompose in one year. The decomposing amounts were multiplied with the nutrient concentrations to give the liberated nutrients per year.

Calculations were done with the help of LOTUS spreadsheets. Organic matter flows calculated with TROPFOR were used as input (Tables 9.4, 9.5, 9.8). The following equations were used.

Need of nutrient

Need of nutrient in year n = form. of plant comp. in year n * conc.

Plant litter pool

Plant litter pool year $_n$ = (pool$_{n-1}$ + supply) * (1 - dec. rate)

Plant litter pool at start (climax situation)

Pool year$_n$ = pool year$_{n-1}$

Pool = (pool+supply) * (1 - dec. rate)

Pool - pool * (1-dec rate) = supply * (1-dec rate)

Pool * dec rate = supply * (1-dec rate)

Pool = supply * (1-dec rate) / dec rate

Or (with very small time steps)

Plant litter pool at start = supply * mean residence time

Plant litter decomposition

Decomp = (old pool + supply) * dec. rate

Nutrient release by decomposition

Release = decomp * conc

K release from leaves = (leaf decomp * K conc + leaf fall * K conc) / 2

Yearly need (uptake) and release of nutrients were calculated for managed natural forests and planation forest using these equations.

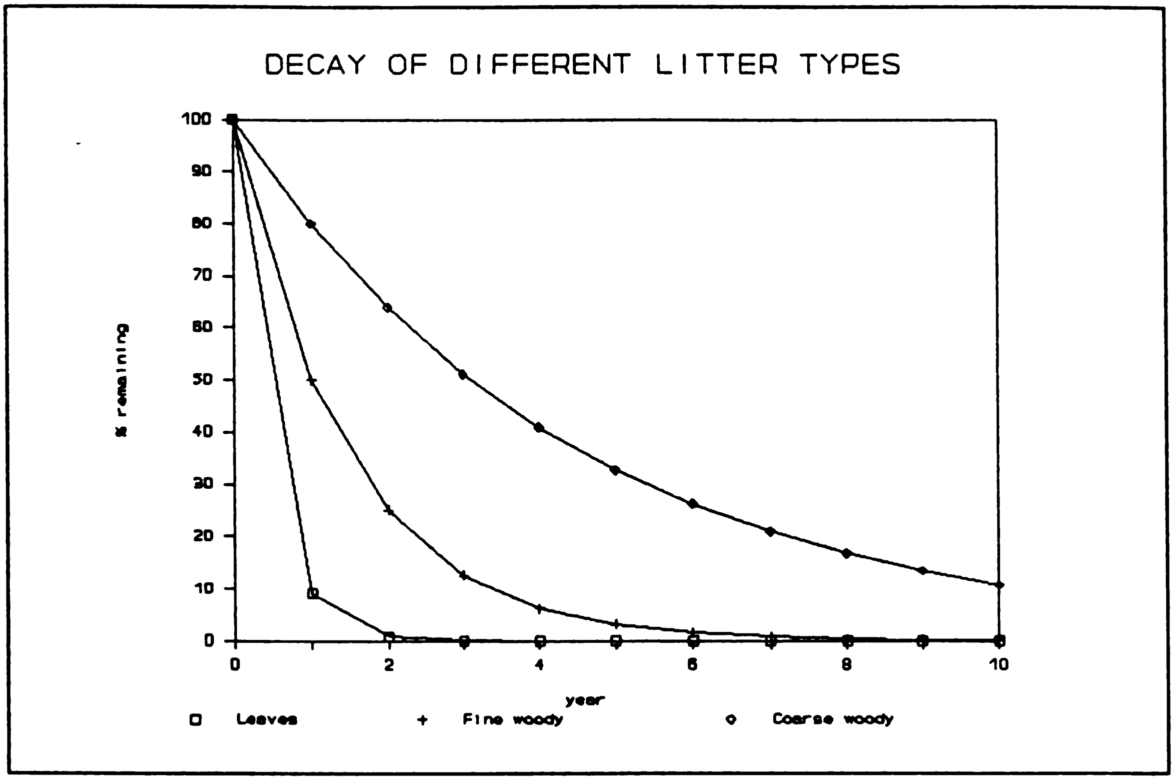

Figure 1. Decay of different litter types

Fig. 1 illustrates the differences in decomposition rate between the litter types. A certain amount of litter (100 %) is added to the forest floor at the end of year 0. The remaining amounts at the end of the following 10 years are shown. Leaves have largely disappeared after 1 year but coarse woody litter has still more than 10 % left after 10 years.

9.4. Natural forest under polycyclic management

The starting situation is the natural forest in which exploitation and refinement take place in year 0. These treatments influence organic matter turnover. Litter fall and decomposition are no longer in a steady state. For each year nutrient flows have to be calculated separately from organic matter turnover. Need of nutrients is determined by the formation of plant components (the incorporation of nutrients) and supply by liberation of nutrients by organic matter decomposition.

The formation of plant components per year is calculated from the differences in amounts at the end of year n and year n-1 of living and dead (heartwood) phytomass and from the litter formed during year n. These litter data form also the base for the calculation of nutrient release from decomposing organic matter. They are given in Table 9.4 for the situation with light exploitation and in Table 9.5 for the situation with strong exploitation with 25 and 50 m^3 stemwood per ha exported in year 0 respectively. Litter additions resulting from treatment (not including exported stemwood) are given in the second line of the years 0 and 10.

Table 9.4. Organic matter flows in lightly exploited managed natural forest (kg/ha/y)

	Formation of plant components					Formation of litter				
year	root	leaf	stem	bran.	seed	root	leaf	stem	branch	seed
0	9995	6502	9161	6681	233	9995	6502	9161	6681	233
						38000	5600	90000	46000	500
1	13950	7980	11240	7810	350	2370	2010	90	1060	140
2	10660	6330	10470	7360	300	3070	6170	120	1360	170
3	11390	7860	10470	7440	310	5660	7800	130	1610	200
4	10550	7090	9380	6850	270	5300	7090	570	2860	220
5	9230	5880	8680	6450	240	4530	5970	850	3870	220
6	8960	5580	8580	6410	230	6670	5710	850	3880	220
7	9660	6320	8760	6460	240	9170	6180	850	3880	230
8	11440	7900	9690	7050	260	11170	7810	980	4280	230
9	10330	6950	9130	6690	250	10740	6970	920	4080	240
10	9370	5970	8780	6520	230	9210	6050	920	3900	240
						31860	4600	81560	32910	430
11	13240	7150	10870	7500	310	2520	2680	100	1250	160
12	10340	6330	10090	7080	300	3270	6170	130	1510	190
13	11400	7870	10140	7190	280	5660	7810	140	1940	200
14	10530	7090	9290	6810	270	5300	7090	850	4110	230
15	9250	5880	8680	6450	230	6170	5970	920	3880	220
16	8980	5580	8580	6410	230	9170	5710	840	3880	230
17	9660	6320	8750	6460	240	9660	6180	850	3870	230
18	11430	7900	9710	7050	260	11170	7810	990	4080	230
19	10340	6940	9120	6690	250	10740	6960	920	4080	240
20	9380	5990	8780	6540	230	9070	6070	850	3910	240
1-10	10554	6786	9518	6904	268	6789	6176	628	3078	211
11-20	10455	6705	9401	6818	260	7273	6245	659	3251	217

Average values of the formation of plant components for the years 0-10 and 11-20 are slightly higher than the climax values (year 0) because of the extra room for growth caused by the treatment and the lower maintenance rates. The average litter production values do not include the litter of the treatments. They are lower than the climax values especially for stems because stems have very low mortality rates when the phytomass is below the climax amount.

Table 9.5. Organic matter flows in strongly exploited managed natural forest (kg/ha.y)

	Formation of plant components					Formation of litter				
year	root	leaf	stem	bran.	seed	root	leaf	stem	branch	seed
0	9995	6502	9161	6681	233	9995	6502	9161	6681	233
						43000	6800	89000	56000	600
1	14690	8680	11710	8130	370	2210	1510	80	870	120
2	11050	6330	10970	7650	310	3000	6170	100	1190	160
3	11420	7870	10930	7690	320	5380	7810	130	1480	190
4	10540	7080	9660	7010	280	5300	7080	140	1750	220
5	9240	5890	8670	6450	240	4670	5980	850	3670	220
6	8960	5570	8590	6410	230	4660	5700	920	3870	220
7	9680	6320	8750	6460	240	7670	6180	850	3880	230
8	11410	7910	9710	7060	270	11660	7820	990	4290	230
9	10350	6940	9120	6690	230	10240	6960	910	4080	230
10	9380	5990	8780	6530	240	9220	6070	850	3900	240
						31890	4600	76820	30040	430
11	13270	7150	10860	7500	310	2520	2680	100	1250	160
12	10350	6330	10060	7070	300	3270	6170	130	1510	190
13	11370	7870	10130	7190	280	5650	7810	140	1940	200
14	10550	7090	9290	6820	270	5300	7090	850	4120	230
15	9240	5880	8680	6440	230	6170	5970	920	3870	220
16	8990	5580	8570	6410	230	9670	5710	840	3880	230
17	9670	6320	8760	6460	240	9170	6180	850	3880	230
18	11420	7900	9710	7060	260	11170	7810	990	4080	230
19	10340	6940	9120	6680	250	10740	6960	920	4080	240
20	9390	5990	8790	6530	230	9080	6070	850	3900	240
1-10	10672	6858	9689	7008	273	6401	6128	582	2898	206
11-20	10459	6705	9397	6816	260	7274	6245	659	3251	217

During the years preceding the treatment, liberation and uptake are in balance (climax situation). In year zero, harvesting and silvicultural treatment take place, producing much litter of which decomposition reaches a peak in year 1. Summaries of the nutrient flows are given in Tables 9.6 and 9.7. Detailed yearly balances of plant and litter formation, litter amounts and decompositions and nutrient flows are shown in Appendix IV.

Litter amounts peak at the end of the years 0 and 10 because of treatment. Litter decomposition peaks during the years 1 and 11 and decreases slowly to levels that lie even below the climax rates. Nutrient release follows closely the organic matter decomposition, even for K that reacts slightly faster than the other elements being less bound to the organic carbon. Nutrient need (uptake) fluctuates less than nutrient release. The first, the third and the eighth year after treatment show an increased uptake. During the first year the room left by the killed vegetation is filled up. The third and eighth year are the same favourable year climatically. The years 1983-1987 were used 4 times to make 20 year input. The third year

(1985) has the highest insolation and therefore higher production and nutrient uptake. It returns in the years 8, 13 and 18 (Table 4.3). When these favourable years are long after treatment (years 8, and 18) and, therefore, at low litter levels, nutrient shortages occur that will be claimed from the soil buffer.

Table 9.6. Summary of nutrient flows in managed natural forest under light exploitation (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 turnover with O.M.					
- release	244	16	157	196	29
- uptake	240	15	155	188	28
Export with harvest:					
- 25 m³	2.2	0.1	1.9	4.6	0.4
Maximum yearly surplus	143	11	83	214	26
Maximum yearly shortage	36	3	21	48	0
Export with leaching, erosion	5	0.3	8	8	6

Table 9.7. Summary of nutrient flows in managed natural forest under strong exploitation (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 turnover with O.M.					
- release	245	16	157	197	29
- uptake	241	16	156	189	28
Export with harvest:					
- 50 m³	4.4	0.3	3.8	9.2	0.7
Maximum yearly surplus	159	12	90	237	28
Maximum yearly shortage	37	3	22	50	0
Export with leaching, erosion	5	0.3	8	8	6

Surpluses and shortages in this managed natural forest are relatively small. A surplus of, for instance, 90 kg K can easily be taken up by the soil, giving an average increase of K-adsorbed from, for instance, 4 to 4.04 cmol(+)/kg in the layer 0-50 cm. For a surplus of 237 kg Ca/ha, the adsorbed amount of Ca only has to increase with 0.19 cmol(+)/kg of soil in the same layer. Leaching losses are expected to remain very low under this land use with both exploitation levels.

Shortages are very small, there is an average surplus of nutrients caused by the decrease in phytomass during the management cycle. Cumulative shortages over more years (Chapter 9.6) are limited. It is expected that they can easily be withdrawn from the soil buffer, even from the low fertility soil.

