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EFFECTS OF LANDUSE AND WEATHERING ON AVAILABLE NUTRIENTS IN VOLCANIC ASH SOILS OF COSTA RICA

A comparative study

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**CENTRO AGRONOMICO TROPICAL DE
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The overall objective of REPOSA is the development of an interdisciplinary methodology for land use evaluation at various levels of aggregation. The methodology, based on a modular approach to the integration of different models and data bases, is denominated USTED (*Uso Sostenible de Tierras En el Desarrollo*; Sustainable Land Use in Development).

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REPOSA es financiado por la UAW bajo su Programa del Uso Sostenible de la Tierra en los Areas Trópicos. La sede de REPOSA está ubicada en la Estación Experimental Los Diamantes del MAG en Guápiles.

CONTENTS

Tables often referred to:

ANNEXES

Abstract

In the present study two soiltypes; a highly depleted, old soil and a young, fertile soil are compared under three landuse types.

The focus of the study is soil moisture and its chemical composition. As a reference, soil sample analyses and mineralogical data are used. Due to a higher data resolution of the young soil sampling period, the young soil data are treated more extensively.

In the weathering of the young soil under forest, NO_3 and other organic acids were found to play a major role, even though average pH values were still high (about 5). Rain events triggered biomass decomposition to high levels within a day, reflecting the high activity of soil organisms.

The conversion of forest to grassland on young soil was found to enhance the base saturation of the soil and lower the Ca/Mg ratio on the exchange complex and in soil moisture, indicating that a main after effect of logging on these soils is enhanced weathering. The main proton donor for this enhanced weathering (CO_2)is thought to come from the decay of refractory forest remains and humic material in the soil.

The conversion of grassland to plantation led to a lowered base saturation accompanied with extreme concentrations of nutrients in the soil moisture, reflecting the ineffectiveness of used fertilisation techniques.

In de old soil under forest, nutrient losses were, as expected, much lower than in the young soil. Seaspray was found to have a large influence on the old soil forest nutrient regime.

The conversion to grassland on old soil resulted in a lowered base saturation, because the main nutrient holding compartment, the vegetation,(and its seaspray scavenging ability) was removed.

Conversion to plantation led to a situation similar to that of the young soil plantation, along with a pronounced dryness.

1. Introduction

1.1. The aim of the study

When planning the land use of an area, a quantitative knowledge of the effect of land use on the availability of plant nutrients is of capital importance. In this study the evolution of available nutrient content and weathering regime of a young- and an old tropical soil under a sequence of land use types is examined. The study area is the Atlantic Zone of Costa Rica.

1.2. The Atlantic Zone

The Atlantic Zone of Costa Rica comprises the area lying between the Cordillera Central and Cordillera de Talamanca mountain ranges and the Caribbean coast. It covers an area of about 80 by 200 km, and is part of the Limon basin. Climatological conditions are relatively constant throughout the year. Mean annual air temperatures are about 28 degrees and annual precipitation usually exceeds 3500 mm.

The natural vegetation cover was mostly tropical rainforest. In the last two to four decades extensive deforestation, by commercial logging and reclamation for agriculture, has left only about 25% of the original vegetation cover. Current land use is dominated by large scale cattle raising and banana cultivation on plantations. On a smaller scale subsistence agriculture takes place, in commercially logged areas and on former haciendas. Forest clearing for these haciendas has greatly enhanced deforestation in the past.

1.3. Ecology, biogeochemical nutrient cycling, depletion

The rapid changes of land use in the Atlantic Zone over the last decades may seriously disturb ecological balances and, subsequently, the natural nutrient 'economy' of the area.

Plant nutrients play a major role in the ecology of an area. In an ecosystem a constant biogeochemical cycling of nutrients takes place, involving assimilation of elements from the geosphere into the biomass and subsequent release into the geosphere by mineralisation (Rodin and Basilevich, 1967). Within an ecosystem, nutrients may be thought of as occuring in any one of the following six basic compartments (modified from Trudgill, 1979):

1. Atmosphere
2. Living and dead organic matter
3. Available free nutrient pool (soil moisture, topsoil to end of root zone)
4. Potentially available free nutrient pool (soil exchange complex)
5. Unavailable free nutrient pool (adsorbed and dissolved elements beneath the rooting zone)
6. Primary and secondary minerals (in soil and rock)

This study is mainly concerned with the major basic cations: K, Na, Ca and Mg, in the plant available nutrient pool (3). The other main solutes of the available free nutrient pool: H_4SiO_4, NO_3, SO_4, Inorganic Carbon an Cl, as well as Al and PO_4 are also examined, to obtain a better understanding of the processes taking place within this compartment and its interaction with the other nutrient pools.

Nutrient removal from the available free nutrient pool of the root zone is often not balanced by external nutrient inputs. This may result in a net loss of nutrients from this nutrient pool. The pool can be recharged by mineral weathering, biomass decomposition and (plant driven) ion exchange processes within the soil. In an established ecosystem the nutrient removal and addition processes are assumed to approach a state of dynamic equilibrium, or steady state, in which all sources and sinks are balanced and the size of intermediate compartments, like the root zone soil moisture, doesn't change much. If this steady state is disturbed, for instance by extensive logging in a mature forest, depletion of the soil may eventually be the result.

The weathering rate of a soil is usually, among others, a function of its water percolation rate, and thus of rainfall and soil porosity. Another major factor influencing weathering rate is soil temperature. Mineral dissolution speeds up at higher temperatures, and soil biota that contribute to weathering (by homogenizing soil material and by the release of organic acids from dead biomass) have their optimum temperatures of activity in the high regions of soil temperature. (Trudgill, 1979). Average air temperatures and rainfall in the tropics are high. The volcanic parent material in the Atlantic Zone is generally porous, and it's mineralogic composition (mainly volcanic glass, augite and plagioclase, annex 5.2) makes it very liable to rapid weathering. Furthermore, during soil formation soils with Andic properties are formed, increasing the porosity.

These factors contribute to rapid weathering and leaching, making the soils of the Atlantic Zone susceptible to nutrient depletion. Consequently, many older soils in the area suffer from nutrient deficiency. For these depleted soils the main nutrient reservoir is contained in the biomass, which explains why forests on such old soils are to be classified as 'non renewable sources'. After logging, most of the nutrients will have disappeared, and the conditions will become very unfavourable for pioneer plants and agradating forest vegetation.

1.4. Tropical ecology, effects of human intervention

Tropical rain forests can be characterized as ecosystems containing a large biomass, a large pool of chemical elements and rapid cycles of elements between the organic components and the substrate (Golley et al., 1975). This rapid cycling implies that a large part of the nutrients is loosely bound to the system. The efficiency of a tropical forest in recycling its own nutrients is believed to be determined by the substrate. Forests growing on relatively fertile soils tend to be less 'economical' in their nutrient use than mature rain forests on heavily leached, depleted soils. The latter have become highly adapted to their biotope with time and are supposed to approach a steady state situation, in which their turnover of elements from and to the soil is more efficient than that of still growing forests. Their nutrient cycle is tight, resulting in a low loss of nutrients (Van Breemen, personal communication).