A double harvest of 50 m^3 stemwood per 20 years has very little influence on the average turnover. Maximum yearly surpluses and shortages are slightly larger. Average yearly exports from the ecosystem by harvest of stemwood are still lower than the yearly inputs from the atmosphere and from weathering. Only for Ca the exported amount is slightly higher. Under good management (careful extraction, avoidance of open spaces and no erosion on extraction roads) nutrient exports with leaching and erosion could decrease slightly because of less abundance of nutrients and management could continue for several cycles without noticeable decrease in production even on the soils of low fertility that still have some reserve of nutrients. On the poorest soils small gifts of Ca, P and K might be effective.

9.5. Teak plantation

Organic matter flows in the forest plantation were calculated by simulation in Chapter 7. The corresponding organic matter flows are given in Table 9.8. They form the base for the calculation of nutrient flows. Compared with managed natural forests, phytomass amounts are much lower and fluctuate much more in the plantation. There are more treatments in the plantation and there is more extraction of wood. Additional litter produced by these treatments (three thinnings) are presented in the second line of the years 5, 10 and 15.

Table 9.8. Organic matter flows in a teak plantation (kg/ha.y)

	Formation of plant components					Formation of litter				
Year	root	leaf	stem	bran.	seed	root	leaf	stem	bran.	seed
0	0	0	0	0	0	0	0	0	0	0
1	11270	6690	8990	1280	0	570	5330	20	40	0
2	11970	11200	16450	5050	10	1680	10190	70	370	0
3	11690	12530	18630	5890	50	2510	11460	150	840	10
4	9640	11530	17950	5810	60	3090	10550	220	1290	10
5	7960	9560	16280	5450	100	3520	8650	420	1600	30
						10330	1360	4840	4840	40
6	10660	8120	17090	5680	140	2820	5940	260	1490	40
7	9190	8050	16160	5390	150	3470	7930	1340	1780	60
8	9880	9320	16920	5440	180	4810	9280	1690	2020	80
9	9730	8690	16920	5270	200	4880	8690	1690	2240	110
10	8390	7810	15970	4880	210	4230	7860	1550	2320	120
						14660	1590	8420	7830	150
11	10730	7900	16920	5280	260	2820	6420	260	1910	120
12	9190	8050	15940	5090	270	3480	7930	1270	2100	140
13	9880	9330	16700	5220	290	4810	9290	1690	2260	170
14	9710	8680	16720	5090	280	4870	8680	1700	2430	200
15	8400	7810	15830	4740	250	4240	7860	1550	2460	210
						17920	1590	11040	9440	240
16	10730	7900	16830	5200	280	2820	6420	260	1990	170
17	9190	8050	15890	5040	270	3480	7930	1270	2160	190
18	9880	9330	16680	5170	270	4810	9290	1690	2310	210
19	9710	8680	16730	5060	250	4870	8680	1700	2460	220
20	8400	7810	15810	4720	230	6240	7860	1540	2490	220
1-5	10506	10302	15660	4696	44	2274	9236	176	828	10
6-10	9570	8398	16612	5332	176	4042	7940	1306	1970	82
11-15	9582	8354	16422	5084	270	4044	8036	1294	2232	168
16-20	9582	8354	16388	5038	260	4444	8036	1292	2282	202

Leaf litter production is at about the same level as in natural forest, with peaks in years of thinning. Litter production of roots, stems and branches is smaller than in natural forest because of low phytomass levels.

Nutrient concentrations in plant components of teak differ from those in natural forests. In Table 9.9 provisional data are given taken from literature (e.g. Hase, 1981, Poels and Bijker, 1993). With these concentrations nutrient flows are calculated from organic matter flows.

Table 9.9. Provisional concentrations (%) of plant components of teak

	N	P	K	Ca	Mg
Leaves	1.80	0.15	1.20	0.90	0.22
Branches	0.40	0.06	0.50	0.72	0.10
Stems	0.29	0.04	0.25	0.61	0.09
Roots	0.80	0.08	0.38	0.43	0.08
Flowers, seeds	1.00	0.22	0.65	0.60	0.10

A summary of the nutrient flows given in Table 9.10. Detailed yearly balances of plant and litter formation, litter amounts and decompositions and nutrient flows are shown in Appendix IV. During the whole growing period, large shortages (release - uptake) occur, in sharp contrast to the managed forest (Tables 9.6 and 9.7). Main cause for these shortages are the lack of phytomass at the start of the plantation and the fast phytomass increase during the cycle. The, in comparison with the native forest, small phytomass of the grass vegetation has not been taken into account. Decrease of this phytomass around planting (by tillage) or thereafter (by competition from trees or weeding) will produce some nutrients.

Table 9.10. 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 turnover with O.M.					
- release	210	19	138	128	27
- uptake	307	31	211	258	47
Export with harvest (381 m^3)	33.2	4.6	28.6	69.8	10.3
Maximum yearly surplus	-	-	-	-	-
Maximum yearly shortage	179	21	120	201	27
Export with leaching, erosion	5	0.3	8	8	6

Average nutrient uptake is higher than release from organic matter decomposition for all elements, indicating shortages in the short run. Shortages in the long run are caused by the export with harvest. Average yearly exports from the plantation are much higher than from managed natural forest and also higher than atmospheric and weathering inputs combined.

9.6. Comparison of nutrient flows between managed natural forests and plantations

The difference between managed natural forest and plantation is shown more clearly in

Table 9.11 where cumulative surpluses and shortages are given over more years. The given data are maximum amounts that can be found by combining years.

Table 9.11. Maximum cumulative surpluses and shortages of nutrients (kg/ha)

	N	P	K	Ca	Mg
Managed natural forest light exploitation					
Surpluses	309	22	247	522	136
Shortages	115	9	56	173	0
Managed natural forest strong exploitation					
Surpluses	317	23	246	526	135
Shortages	128	10	64	191	0
Teak plantation					
Surpluses	-	-	-	-	-
Shortages	1848	230	1294	2455	285

In managed natural forests, nutrient surpluses build up during the first 5 years after treatment, followed by shortages till the next treatment (see also Appendix IV). 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 Mg no shortages occur because demand is low and atmospheric and weathering inputs relatively high.

For teak the situation is completely different (Appendix IV). During the whole growing period there are shortages. Maximum shortages are reached in year 2 and 3 when build-up of phytomass is at its peak and litter fall still small. Cumulative shortages over the whole cycle of 20 years are enormous and nutrient deficiencies will surely occur on the well drained soils of low fertility and probably even on the young rich soils for some elements. High fertilizer gifts are needed to reach the maximum production levels as determined in Chapter 8. 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.

10. DISCUSSION

Net primary production of tropical forests in the Atlantic Zone of Costa Rica is very high under favourable conditions (good drainage and sufficient supply of mineral nutrients). This is the case for both native forests and plantations. In this study we concentrate on this nutrient supply. Three forest types are considered: undisturbed natural forest, natural forest under polycyclic management and forest plantations. The soil is well drained and the climate is that of Los Diamantes, Guapiles during 1983-1987.

The yields were calculated assuming no nutrient limitation (Chapters 6-8). If limitations occur, yields will be lower. Whether limitations occur depends on the fertility and buffer capacity of the soil, on the biological nitrogen fixation and on fertilizing.

The undisturbed forest has a sufficient supply of nutrients under normal conditions. A large amount of nutrients cycles in the organic matter cycle and the small losses are compensated by small inputs by mineral weathering and by the atmosphere.

In the case of managed natural forests and plantations the nutrient cycles are disrupted by human interference and nutrient shortages may occur. The interference has 2 aspects: export of nutrients with harvest and changes in the organic matter cycle that cause irregular demands and supply of nutrients. In both aspects the situation is more favourable in the case of managed natural forest.

There is a large difference in amount of extracted stemwood. 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, stemwood of thinnings is removed during the cycle and a complete cut is executed at the end with all stemwood removed. This higher export of stemwood is may pose problems to the nutrient supply in the long term.

According to the calculations in Chapters 7 and 8 the exports of stemwood during a cycle of 20 years could amount to 15 or 30 t/ha in case of managed natural forest and 229 t/ha in case of teak. Exports of nutrients with it are given in Tables 9.6, 9.7 and 9.10. Spread over the years the exports are generally lower than the inputs by the atmosphere and by weathering for the managed natural forest but several orders of magnitude higher for the plantation on low fertility soils. 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 may be sustainable, but more weathering research is necessary to make better estimates.

Fluctuations in phytomass result in surpluses and shortages of nutrients. These fluctuations are much larger in the plantation. To avoid nutrient losses at one time and decreased growth at another, a sufficient nutrient buffering capacity of the soil is needed. This buffering capacity is related to soil depth, CEC and organic matter content. Cumulative surpluses and shortages over more years have been calculated for both land uses. Maximum values are given in Table 9.11. The soil buffer to supply nutrients should be as large as the values under shortages and the soil buffer to hold nutrients should be as large as the values under surpluses. For managed natural forest a modest nutrient buffering capacity is sufficient to avoid losses and shortages. For the plantation there are high demands on the nutrient supplying capacity of the soil, surpluses do not occur during the first cycle.

The more unfavourable nutrient condition for the plantation is partly caused by the difference in starting situation. Managed natural forest starts from undisturbed forest with a high phytomass, the plantation is established on deforested land. If a plantations would be started on forest land, shortages (Table 9.11) would be much lower during the first cycle.

Long term shortages by wood export would remain the same. The difference in starting situation is, however, realistic, so in practice it will be the normal situation. The Atlantic Zone has lost most of its natural forest. The remaining forest is protected in national parks or reserves or allocated to sustained management. Conversion of natural forest to plantations is generally not allowed.

Calculations were made 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 on Soil type II, but this could be prohibitively expensive.

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 wind throw. To simulate forest growth in swamps, much more data are needed. 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.

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 a high ecological value and good soil protection.

The LUT Plantaciones Forestales: the growing of teak or other tree species in plantations produces higher amounts of stemwood 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 the linear programming of land use options in the Atlantic Zone by "Proyecto de cooperación CATIE/UAW/MAG" in Guapiles to following results are presented:

Managed natural forest gives once per 20 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. 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.

The calculated production level of the forest plantation (teak) under optimal conditions amounts to 229 t/ha or 381 m^3/ha per 20 years. Teak can only grow on the well drained soil types I and III. On the poorly drained soil type II some other species might be possible. The exported stemwood in case of teak contains 663 kg N, 92 kg P, 572 kg K, 1395 kg Ca and 206 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 exports 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 would be enough to supply the necessary Mg, for K still small and for Ca and P large shortages would develop in the long run.

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APPENDIX I. AVERAGE MONTHLY AND YEARLY CLIMATIC DATA LOS DIAMANTES, COSTA RICA (83-87)

Los Diamantes: $10^{0}13'$ N, $83^{0}46'$ W, elevation 249 m above sea level

MONTH OR YEAR	RAIN mm/d	AVRAD MJ/m2.d	TMAX	TMIN	VAPP GEM mbar	WIND m/s
8301	307.6	13.4	27.4	19.8	25.3	0.9
8302	305.2	15.6	28.5	20.3	25.9	1.0
8303	356.6	15.3	28.9	21.4	27.1	1.1
8304	94.9	18.5	30.2	20.8	27.1	1.0
8305	662.2	16.6	29.7	21.6	28.2	0.9
8306	195.8	17.3	30.6	21.6	29.1	0.8
8307	384.1	15.1	29.1	21.6	28.5	0.9
8308	462.2	16.1	29.6	21.4	28.0	0.8
8309	367.1	14.4	29.7	20.9	27.6	0.8
8310	694.1	11.2	28.7	20.7	27.0	0.8
8311	276.9	10.8	28.5	20.5	26.9	1.0
8312	194.0	10.9	28.0	19.3	25.0	1.0
8401	399.1	12.6	26.7	18.3	23.3	0.9
8402	330.0	14.7	28.1	18.7	24.2	1.0
8403	91.0	17.1	28.7	18.6	24.3	1.1
8404	91.0	19.3	30.0	19.8	25.3	1.0
8405	426.4	15.8	29.0	20.4	26.7	0.9
8406	456.4	13.9	29.1	20.9	27.2	0.8
8407	277.1	15.5	29.0	20.1	26.2	0.9
8408	593.8	12.9	28.5	20.6	27.0	0.8
8409	302.9	16.5	29.2	20.2	26.8	0.8
8410	345.9	11.7	27.8	20.6	27.0	0.8
8411	371.7	11.3	27.0	20.0	25.3	1.0
8412	352.5	13.0	27.5	19.3	24.2	1.0
8501	95.6	15.2	27.0	17.8	22.3	0.9
8502	310.7	17.6	27.1	18.9	23.4	1.0
8503	80.2	20.3	28.2	18.2	23.1	1.1
8504	113.0	21.2	29.2	18.6	23.9	1.0
8505	162.9	17.6	29.8	20.2	26.4	0.9
8506	628.7	13.5	28.4	21.2	27.7	0.8
8507	282.8	14.6	28.0	20.4	26.5	0.9
8508	539.1	14.3	27.9	20.4	26.6	0.8
8509	289.7	17.9	29.2	20.2	26.4	0.8
8510	359.0	14.4	28.6	20.0	26.8	0.8
8511	346.1	13.7	27.9	19.7	25.7	1.0
8512	228.0	13.9	27.3	19.3	24.7	1.0
8601	367.1	13.6	26.2	17.6	23.0	1.2
8602	51.6	18.0	27.8	17.6	22.9	1.2
8603	312.1	15.3	26.8	18.7	23.6	1.2
8604	227.1	15.6	27.8	19.7	25.5	1.1
8605	202.1	16.7	29.1	20.5	26.9	1.0
8606	479.3	14.1	28.7	21.2	27.6	0.9
8607	436.1	14.4	27.7	21.1	27.1	1.1
8608	527.3	14.4	28.2	21.3	27.6	0.9
8609	551.6	15.3	28.7	21.1	27.5	0.9
8610	372.8	13.9	28.3	20.6	27.2	0.7
8611	229.0	14.5	28.4	20.5	26.8	1.0

8612	164.0	15.1	28.2	19.4	24.7	1.0
8701	344.1	13.9	27.0	18.8	24.0	0.9
8702	143.0	13.0	26.8	20.1	24.6	1.0
8703	68.4	17.3	29.2	20.4	26.1	1.1
8704	391.7	14.1	27.5	20.6	25.9	1.0
8705	296.7	16.5	29.3	21.1	27.4	0.9
8706	433.4	13.5	29.5	21.8	28.8	0.8
8707	490.6	13.4	28.6	21.6	28.1	0.9
8708	398.6	14.2	28.7	21.3	27.8	0.8
8709	312.1	16.0	29.3	21.3	27.9	0.8
8710	715.2	13.7	28.9	21.1	27.0	0.8
8711	224.5	14.6	28.8	20.8	26.8	1.0
8712	425.9	13.8	28.1	20.7	26.2	1.0
1983	4300.7	14.59	29.1	20.8	27.2	0.92
1984	4037.8	14.52	28.4	19.8	25.6	0.92
1985	3435.8	16.16	28.2	19.6	25.3	0.92
1986	3920.1	15.04	28.0	19.9	25.9	1.01
1987	4244.2	14.52	28.5	20.8	26.7	0.92
AVERAGE	3987.7	14.97	28.4	20.2	26.1	0.94

<u>Explanation</u>:

MONTH 8612: December 1986
RAIN: rainfall
AVRAD: short wave radiation
TMAX: daily maximum temperature
TMIN: daily minumum temperature
VAPP: actual average vapour pressure
WIND: average daily wind speed

APPENDIX II. INPUT FILE FOR THE LA SELVA SOIL AND 3 STANDARD ATLANTIC ZONE SOIL TYPES

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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
```

<u>Explanation</u>:
line 1: soil type
line 2: number of positions in θ-h and K-h tables
line 3: infiltration rate in cm/d
lines 4-6: θ-h table
lines 7-9: K-h table

APPENDIX III. 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      3.0
Tdwi      rdi       dvrc1     dvrc2     rri       kdif      cvl       cvo       cvr       cvs
147000.   50.       0.0003    0.0003    0.3       0.800     0.720     0.720     0.720     0.720
Spa       ssa       q10       rml       rmo       rmr       rms       perdl     perrt     perst
0.0000    0.0000    2.0       .0069     .0011     .0025     .0004     0.100     .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        12        13        14        15        16        17        18        19        110
4         6         6         6         4         8         4         12        4         6
          frtb fraction to root
          0.00      0.35      2.00      0.35
          Fltb fraction to leaf
          0.00      0.50      0.20      0.50      2.00      0.50
          Fstb fraction to stem
          0.00      0.30      0.20      0.30      2.00      0.30
          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      25.00     2.00      25.00
          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      0.19      0.20      0.19      2.00      0.19
```

```
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     3.0
Tdwi     rdi      dvrc1    dvrc2    rri      kdif     cvl      cvo      cvr      cvs
100.     50.      0.0003   0.0003   0.3      0.800    0.720    0.720    0.720    0.720
Spa      ssa      q10      rml      rmo      rmr      rms      perdl    perrt    perst
0.0000   0.0000   2.0      .0077    .0011    .0025    .0004    0.100    .0006    .00012
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
8        8        8        8        4        8        4        12       4        8
         FRTB fraction to root
         0.00     0.50     0.10     0.35     1.00     0.35     2.00     0.35
         FLTB fraction to leaf
         0.00     0.50     0.10     0.40     1.00     0.40     2.00     0.40
         FSTB fraction to stem
         0.00     0.50     0.10     0.46     1.00     0.45     2.00     0.45
         FOTB fraction to storage organs
         0.00     0.00     0.10     0.00     1.00     0.01     2.00     0.01
         SLATB specific leaf area
         0.00     0.0010   2.00     0.0010
         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     25.00    2.00     25.00
         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     0.00     0.10     0.14     1.00     0.14     2.00     0.14
```

For: explanation of codes, see Appendix V (not included)