When natural vegetation is cleared, and the soil is put into agricultural use, part of the initial biological nutrient pool, and the accompanying nutrient cycle of the vegetation, is lost. Removal of trees causes great losses of nutrients contained within the biomass, although nutrients contained within the foliage may be left behind. Soil compaction, enhanced surface erosion and mechanical surface reworking destroy the soil's structure and important parts of the soil litter layer and A-horizon are removed. Input of herbicides and pesticides and crop harvesting may result in soil toxicity and further removal of nutrients. Annual crops will rapidly exhaust the pool of nutrients most needed for the continuation of natural plant life (nutrients that have a high concentration in fruits, like potassium and phosphorus) (Trudgill, 1979; Bruynzeel, 1990). Fertilizing, common practice in developed countries, is often insufficiently performed in the tropics, due to economical constraints.

Replacement of natural (forest) vegetation by grassland gives rise to similar problems: high initial nutrient losses and loss due to removal of grass (the production of milk and meat).

The severity of an agricultural intervention is determined by its scale and by the vulnerability of the area subject to change. Naturally, the construction of a hacienda, a banana plantation, or commercial logging will affect the ecosystem more seriously than a slash-and-burn cultivation cycle, the former destroying the ecosystem's 'fabric' on a much larger scale. Small patches of land temporarily used are far easier for forests to reclaim than the 'ecological deserts' created by acres of logging or banana plantations. Furhermore, abandoned cattle- or plantation area's are often occupied by squatters; landless subsistence farmers, whose agricultural practices are likely to contribute to further soil degradation, because of their limited knowledge and economical resources. Highly weathered, depleted soils will be affected more by an agricultural intervention than relatively base mineral rich soils.(Simonson, 1970) (Unfortunately, the former are the soils most often granted to landless farmers, after large scale economical exploitation, (plantations, haciendas) has used up most of their still available nutrients.)

In order to maintain soil fertility under agriculture, a careful planning of land use is essential. Keeping in mind that the soil resources of man are limited, it is deplorable that careful use of land isn't more widely practiced.

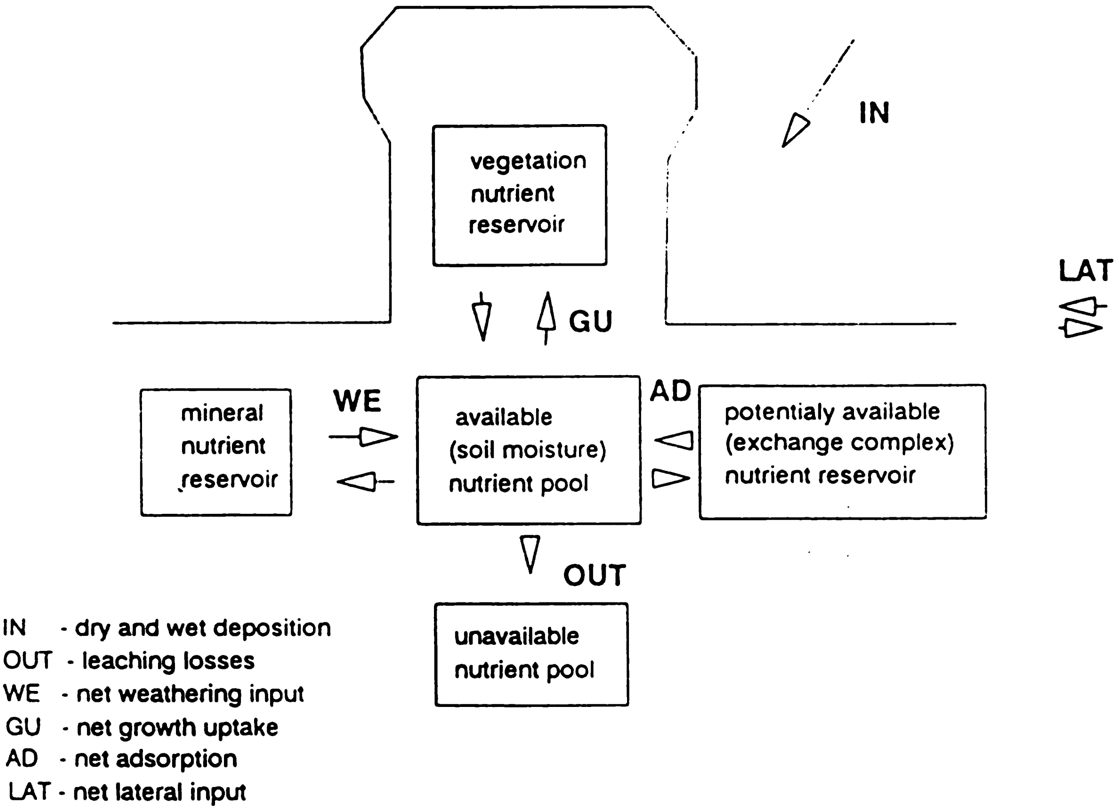
1.5. The present study, nutrient budgets

This study follows the 'evolution' of available nutrient contents and weathering regimes of three different types of land-use on two soil types. This is done by a careful examination and comparison of nutrient outputs, and by making up and comparing nutrient budgets for every investigated site.

The presumption that lies beneath this approach, is that spatial variability of soil nutrient content within the original forest, that covered all sites, was low. The whole study stands or falls with this. Recent data (Burghouts, 1993) suggest that spatial heterogeneity in tropical forest is rule rather than exception. The found results and suggested explaining mechanisms must be seen in the light of these results, and treated with caution. A more or less homogeneous mineralogial and textural composition of the original parent material can be guaranteed by a carefull choice of sites and crosschecked with mineralogical methods (by using an index mineral such as rutile (TiO_2) and micromorphological assurance of textural homogeneity), but the biological history of an ecosystems' soil is much harder to retrace.

In the study, the soil and its vegetation are considered as an integral (open) ecosystem, with several in- and outlets (figure 1.1). Nutrient in- and outputs can then easily be followed. Budgetting comprises a quantitative description of solute inputs into- and their output from the soil moisture nutrient pool. The budget concept helps distinguishing between different nutrient sources and sinks associated with different groups of processes, to get a better grip on the whole cycle. Budget concepts have been widely used, among others in order to quantify the relative importance of anthropogenic and natural sources of H^+ to the acidification of soils and waters (Van Breemen et al., 1984).

An overall nutrient budget of a system can be derived by measuring and estimating in- and outputs of solutes, having first defined the nutrient sources and sinks of the system.



IN - dry and wet deposition
OUT - leaching losses
WE - net weathering input
GU - net growth uptake
AD - net adsorption
LAT - net lateral input

Figure 1.1 Nutrient reservoirs and fluxes in a natural plant-soil ecosystem

The nutrient sources of the investigated systems include:

- dry and wet atmospheric deposition
- lateral influx
- weathering of soil minerals.
- desorption from the exchange complex
- biomass decomposition
- Anthropogenic inputs

Nutrient sinks include:

- leaching
- lateral runoff and surface erosion
- reverse weathering (formation of secondary minerals)
- adsorption at the exchange complex
- biomass growth uptake (Bruynzeel, 1983)
- Anthropogenic outputs

- **Dry and wet deposition** find their source in fine atmospherical dust and aerosols. These are mainly the result of wind erosion, sea spray mixing with air and volcanic activity. The dust and aerosols are scavenged by rain (wet deposition) or settle naturally. (Another important dry deposition input factor, especially for phosphorus, can be bird droppings. Total nutrient amounts following this pathway are, however, usually low.) (Minderman en Leeflang, 1968. Trudgill, 1979).