APPENDIX IV. ORGANIC MATTER AND NUTRIENT BALANCES

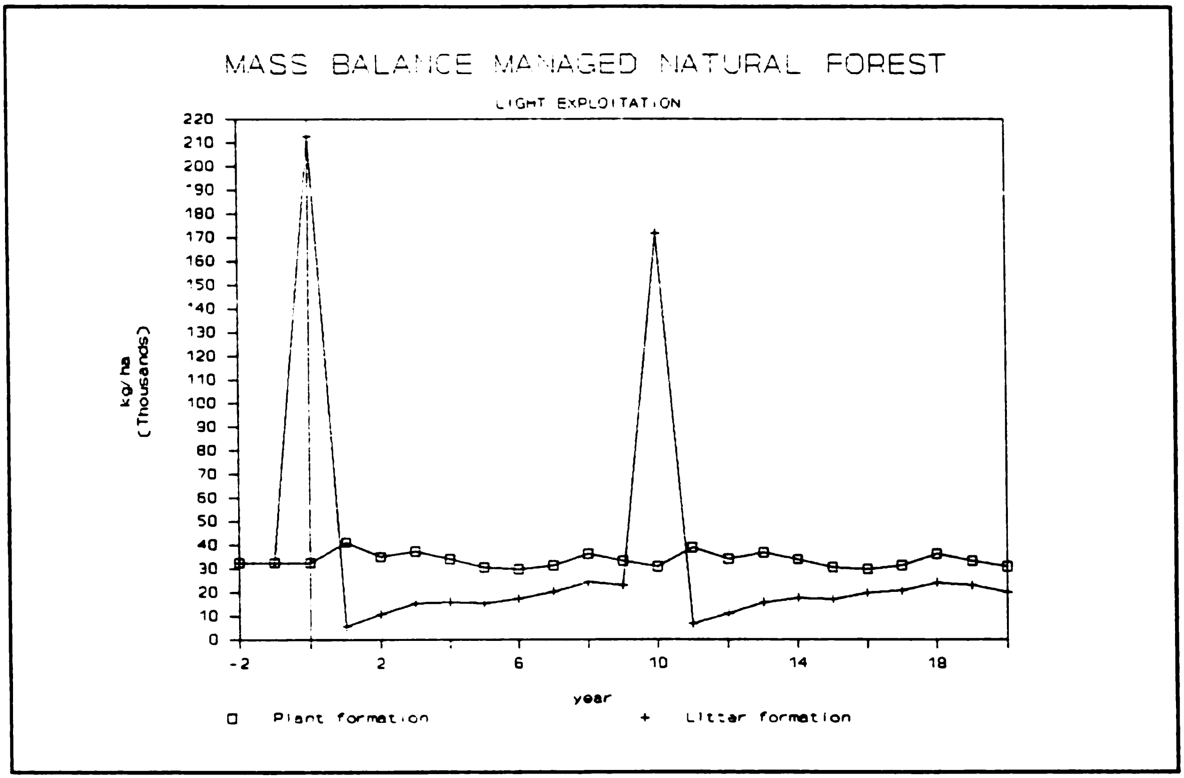

Figure 1. Formation and death of plant components

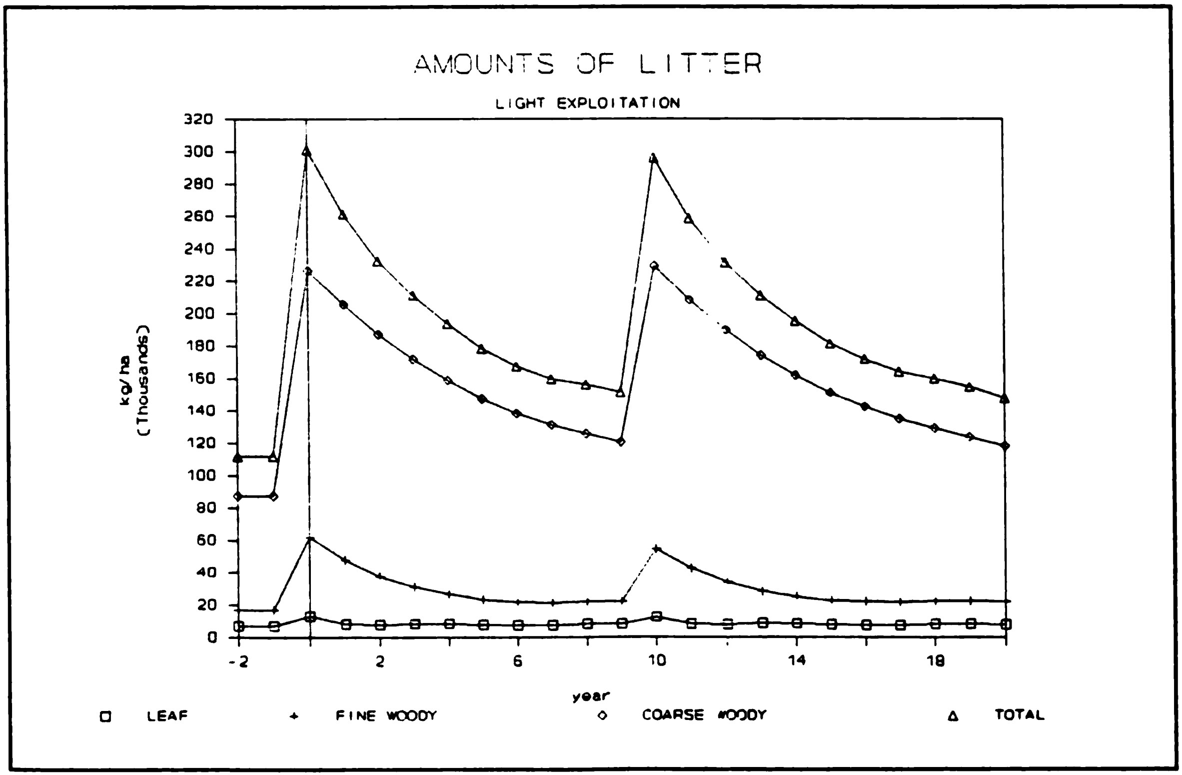

Figure 2. Litter amounts in lightly exploited natural forests

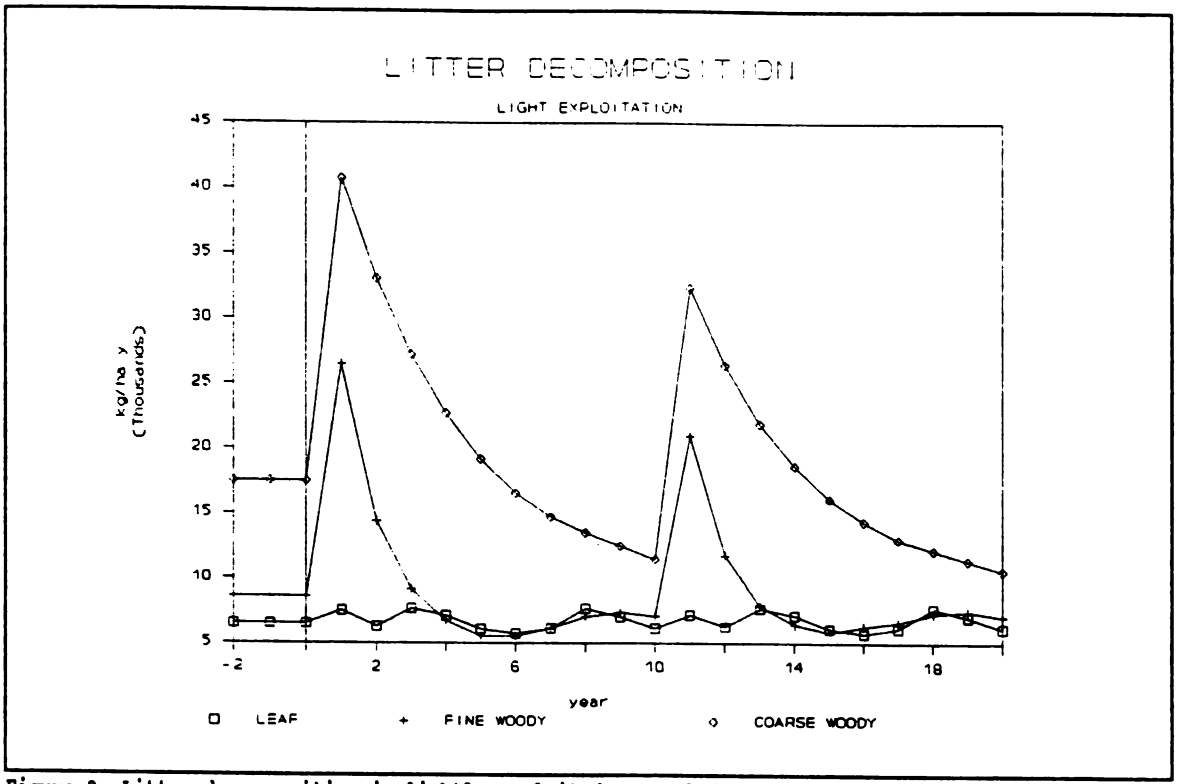

Figure 3. Litter decomposition in lightly exploited natural forest

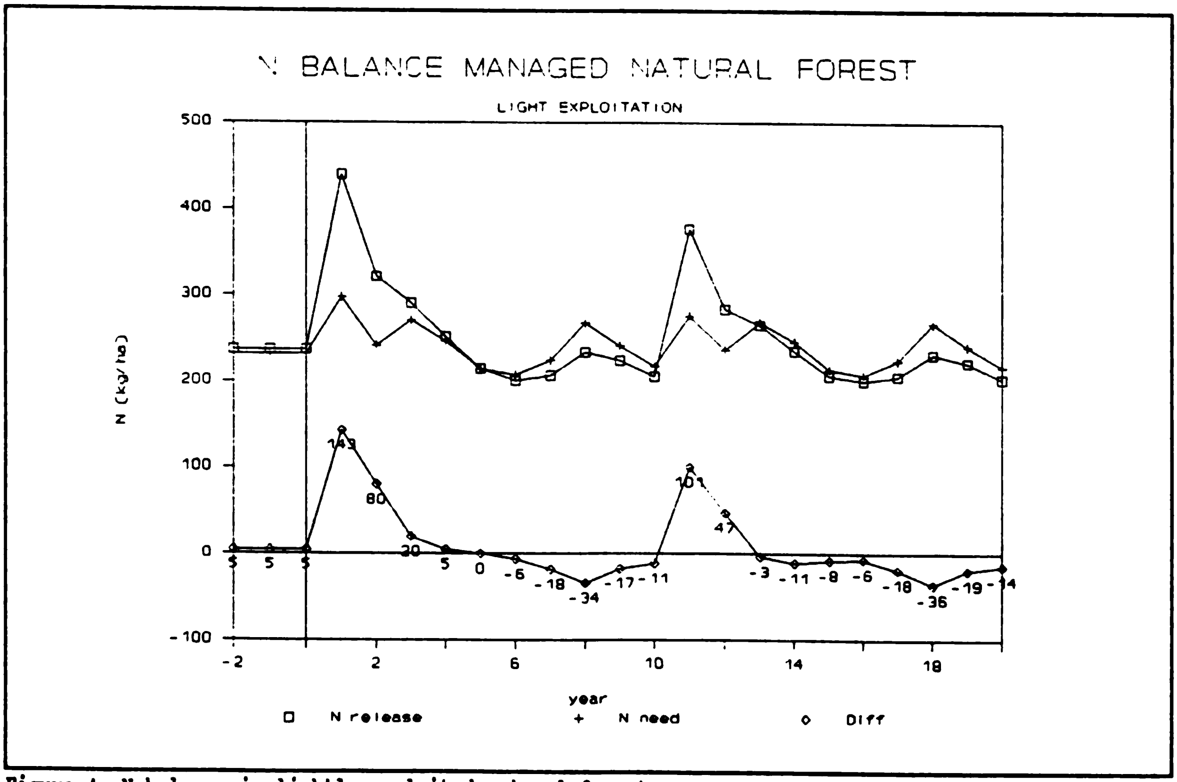

Figure 4. N balance in lightly exploited natural forest

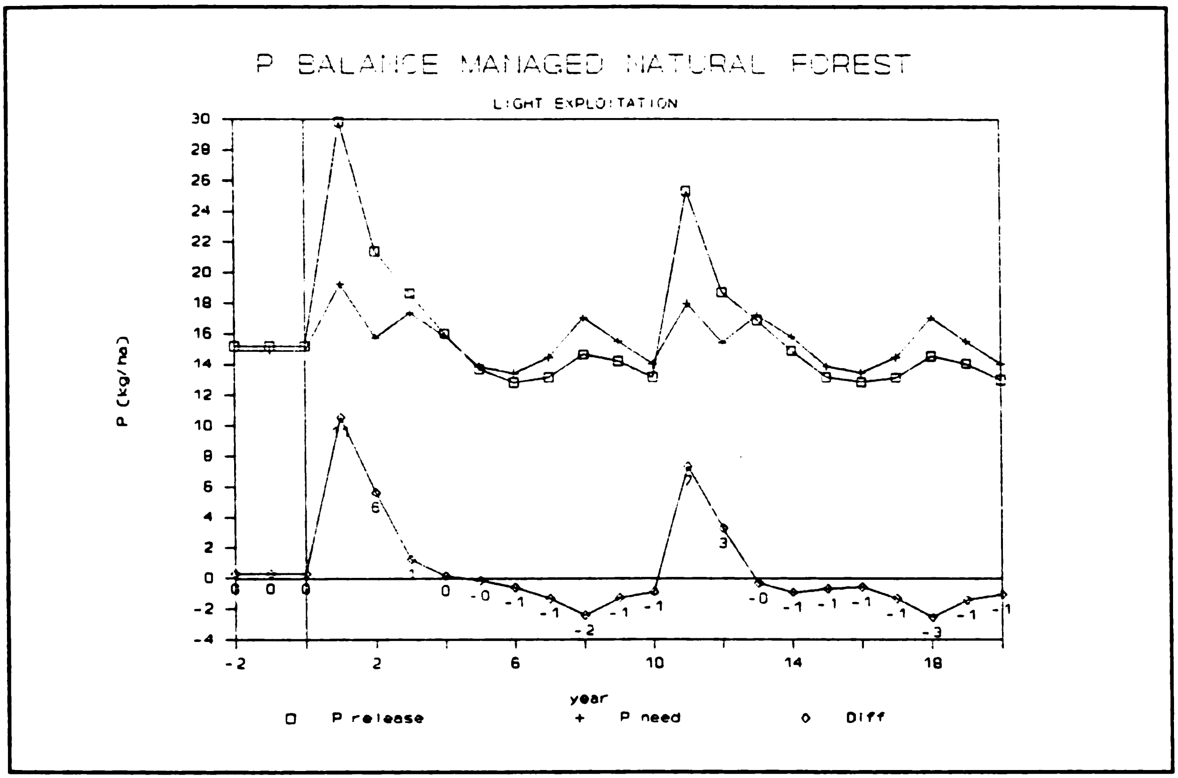

Figure 5. P balance in lightly exploited natural forest

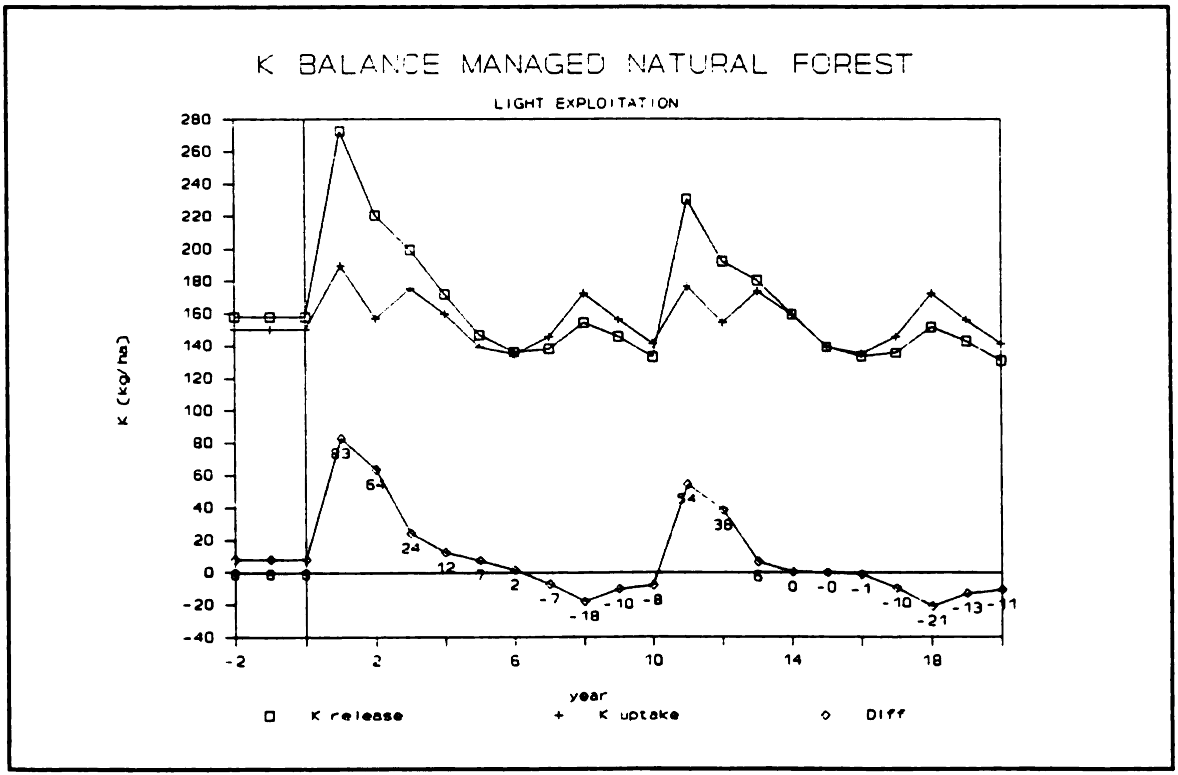

Figure 6. K balance in lightly exploited natural forest

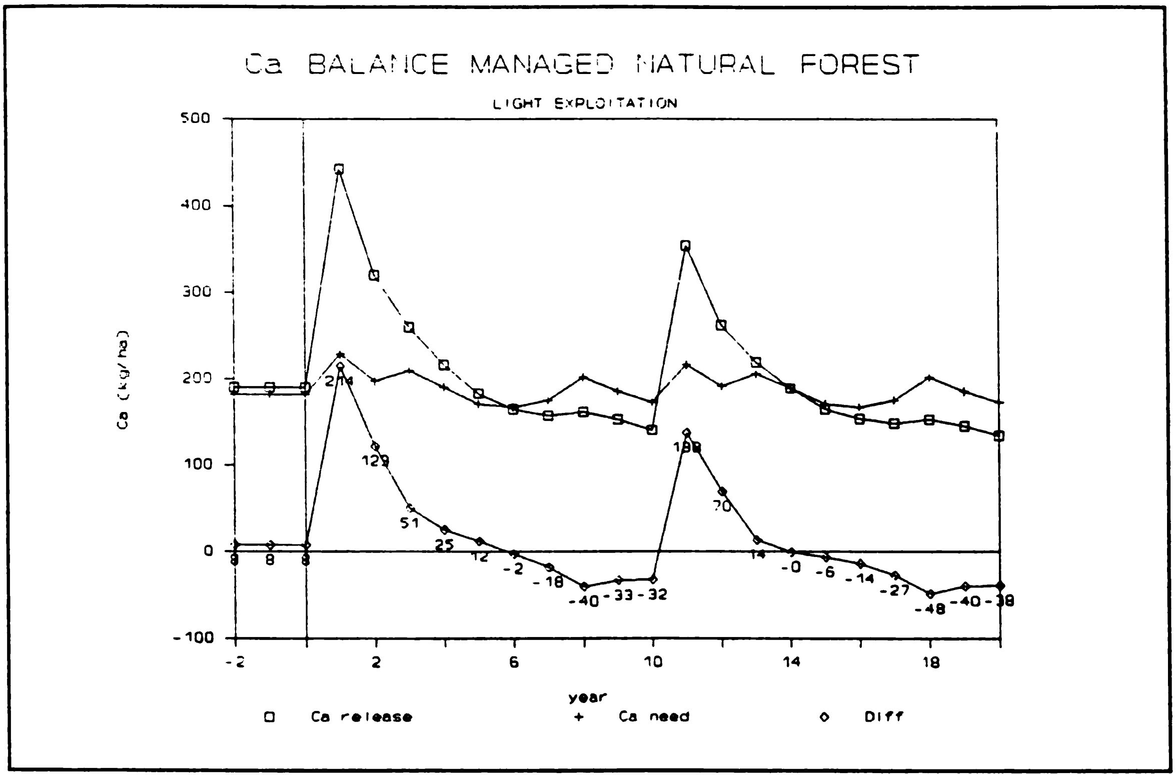

Figure 7. Ca balance in lightly exploited natural forest

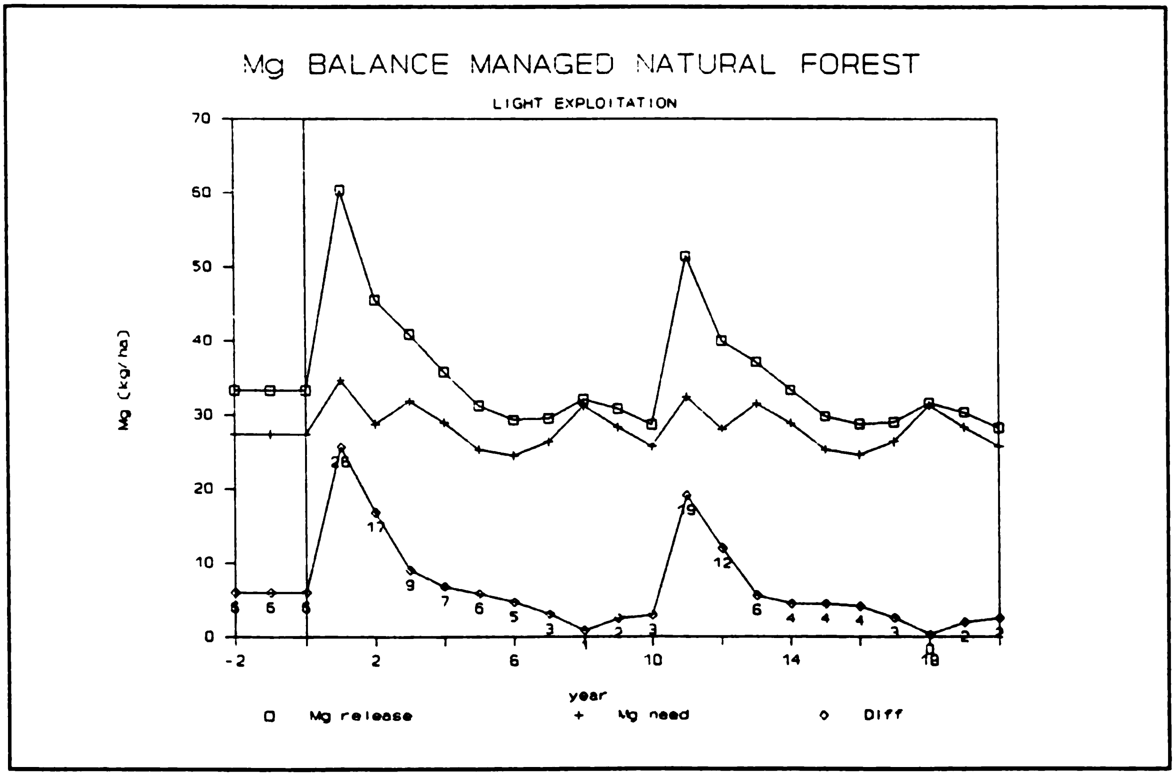

Figure 8. Mg balance in lightly exploited natural forest

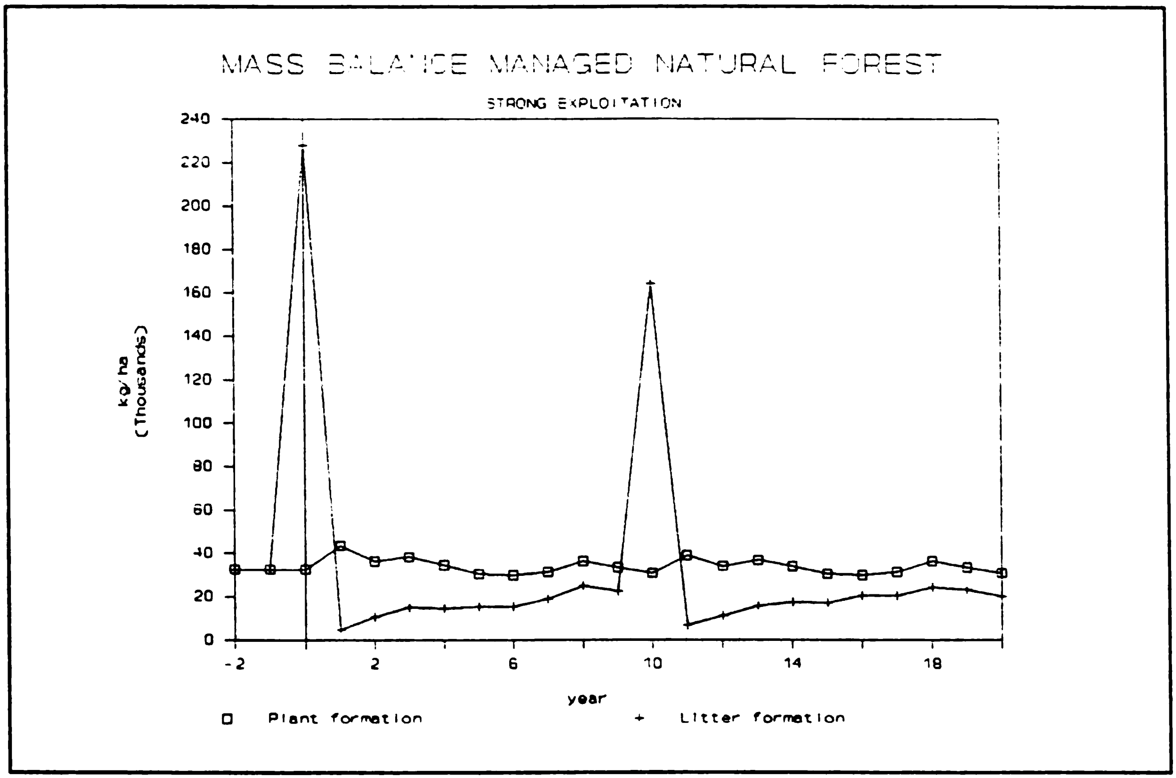

Figure 9. Formation and death of plant components