- **Lateral in- and outputs** are the result of nutrients carried (in eroded material) by overland and subsurface flow of excess precipitation. Deposition of this type will be most pronounced at the bottom of slopes and in valleys, and erosion loss will be greatest on steep slopes (Bruynzeel, 1990).

- **Weathering of soil minerals** essentially involves a sequence of dissolution processes, during which initial primary minerals are degraded into an array of secondary minerals, each further depleted in nutrients. During soil formation nutrientrich basic minerals of the parent rock slowly disintegrate under the influence of dissolved biogenic acids, releasing their nutrients. Nutrients that are incorporated in secondary minerals (reverse weathering) are often eventually released into solution again (Simonson, 1970).

- **Biomass decomposition and growth uptake** can be summarized as the 'biomass net growth uptake'. For a mature natural forest on a poor substrate the net growth uptake reaches its lowest value and approaches zero (steady state). For annual crops net growth uptake reaches its maximum values. (Golley et al., 1975).

- **Adsorption at and desorption from the soil exchange complex** depend greatly on external factors like the type of vegetation and the season. The exchange complex serves as a buffer, temporarily storing nutrients. For a mature natural vegetation the adsorption-desorption processes are assumed to have reached a steady state in which the net adsorption is zero. Changes in landuse will typically disturb this balance.

- **Leaching** is the result of soil moisture percolating down the soil and out of the rooting zone. The soil-plant system under investigation is a subsystem of its local catchment and eventually lies within the global biogeochemical cycle. Rainfall, and gravity potential, as determined by local relief, result in a continuous introduction of fresh water to the topsoil, usually with a low concentration of elements. On its way out of the soil this water scavenges part of the nutrients, producing a situation of net nutrient loss. (Simonson, 1970).

- **Athropogenic in and outputs** can be summarized as net human input. This net input can be extremely negative, as in logging, or extremely positive, in the case of for example overmanuring. Human impact is almost always large, and net human input is almost never zero, due to the continuous nature of in and outputs in time and space.
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1.6. A nutrient budget for primary forest

With the previously described sources and sinks, and the compartments defined in section 1.3, (see also fig. 1.1), a nutrient budget can be made for the available free nutrient pool:

$$\Delta PS = \mathbf{FSout} - \mathbf{FSin} - \mathrm{FSwe} - \mathrm{FSlat} + \mathbf{FSgu} + \mathrm{FSad} \qquad 1.1$$

Where:

ΔPS	change in the total Pool of Solutes in the soil moisture of the root zone
FS	Flux of Solutes from or to the availabe free nutrient pool
in	input by deposition (wet)
out	output by leaching
we	net input by weathering (can be negative: reverse weathering)
lat	net lateral input (can be negative)
gu	net growth uptake output (can be negative)
ad	net adsorption output (can also be negative)

The new compartment introduced here is lateral input. It is of course no compartment in the sense of section 1.3, but its effect has got to be taken into consideration when measuring on a relatively small spot within a catchment.

For the sake of convenience, for all systems, during the short time interval of sampling, a state of partial equilibrium is assumed, in which:

$$\Delta PS \approx 0. \qquad 1.2$$

The simplest way to make up a nutrient balance is measuring the nutrient input by precipitation and output by percolation on a site with minimal FSlat (by chosing a site with a lowest possible slope, minimal surface erosion and runoff). Equation 1.1 becomes:

$$\mathrm{FSout} - \mathrm{FSin} = \mathrm{FSwe} - \mathrm{FSgu} - \mathrm{FSad} \qquad 1.3$$

Of course in doing this the contribution of dry deposition is assumed to be neglegible. This may seem a gross oversimplification. However, the high rainfall of the study area will scavenge most of the aerosols, so dry deposition can probably be disregarded.

Also, the bulk of the intermediate and eventual secondary minerals formed in the soils under investigation are non nutrient containing: Allophane, Halloysite, Kaolinite and Gibbsite. (See. annex 2.2). Reverse weathering is therefore not a probable nutrient sink.

When measuring FS**out** in the field, effects of preferential flow, and (sub)surface runoff (FS**lat**) can greatly distort final results. These effects can be minimised with a careful choice of the experimental site.

In this study, nutrient discharge, FS**out**, was measured at the bottom of the rooting zone. Streamflow discharge from the system's catchment was not considered, since this does not necessarily reflect the total loss of 'plant available' nutrients. The reason for this lies in the fact that the soil's weathering base may lie well below the rooting zone, supplying nutrients to the stream that are not related to the root zone available nutrient pool. (Bruynzeel, 1990).

1.7. Nutrient budgets for agricultural systems

For agricultural systems, be it grassland or plantation, a similar balance can be made up. The budget becomes:

$$\Delta PS = FS_{out} - FS_{in} - FS_{we} - FS_{lat} + FS_{gu} + FS_{ad} - FS_{anth} \qquad 1.4$$

With as an extra term:

FSanth net anthropogenic input (fertilizing, harvesting: can be negative)

Here too, FS**lat** and other above mentioned factors can be minimised by a careful choice of site. However, human nutrient inputs by fertilisation and outputs by harvest and meat / milk production need to be known as well. The equation becomes

$$FS_{out} - FS_{in} = FS_{we} - FS_{gu} - FS_{ad} + FS_{anth} \qquad 1.5$$

(Similarly to the natural system, for the short measuring period, partial equilibrium for the soil moisture is assumed, in which the change in the moisture pool, ΔPS, is taken to be neglegible).

After balances have been made up for the three land use types on both soils, comparing them should give an idea of how the nutrient status of both soil types evolves under different land use, and how this influences soil weathering regimes and weathering rates.

2. The study areas

2.1. Introduction

Two locations were selected to carry out the study. The first study area, La Lucha (from now on to be called LLA), is a small scale, government backed agricultural settlement, located in the Neguev district (fig. 2.1). The area, a former hacienda, was occupied about ten years ago by landless farmers and subsequently granted to them by the governmental Institute of Agricultural Development IDA in the early eightees. Since then, it has been subject to subsistence agriculture and domestic cattleraising.

Farmers own parcels of about 15 ha. Various crops for the local market and home use, like plantain, cassava, pineapple and heart of palm (palmito) are raised. Most farmers own some cattle as well.

The second study area, 'Lomas de Sierpe' (from now on to be called LMS), is a 450 ha (still expanding) banana plantation, located just west of the Lomas de Sierpe hills (fig. 2.1). This area has also been a cattle raising area, from the beginning of the eighties until 1992, when it was bought by private foreign investors. Planting started in mid 1992..

Both areas were completely covered by primary rainforest up until the late fiftees.