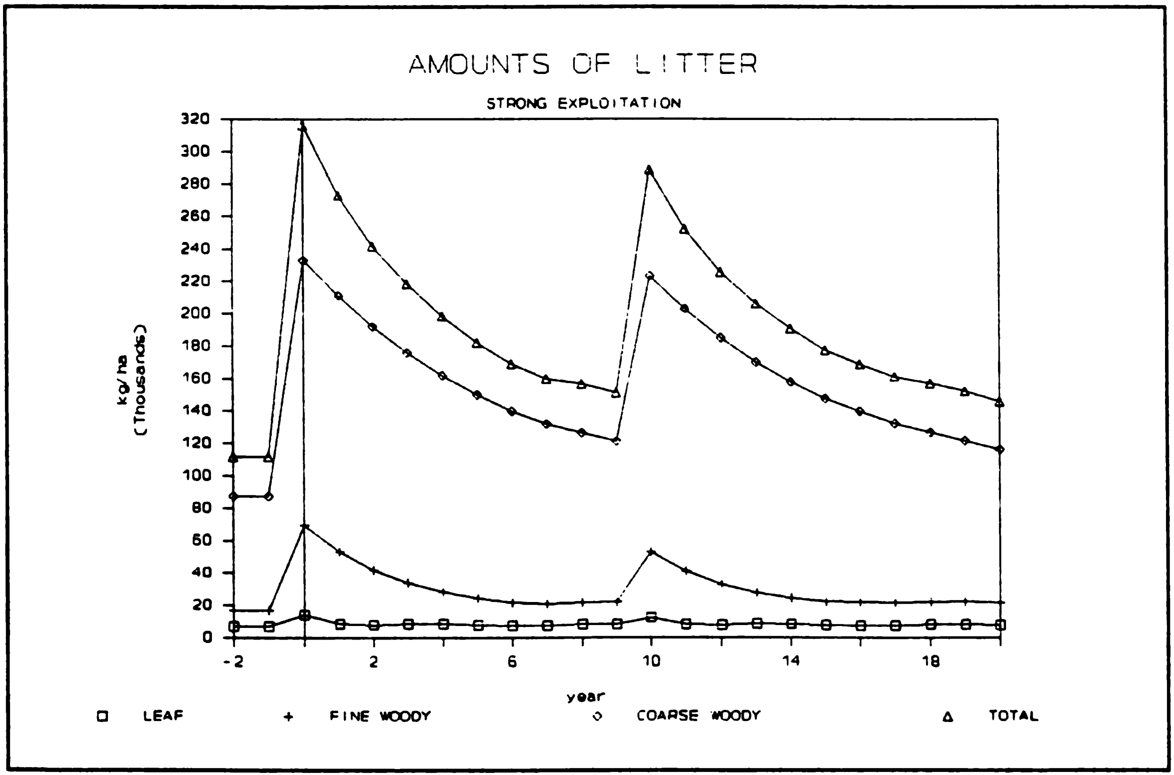

Figure 10. Litter amounts in strongly exploited natural forests

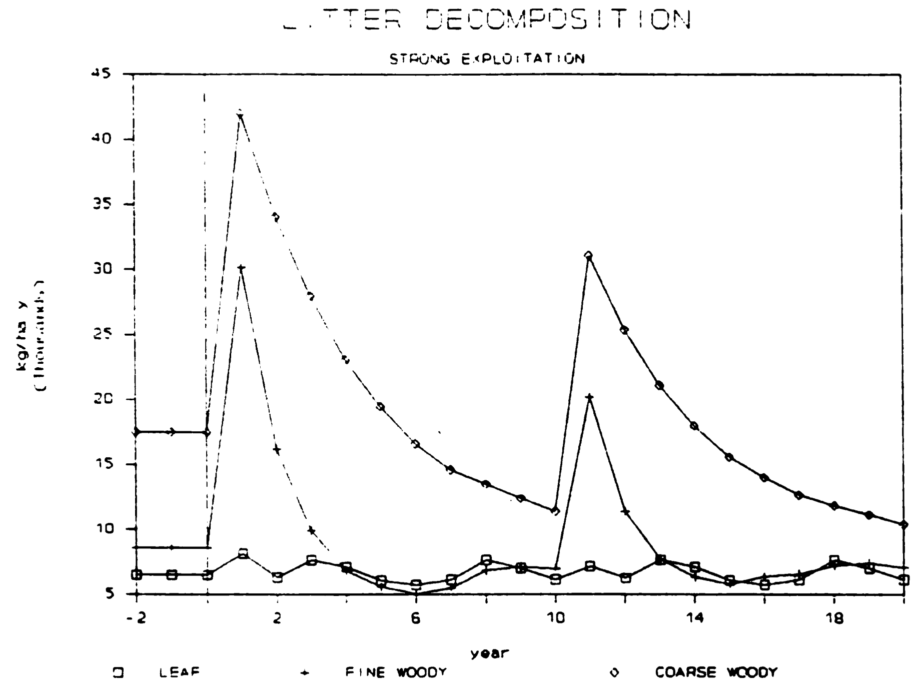

Figure 11. Litter decomposition in strongly exploited natural forest

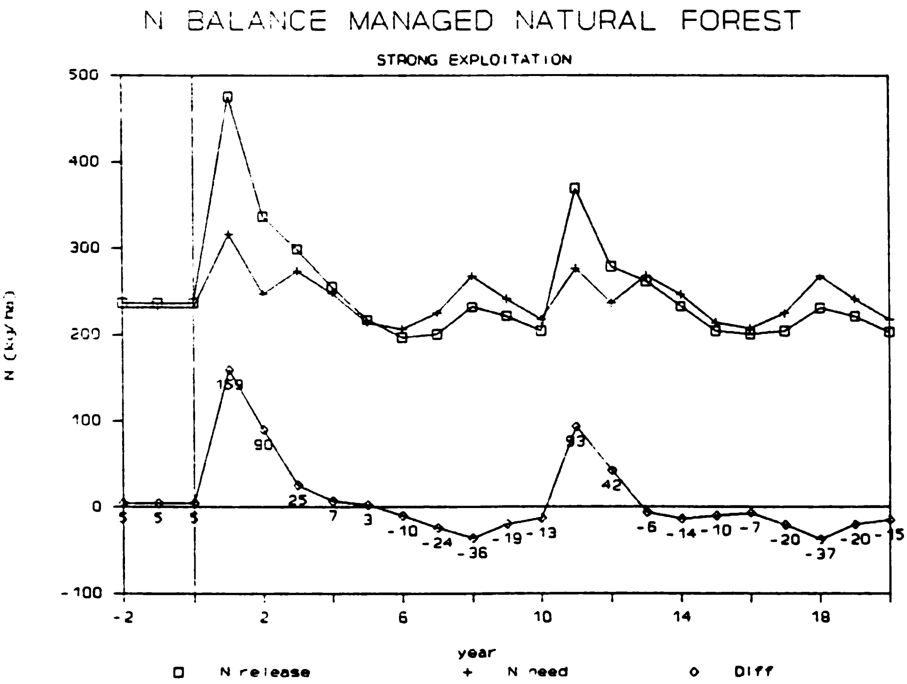

Figure 12. N balance in strongly exploited natural forest

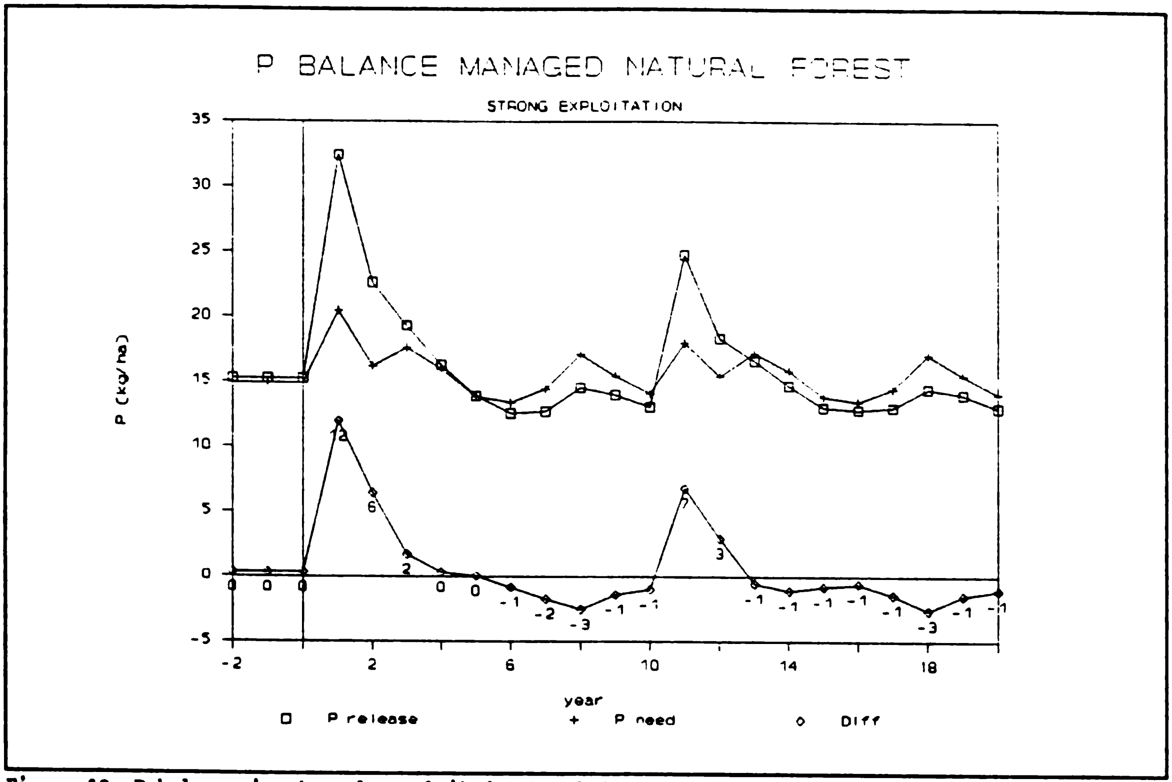

Figure 13. P balance in strongly exploited natural forest

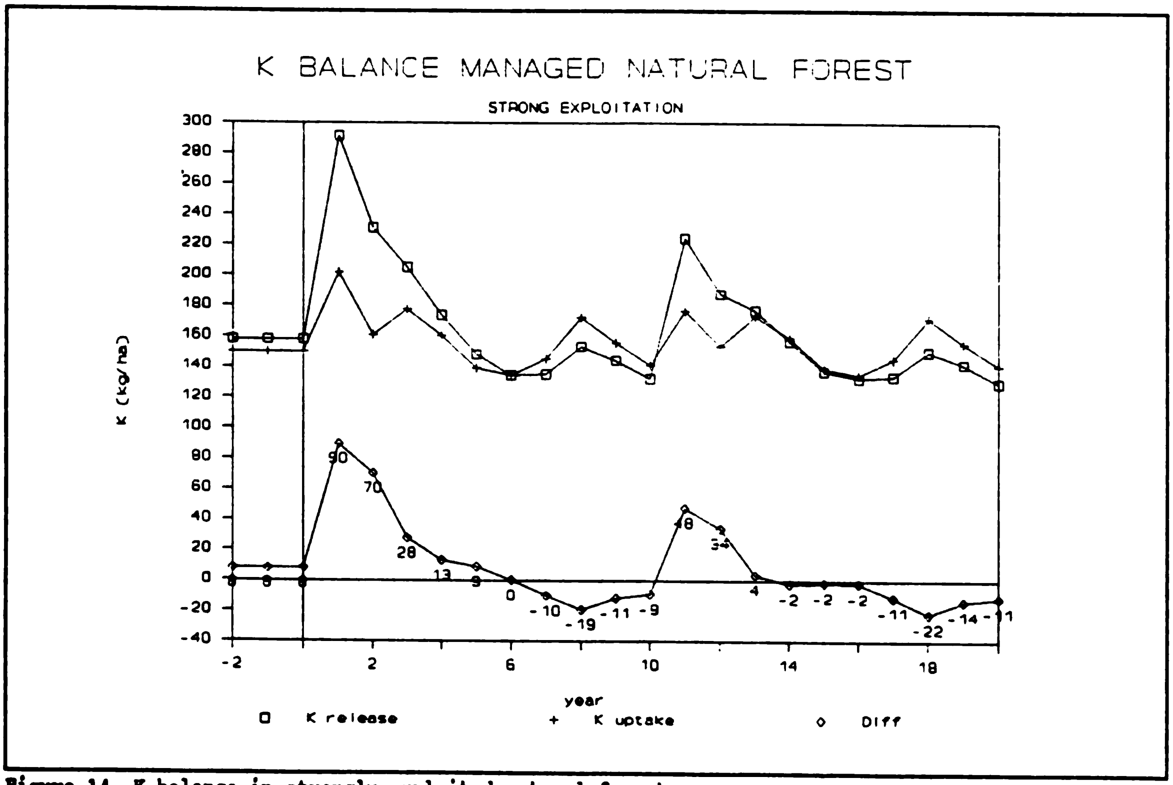