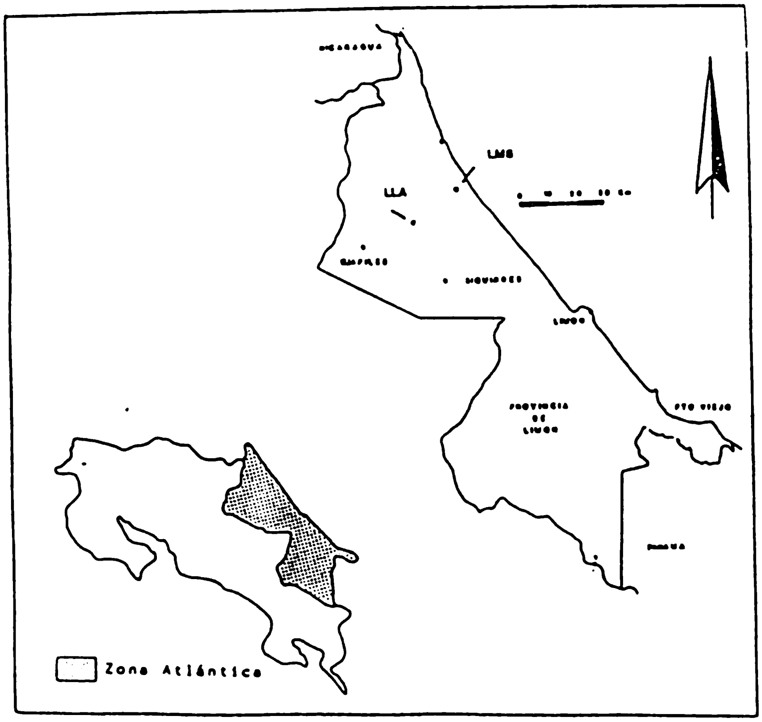


figure 2.1. Location of the Atlantic Zone of Costa Rica and the LLA (La Lucha) and LMS (Lomas de Sierpe) sampling locations.

2.2. Geology and geomorphology, soils

The study areas lie within the Atlantic Zone of Costa Rica. This zone forms part of the Limon Basin, an andesitic back-arc sedimentary basin (Weyl, 1980). Most of the basins' surface is covered by alluvium derived from the Central American volcanic arc. At the foot of the volcanoes, this material is found as alluvial fans and lahar deposits. In the alluvial plain it is mainly found as sandy to loamy fluvial deposits of volcanic material. Approaching the eastern coast, some extinct alkalibasaltic volcanic cones crop out. The coastline is made up of beachridges of the same volcanic sands.

The studied LLA soil type ('Neguev type'), an Ultisol, is an old, strongly depleted soil type (Annex 2.1). It has been formed from essentially the same parent material as younger, more fertile soils in the area. Neguev type soils are found on small 'red hills' scattered trough the Atlantic zone, that tend to grow lower towards the coast. The hills are believed to be relicts of Pleistocene volcanic alluvium (Nieuwenhuyse, personal communication).

Pleistocene sediments were deposited during the last interglacial, at a sealevel and erosion base higher than the current one. As a consequence of sea level drop during the last glacial maximum, the sediments became dissected, forming a steep topography of hills and valleys. Subsequent Holocene sealevel rise led to sedimentary infilling and partial burial of this landscape, giving rise to the actual geomorphology. Impeded drainage caused by the Holocene infilling results in swampforming in many valleys in 'red hill' area's.

The Pleistocene parent material is strongly weathered, down to several meters below the surface. Mineralogical analysis indicates that the mineral soil fraction consists mainly of gibbsite (sand and silt fraction), kaolinite and halloysite (clay fraction). For a more detailed soil micromorphological description see annex 2.2.

The studied LMS soils, Fluvisols with andic properties, are Holocene, relatively fertile soils. The area is located in the aluvial plain just west of the extinct volcanic cones of the Limon basin. Parent material consists mainly of Holocene alluvium. The age of the parent material is aproximately 2 Ka. The alluvium can be divided in two main groups: Coarse sandy fluvial deposits that can be found as ridges filling former riverbeds. These coarse sandy deposits are believed to be the result of catastrophic saturated flow events during heavy rainfall. The second type are loamy to clayey fluvial deposits, that can be considered as overbank deposits. Miscellaneous soil types are basin clay deposits and neguev type hillocks.

Summing up, one LLA soil type was investigated:

- A welldrained soil with a highly weathered (gibbsitic) substrate

The investigated LMS soils can be divided into two main units:

- Welldrained soils with a coarse sandy base rich substrate
- Poorly drained soils with a loamy base rich substrate

As an indication, in table 2.1 some soil analysis data are summarized.

Table 2.1. Some soil data of LMS fluvisols with andic properties and a LLA ultisol. The LMS loamy- and sandy soil are under banana plantation, whereas LLA soil is under forest

			<- (cmol/kg) ->				ammoniumoxalate extractable	base		
Depth(cm)	pH KCl	tot.ac.	ex. Al	ex.H	Fe(%)	Si(%)	Al(%)	CEC*	satur.(%)	Corg(%)
1LMS, sandy soil										
0-10	4.56	0.78	0.54	0.23	0.8	0.6	1.9	13.4	31	3.9
30-40	5.3	-	-	-	0.7	0.6	1.7	6.9	36	1.2
90-100	5.18	-	-	-	0.6	0.4	1.0	5.7	49	0.5
LMS, loamy soil										
0-10	4.24	3.90	2.26	1.64	1.4	0.2	1.1	23.7	41	4.0
30-40	4.54	0.60	0.25	0.35	1.2	0.2	0.7	21.9	73	1.1
70-80	4.59	0.11	0.05	0.06	0.6	0.1	0.3	22.8	77	0.7
LLA soil										
0-10	3.88	7.36	6.24	1.12	0.9	0	0.5	17	3	3.7
30-40	4.03	5.02	3.30	1.71	0.3	0	0.5	8.4	2	0.7
100-110 4.03	5.42	4.09	1.34	0.3	0	0.5	10.3	3	0.7	

* The discrepancy between CEC and total positive charge (see also table 5.20) is treated in section 3.7.

3. Materials and methods

3.1. Introduction

For a comparative study of how land is affected by change in land use type, a 'chronosequence' of land use types is the most convenient. The usual scenario for landuse change is from primary forest to agriculture, and as the soil becomes depleted, to grassland. The studied soils have undergone a somewhat different land use sequence, evolving from forest to grassland and subsequently to plantation, but the principle remains the same.

In this study two end member soils of the chain of soil types constituting the soil weathering sequence of volcanic alluvium under tropical conditions are compared. A relatively young, fluvic andisol on riversands of volcanic origin, at LMS, and a highly weathered, Pleistocene ultisol of mainly gibbsitic material at LLA . For both soil types a land use chronosequence is studied.

During January to March 1993, nutrient fluxes were measured on ultisols in the LLA vicinity. Sites were chosen under the three main land use types of the area; (altered) primary forest, palmito plantation and grassland.

During March to June 1993, samples were taken from young fluvisols with andic properties in and around the LMS banana plantation. Sites were selected under primary forest, within the plantation, and under grassland.

To estimate nutrient fluxes, the folowing assumptions were made:

1. Hydrological characteristics of soils and plant evapotranspiration values as derived from literature and other secondary sources apply to the study area.
2. lateral in- and outputs under all sites are neglegible.
3. dry deposition and reverse weathering are neglegible.

- **FSin** was calculated from (adapted, see section 5.2) rainfall measurements and measured nutrient concentrations in rainwater.

- **FSout** was determined by measuring solute concentrations below the rooting zone, and modelling water fluxes in the subsoil with help of measured and literature derived parameters.

The general equation used for nutrient flux calculation from the available data, is:

$$FSi\ (kg\ ha^{-1}\ yr^{-1}) = Ci \times Fi \times m \times yearfact. \times 10^{-5} \qquad 3.1$$

Where:

FSi	cumulative flux of solute in flux Fi (kg ha^{-1} yr^{-1})
Ci	solute conc. in flux Fi (mmol/m^{-3})
Fi	cumulative solvent flux i during sampling period (mm)
m	atomic weight of solute (g/mole)
yearfact.	365 / time interval of sampling period (days / days)

3.2. Selection of soil moisture sampling sites

For LLA soils the following three types of landuse were selected:

- (altered) primary forest
- ten year old grassland
- five year old palmito plantation

Sampling sites were on the rather large (0.2- 0.4 ha) summits of red hillocks. The hydrological situation was thus chosen as simple as possible, **FSlat** influence was minimised. Preferential flow and (sub) surface runoff were assumed to be neglegible (no large cracks were observed in the soil).

For the forest, sampling sites were chosen that had remained more or less undisturbed in the past decades, and presumably also in the preceeding ages. This was done by chosing sites with little or no undergrowth (disturbance of primary vegetation often causes thick undergrowth). Possible effects of past agricultural practices of early indigenous inhabitants was ruled out by chosing sites on spots not likely to have been used for such practices (high density of mature trees).

Local variabilities in soil structure were minimised as much as possible, by chosing the sites relatively close together, (fig. 3.1 a). In this way, possible deppositional grain size effects of the Pleistocene alluvium, that may have resulted in a different soil formation history and subsequently in different soil properties, were ruled out as much as possible.

For LMS soils three comparable types of landuse were selected:

- well-drained sandy soil under primary forest
- well-drained, sandy soil under ten year old grassland
- well-drained, sandy soil under a half year old banana plantation
- moderately well-drained, loamy to clayey soil under the same plantation .

Sites were selected using the same criteria as for LLA soils; at highest points in the local relief, with a relatively large horizontal area within the landscape. Thus the influence of **FSlat** was, also here, made as small as possible. The sandy soils were selected in a former riverbed, filled with coarse grained volcanic alluvium deposited during a cathastrophic saturated flow event, dated 2 ka B.P. (Nieuwenhuyse, pers. com.). Thus a high similarity of grainsize was guaranteed (fig. 3.1 b). The selected loamy sites are probably 'overbank deposits' of the same event. Here too, preferential flow and subsurface runoff efects were assumed to be neglegible.

3.3. Rainfall sampling, meteorological measurements

Rainfall samples were collected using a device consisting simply of a suspended plastic funnel and a polyethylene bottle (fig. 3.2). Because of low element concentrations, rainwater samples are very susceptible to contamination. Bird faeces and insects are notorious contaminants. To reduce the contamination risk as much as possible, plastic bottles were attached at the very moment of sampling. Just before sampling the funnel was cleaned by washing with demineralised water. A plastic 'skirt' was attached to the funnel to prevent rainwater flowing along the outside of the funnel from entering the sampling bottle. Full bottles were immediately removed, to avoid overflow effects.

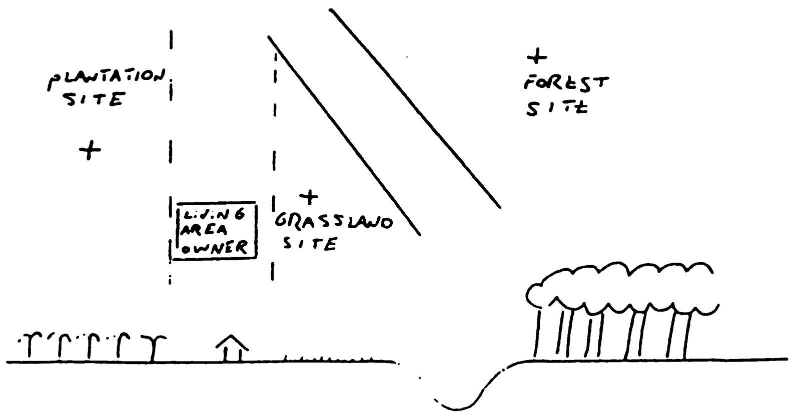


figure 3.1 a. Schematic representation of the LLA sampling area with indicated location of sampling sites. The solid line reprents a small swampdepression between two red hills filled up with holocene deposits.

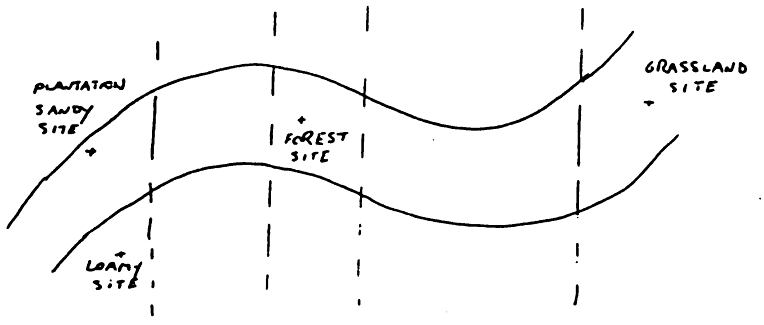


figure 3.1. b. Schematic representation of the LMS sampling area, with indicated sampling sites. Curved lines represent coarse grained alluvium filling up a former riverbed. Dashed lines represent the borders between various land use types.

LLA sampling was done at ground level. Suspecting contamination by road dust, At LMS a device similar to the one in LLA was employed 15 meters above groundlevel, to minimise the risk of contamination.

During the LLA sampling period max. air temperature, relative air humidity and rainfall were measured daily. The first measuring period fell in gthe dry season of the year; January to March '93. The average max. temperature was 32°C and average relative air humidity 85%.

LMS daily meteorological data were derived from a small local purpose weather station. Average air temperatures were round 30°C, average rel. air humidity 87%.
Total rainfall figures over the period are listed in table 3.1.

Table 3.1 Cumulative monthly rainfall depth at the sampling locations

	LLA rainfall (mm)	LMS rainfall (mm)
January	241	312
February	187	339
March	- *	428
April	- *	200
May	- *	346

* not measured

3.4. Soil moisture sampling

Soil moisture samples were collected using RHIZON soil moisture samplers, small tube shaped collectors (ϕ 2.5 mm) of a porous polymer material. Samplers were connected to evacuated 100 ml septum stopper glass bottles. The porous polymer coating of the samplers is airtight when wet, and in this state only permeable to water and its solutes. By applying vacuum to the glass bottles soil moisture was extracted. (for more details see annex 3.1)

Samplers were placed at two depths:

- A depth of aproximately 10 cm, just below the A-horizon
- A depth ranging between 60 and 200 cm, just below the rooting zone.

Rooting zone boundaries for the different vegetation types are listed in table 3.2. Since trees tend to root very deeply, the boundary of the rooting zone was determined arbitrarily for the forest as the depth above which about 90% of the total root mass is present. For palmito the same criterium was applied.