Figure 14. K balance in strongly exploited natural forest

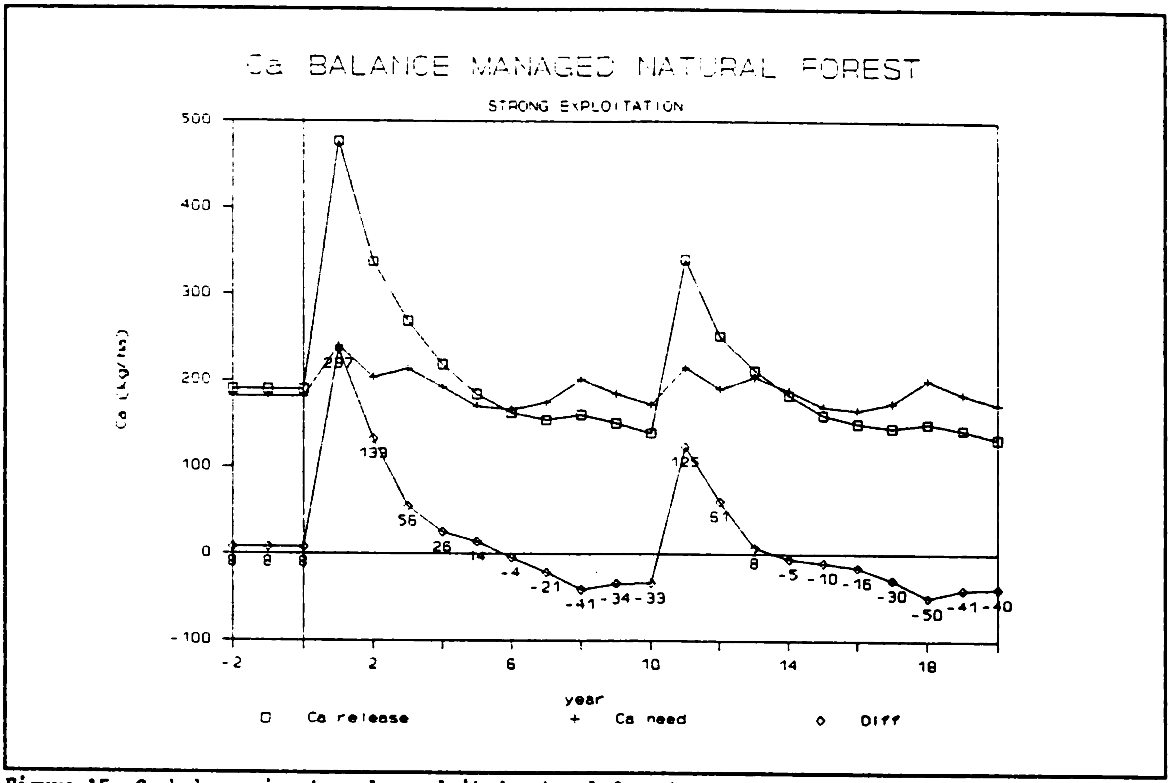

Figure 15. Ca balance in strongly exploited natural forest

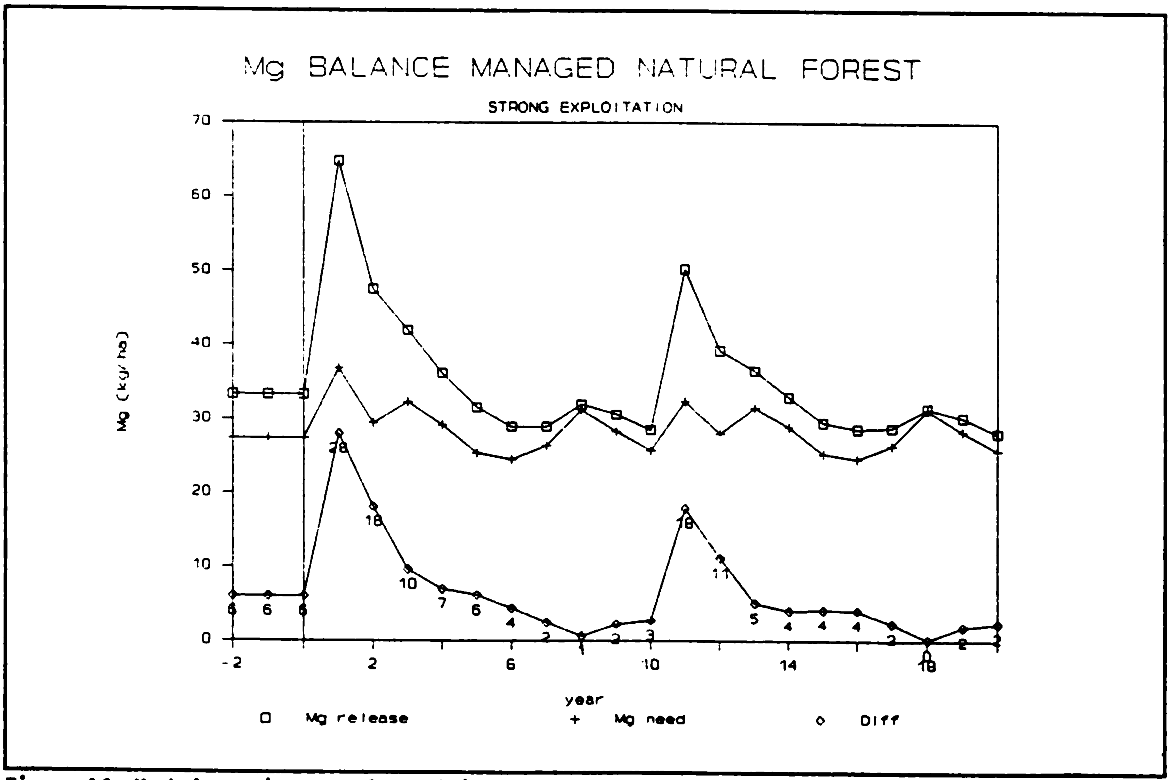

Figure 16. Mg balance in strongly exploited natural forest

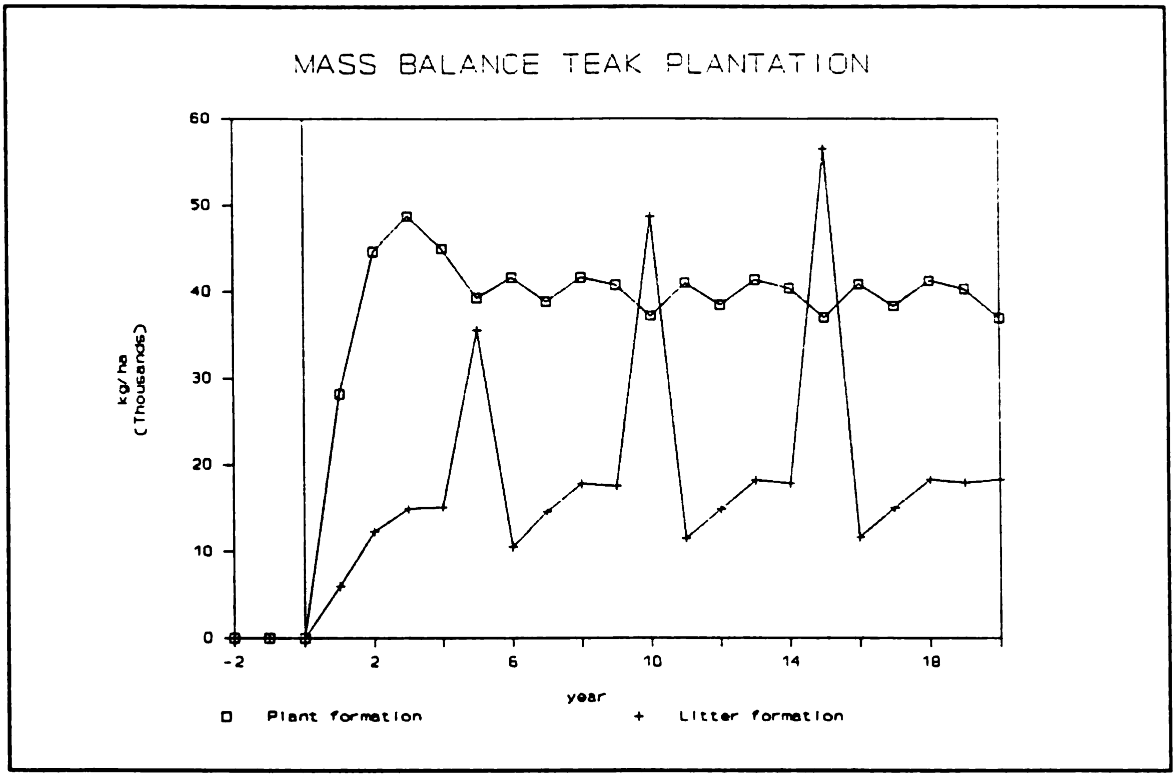

Figure 17. Formation and death of plant components

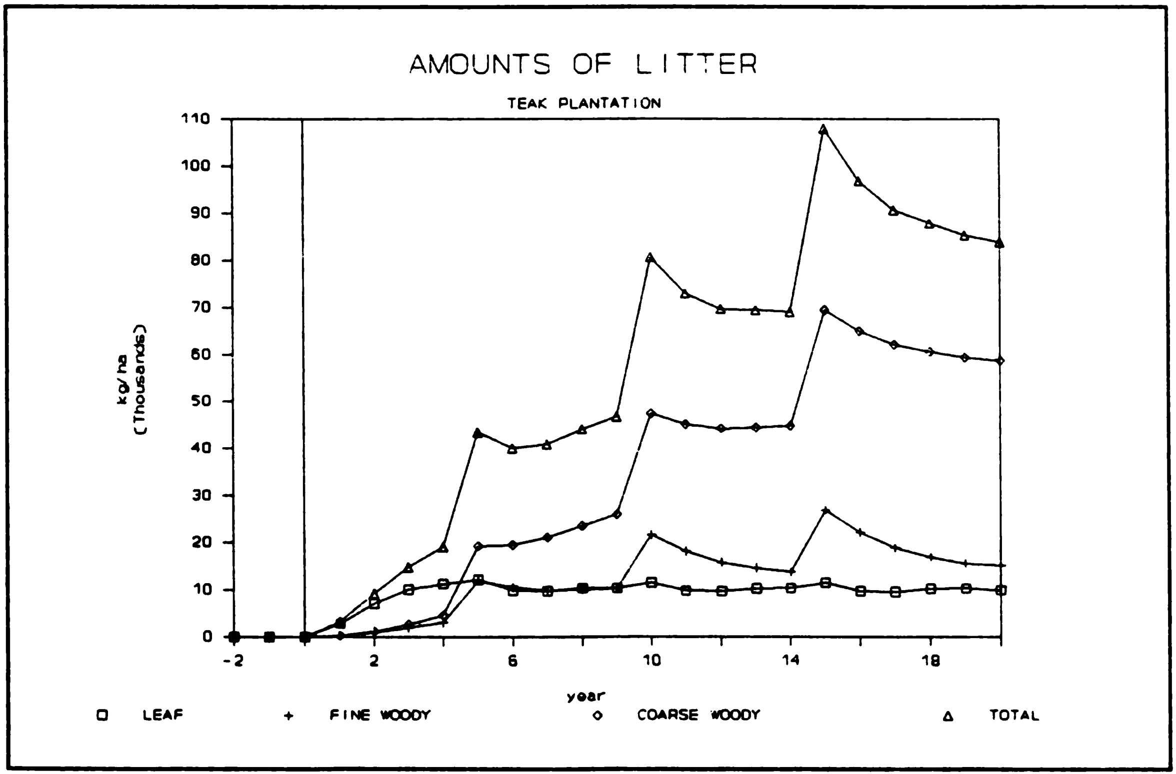

Figure 18. Litter amounts in teak plantation

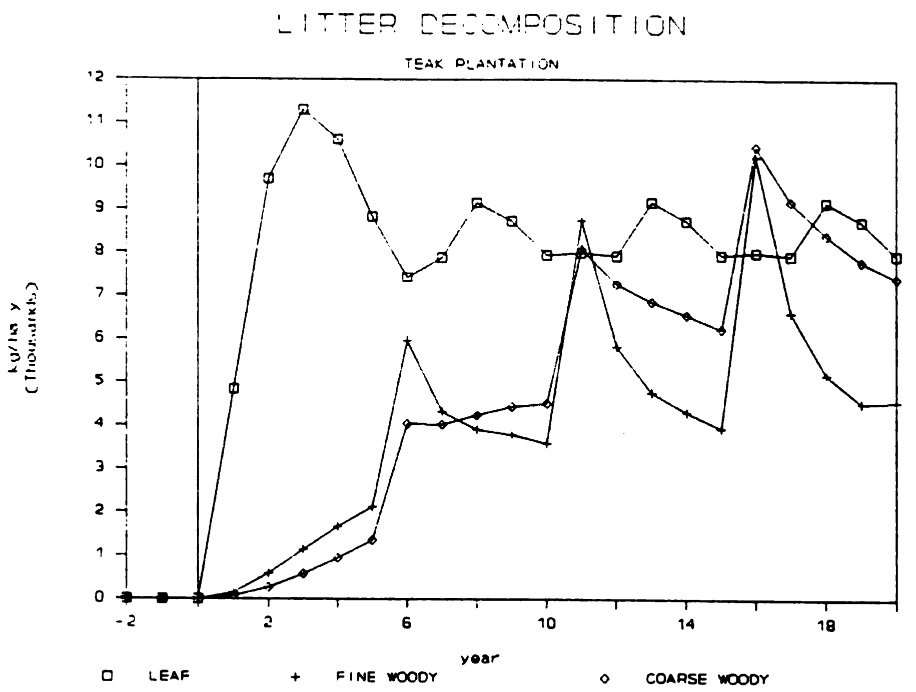