Table 3.2. Lower boundaries of rooting zones of the examined vegetation types on their soils

Vegetation		lower boundary of rootzone (cm)
Forest	(LLA)	180
Forest	(LMS)	190
Grassland	(LLA)	60
Grassland	(LMS)	70
Palmheart	(LLA)	160
Banana	(LMS) sandy soil	100
Banana	(LMS) loamy soil	50

Samplers were placed at an approximate intersampler distance of 20 cm, to avoid mutual interference of moisture extraction zones. The sampling wall of the profile pit wall was covered with a plastic sheet to avoid drying out of the profile, (fig. 3.3), that would have resulted in different percolation patterns, like preferential flow. Three samplers were placed in the topsoil, and three 1samplers below the root zone. Soil moisture samples were pooled per soil horizon, into polyethylene 100 ml bottles.

Samplers were checked everyday for yield, malfunctioning parts were replaced, and samples collected if possible. To avoid microbial and algal growth, three drops of chloroform were added to the pooled samples, which were then stored at 11°C.

Some samples of a well draining the LLA forest area were also taken, to get an idea of gross nutrient removal out of this system. This could not be done for LMS sites since these were drained by canals, that held large amounts of pesticides and fertilizer. For LMS sites, grassland water samples collected below the groundwater table are assumed to represent gross average removed nutrient concentrations.

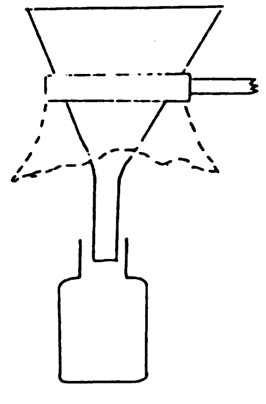


figure 3.2. Rain sampling device. Dashed lines represent plastic-'skirt'. Bottles were attached at the moment of sampling

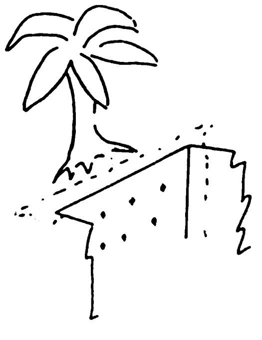


figure 3.3. Schematic representation of a soil moisture sampling site. Dashed lines represent the plastic sheet used to prevent the profile from drying out. The crossed circles represent sampler placements.

3.5. Sample analysis

Samples were analysed at three different laboratories. The services of two local laboratories were used. The first batch of samples was sent to the 'Laboratorio de Suelos del MAG (Ministerio de Agricultura y Ganaderia)', the Soil Laboratory of the the Ministery of Agriculture and Cattleraising, Costa Rica. Later samples were sent to the laboratory of CATIE, the 'Centro Agronomico Tropical de Investigacion y Enseñanza', or Agriconomical Tropical Centre for Investigation and Extention, Costa Rica, because of low resolution of the MAG data.

The greater part of the samples was eventually analyzed at the laboratory of BENG, the Department of Soil Science and Geology of the Wageningen Agricultural University, the Netherlands, this laboratory having the best facilities.

A comparison between the MAG and CATIE laboratory results and between the CATIE and Wageningen laboratory results was made by splitting a number of samples for dual analysis. In this way an idea of the reliability and comparability of analysis results was obtained. Most of the LLA samples were analysed at the MAG laboratory, whereas most of the LMS samples were analysed in Wageningen. Table 3.3 gives a list of the distribution of the different samples among the laboratories.

Table 3.3 Percentage of samples sent to each laboratory

LLA samples	LMS samples	
53 %	-	MAG
24 %	-	MAG & CATIE
9 %	10 %	CATIE
5 %	10 %	CATIE & BENG
9 %	80 %	BENG

- At MAG laboratory samples were analysed on pH (Fisher potentiometer), K, Ca, Na and Mg. (AAS Perkin Elmer 3100).
- At CATIE laboratory samples were analysed on Ec, pH, Ca, Mg, Na, K (AAS perkin elmer 3500) and N (NH_3 and NO_3, Kjeldahl).
- At BENG laboratory samples were analysed on Ec, pH, TIC, SiO_2, K, Na, Ca, Mg, Al, Cl, total - N, SO_4, and PO_4 (AAS Perkin Elmer 3500, Anion auto analyser, colorimeter, C-combustion AAS).

3.6. Rainfall depth and model parameter measurements

In order to be able to model soil moisture output fluxes beneath the root zone of the various sites, several soil parameters were measured. They are listed here.

rainfall depth:

- LLA daily rainfall figures were obtained from a hand operated rain gauge (ϕ 20 cm). The gauge was located at a treeless spot near the grassland site.
- LMS rainfall was measured daily by the local staff using a ϕ 20 cm gauge.

soil moisture content:

- LLA soil moisture contents were determined by determining the wetness of a soil sample taken at 40 cm depth (drying at 105°C). pF measurements could not be made.
- LMS pF measurements at 30 and 60 cm depth were made daily, using tensiometers.

- Initial pF values and wetness were measured at the day the sampling pits were taken into use.

3.7 Soil sampling and measurements

As an additional check, soil samples were taken from the sampling pits and analysed at the BENG laboratory. Samples were analysed on wetness, pH (KCl), total acidity, exchangable Al^{3+}, exchangable H^+, % of organic Carbon, CEC, Base Saturation (%), ammoniumoxalate extractable Fe, Al and Si, and the exchangable main basic cations K, Na, Ca and Mg. For these analyses the BENG laboratory uses standard soil analysis procedures, further details of which can be found in the compiled BENG soil analysis manual. The results of the analyses and relevant calculations can be found in table 5.20.

A conspicuous detail of the analysis results is the discrepancy between the total positive charge (total acidity plus basic cations) and the CEC (that is in fact the total negative charge). This discrepancy is due to the amphoteric character of the allophanic material in the analysed soil. The charge of the allophanic material depends upon both the pH and the ionic strength of the solution it is in (Wada, 1980). CEC was measured in a solution that orders of magnitude more diluted than the solutions used for measuring total acidity and basic cations. This, and the original ionic strengh of the solution, (as represented by the base saturation in figure 3.4) cause the discrepancy.

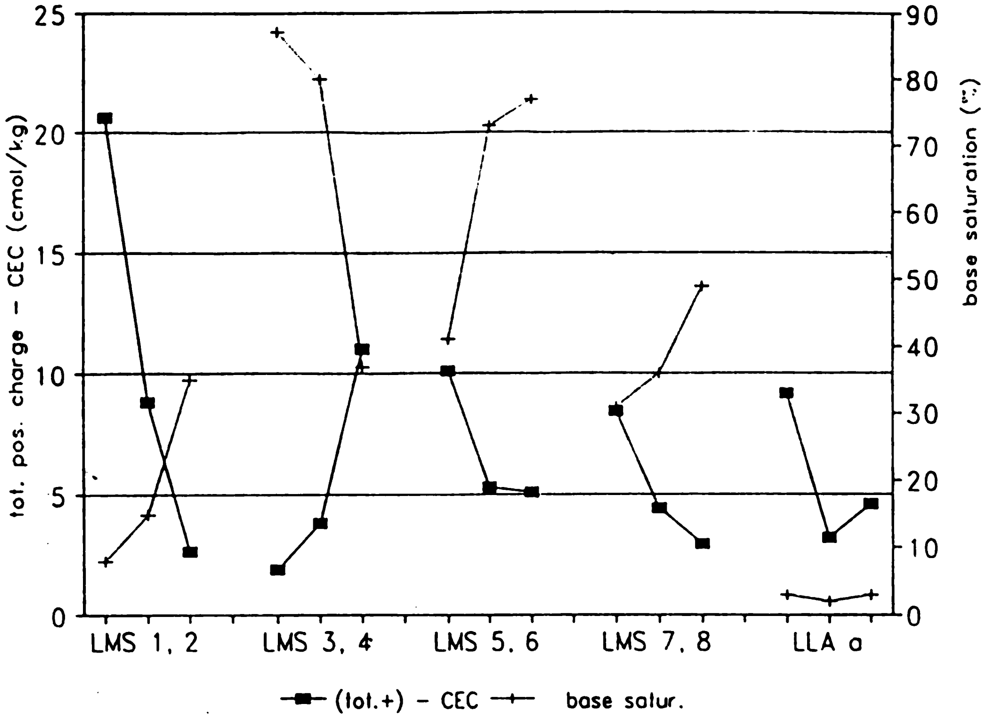


Figure 3.4. A Comparison of soil sample base saturation with the deviation of soil sample total positive charge from CEC.