Figure 19. Litter decomposition in teak plantation

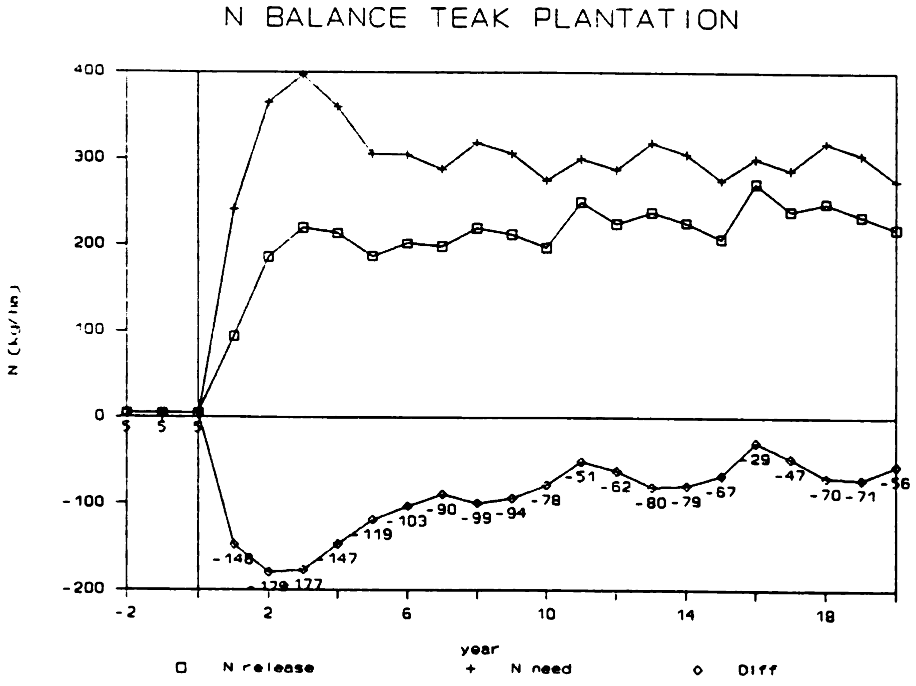

Figure 20. N balance in teak plantation

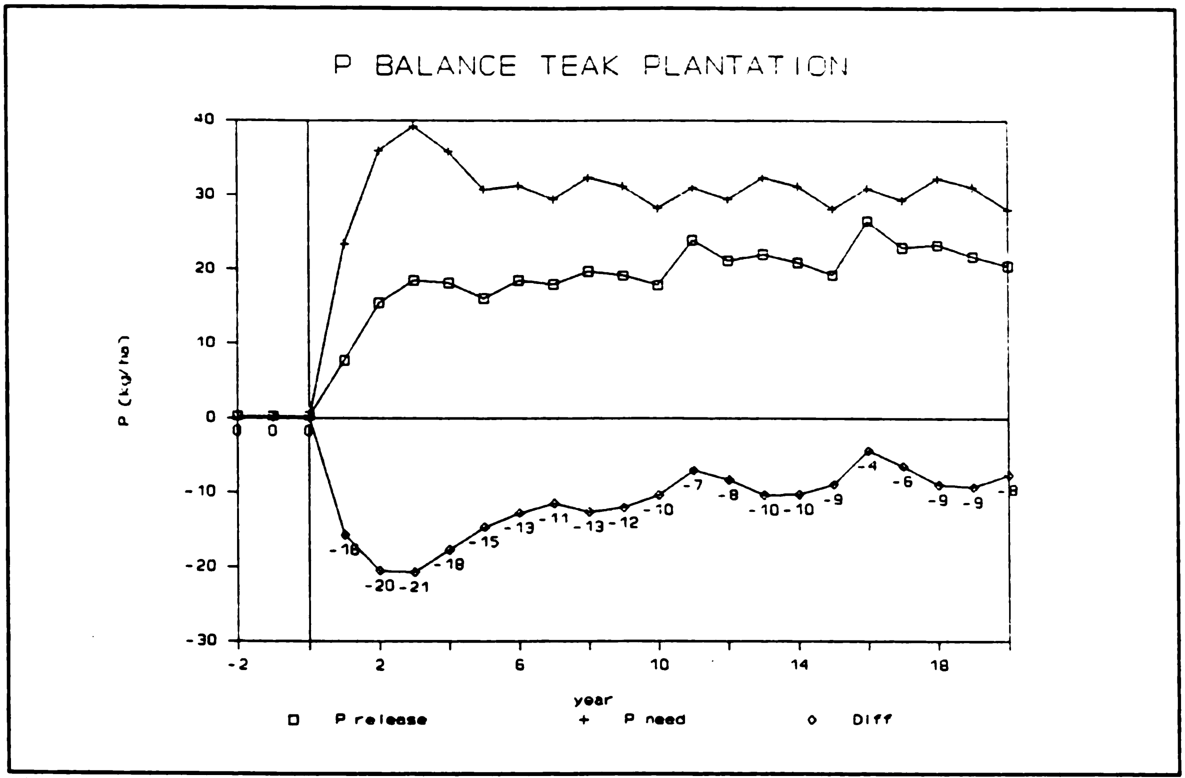

Figure 21. P balance in teak plantation

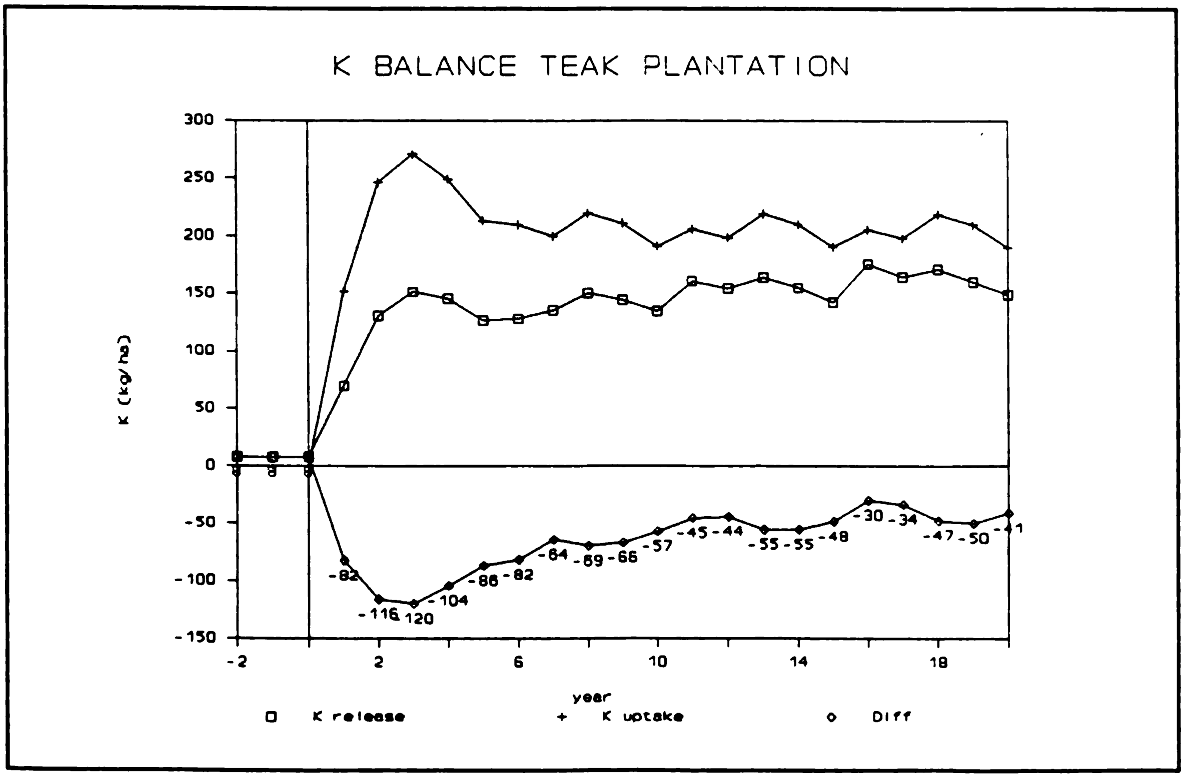

Figure 22. K balance in teak plantation

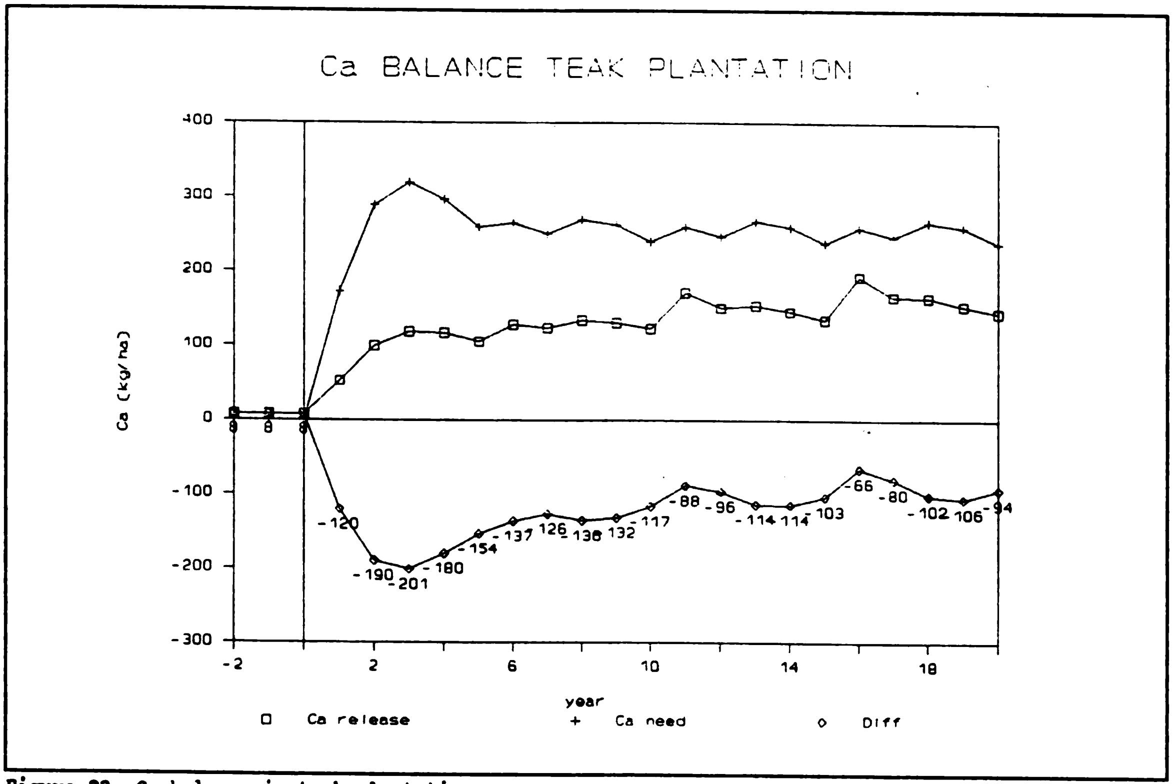

Figure 23. Ca balance in teak plantation

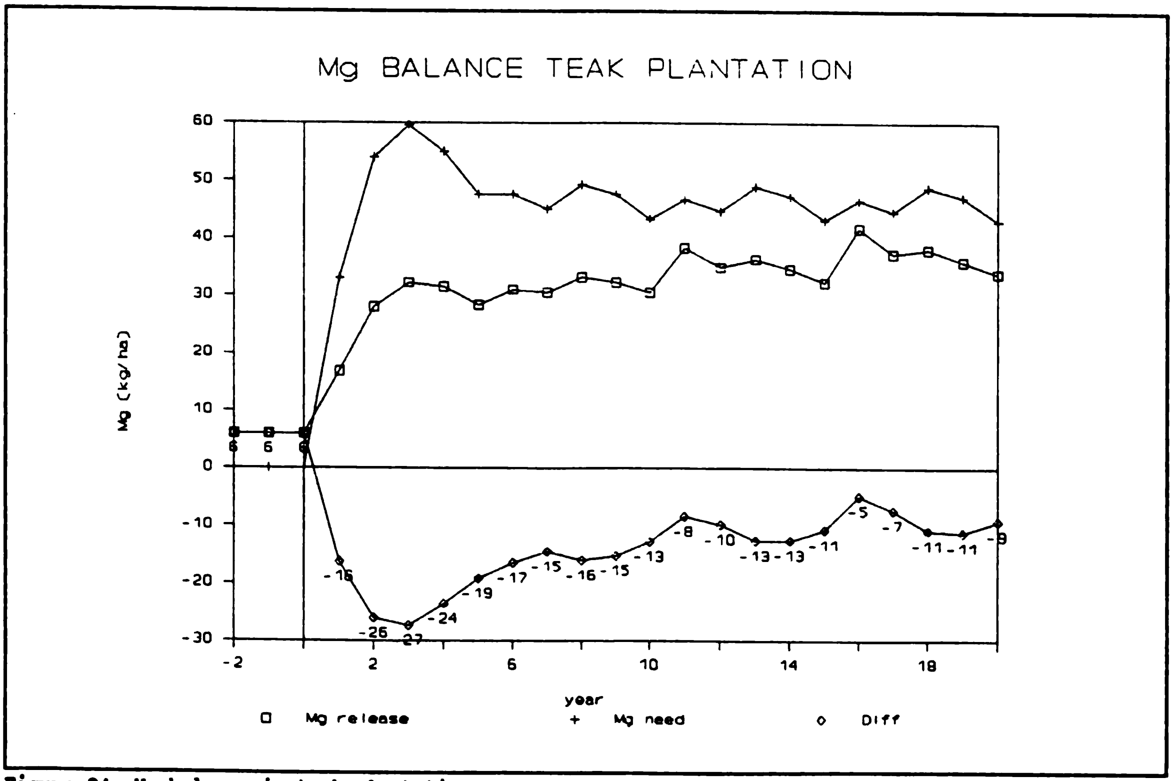

Figure 24. Mg balance in teak plantation