4. Modelling soil moisture

4.1 Introduction

To estimate soil moisture fluctuations and the amounts of water leaving the soil rootzone of each site during the sampling time, a mathematical model, 'LEACHW', was used. LEACHW is the water subroutine of LEACHM, an acronym of 'Leaching Estimation And Chemistry Model', a one dimensional numerical flow model, developed by R.J. Wagenet and J.L. Hutson, of the department of Agronomy, Cornell University, NY.

4.2. Mesh and timestep

LEACHW works with a user defined mesh and calculates the appropriate time step before each new calculation, depending on an estimation of the water infiltration time.

The simulated soil profile is divided into several nodes that represent soil layers. (figure 4.1) The nodes represent the centers of horizontal soil layers of equal thickness. (In the equations of Annex 4.2 they are designated by the subscript i). There are two additional nodes at the top and at the bottom of the simulated profile, which are used to maintain boundary conditions. The mass balancing subroutine uses only the nodes that are defined as soil layers. For the current simulations a soil profile of 2 meters depth, divided into 40 nodes, thus having a mesh size of 5 cm, was taken.

To calculate moisture contents, fluxes and potentials in the soil profile, LEACHW uses a numerical solution to the Richards equation. In order to solve this equation soil hydrological characteristics (K-θ-h relationships, in this case Van Genuchten parameters), boundary conditions (water contents) and sources and sinks, (rainfall, evaporation and transpiration) need to be defined. These are read and/or calculated in various subroutines. The main subroutine then calculates a solution of the Richards equation for each timestep (see flowchart annex 4.1.)

The Richards equation describes the soil water regime for transient flow, as derived from Darcy's law and the continuity equation, according to:

$$\frac{\partial \theta}{\partial z} = \frac{\partial}{\partial z}\left[K(\theta)\,\frac{\partial H}{\partial z}\right] - U\,(z,t\,)$$

Where

θ Soil moisture content (volume fraction))

t time (days)

z depth, positive below surface (mm)

K hydraulic conductivity (mm / day)

H hydraulic head (mm)

U sink term representing water lost by transpiration (day^{-1})

The numerical solution to this equation that LEACHW uses can be found in Annex 4.2.

To prevent numerical instability of the surface pressure potential when potential gradients are steep, the model uses an iterative procedure, to select a surface pressure potential value leading to the desired surface flux.

Constant infiltration of the soil is maintained provided that the porosity of the soil is greater than the specified infiltration flux. For each rain event the maximum time period allowed for infiltration of the specified depth of water is calculated as the water depth devided by the application rate. Water that has not infiltrated at the end of the allotted time for infiltration, is assigned to an excess water term which is included in the mass balance calculations. This excess term represents surface runoff.

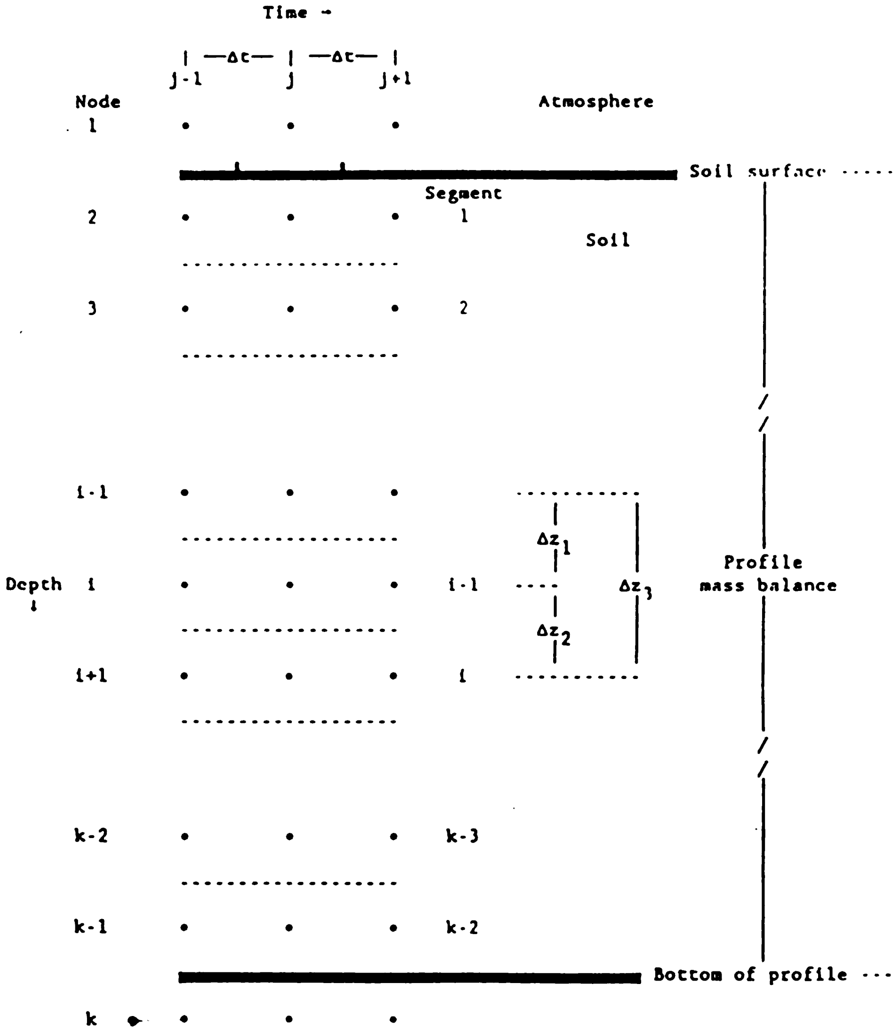


Figure 4.1. LEACHW division of a soil profile in nodes, and calculation time intervals

4.3. Further specifications, requirements

The model is writen in FORTRAN 77, and runs under MS-DOS. For an exhaustive treatment of LEACHW model specifiations and required data, the reader is referred to the users manual. A few minor adaptions concerning model output were made in the FORTRAN listing for convenience. They are incorporated in annex 4.1. A complete listing of the FORTRAN 77 program can be found in the users manual.

The model requires the following boundary condition data:

1. **Soil properties:**

- Hydrological constants for calculating retentivity and hydraulic conductivity
- Initial water content for each soil segment

2. **Soil surface boundary conditions:**

- Irrigation and rainfall amounts and rates of application
- Pan evaporation (weekly totals)

3. **Crop details:**

- Time of planting
- Root and crop maturity and harvest
- Root and cover growth parameters
- a pan factor for adjusting pan evaporation to potential crop evapotransporation
- Lower soil and plant water potentials for water extraction by plants

1. **Soil properties:**

- Hydrological constants: Van Genuchten parameters. LLA parameters were taken from the work of Antje Weytz, LMS parameters were taken from the work of Harald Leumens. They are listed in Annex 4.4.
- Initial water contents were measured in the field at both the LLA and the LMS sites (annex 4.4).

2. **Soil surface boundary conditions**

- Irrigation and rainfall amounts: Rainfall was measured daily at both LLA and LMS (see section 3.4). The rate of rain application was (arbitrarily) taken to be three times the rainfall depth at every day. Sites were not irrigated. Since no information was available concerning the time of each rain event, times were set at 12.00 for each event.
- Pan evaporation: No specific data were available. The maximum literature value was taken for the whole modelled period (3.6 mm/day).

3. **Crop details**

- Time of planting, harvest: The 'crops' modelled were primary forest, grassland, banana and palmheart. Since the latter are perrenial crops, and the grassland was over ten years old, for every modelling case growth was assumed to have reached steady state. This may not be an adequate description of reality, particulary not for the simulated banana, that was still growing during the sampling period and was cut down before the sampling period was over.

- Root and cover growth parameters: Since a steady state was assumed, these values were taken to be zero.
- Pan factor and relative root depth were used as parameters to obtain optimal curvefits with the experimentally found values (see annex 4.3).
- Plant water potentials: Lacking more detailed data, these were given the following constant values for all 'crops':

Wilting point (soil)	(kPa)	-1500
Min. root water potential	(kPa)	-3000
Max. root water potential	(kPa)	0
Root flow resistance term		1.05

4.4. Adjustments of Van Genuchten parameters

Van Genuchten parameters are usually specified for three different soil depths (see Annex 4.4). Using the complete set of specified parameters for the topsoil and the subsoil gave rise to model instability problems. Therefore the whole profile was simulated using only parameters of the lower horizons, since they turned out to give the most realistic results (annex 4.3).

LMS Van Genuchten parameters were only available for banana plantation soil. To simulate the forest and grassland's different water regime, K-sat values were adjusted until reasonable fits were obtained. This is justified by the fact that forest soil is known to maintain a higher moisture content than plantation soils, and by the fact that the grassland sites were subject to a fluctuating water table, that can be approximated modelwise by reducing the saturated hydraulic conductivity (Wagenet, 1983)

For LLA soils, a selection from the Van Genuchten parameters established by A. Weytz for forest, grassland and plantation was made, that satisfied the model requirements best.

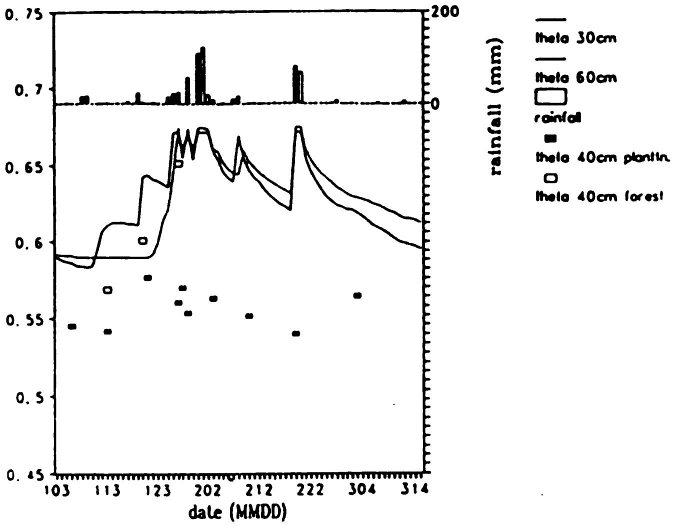
4.5. Monitoring

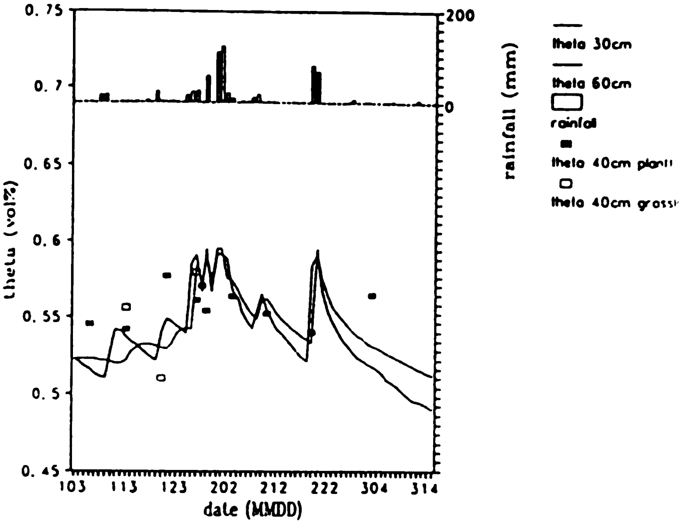
LLA soil water contents were monitored by measuring soil wetness θ (as massfraction of water per dry weight of soil.). Assuming the soil bulk density to be close to 1, (reasonable for a tropical soil, european soils having b.d. values of 1,2 - 1,6), this can be taken to be aproximately equal to a θ as a volume percentage.

LMS soil moisture content was monitored indirectly by in situ measuring of the suction h, that can easily be converted to H (H = p(h)). Since model outputs incorporate both θ and H, calculated moisture curves could be adjusted to match experimental values.

4.6. Modelling results

LEACHW writes the results of every model calculation to various, user defined ASCII files. These files can be imported into a spreadsheet program and visualized. Figure 4.2 - 4.4 show model fits with measured parameters of the three LLA sites, and figure 4.5 - 4.8 show model fites of the four LMS sites.





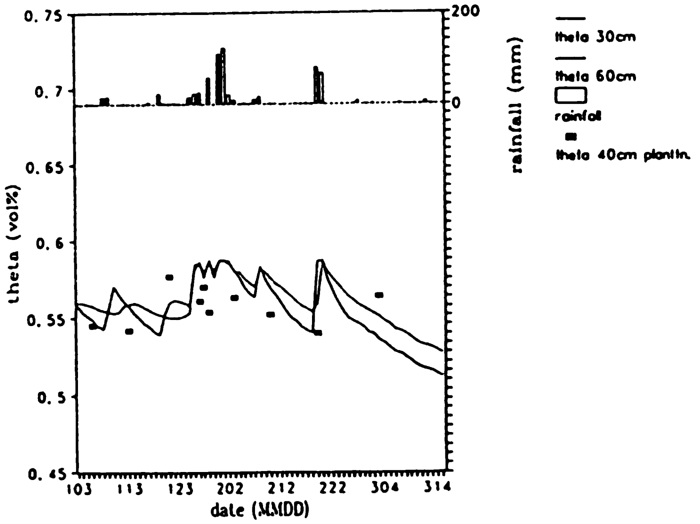
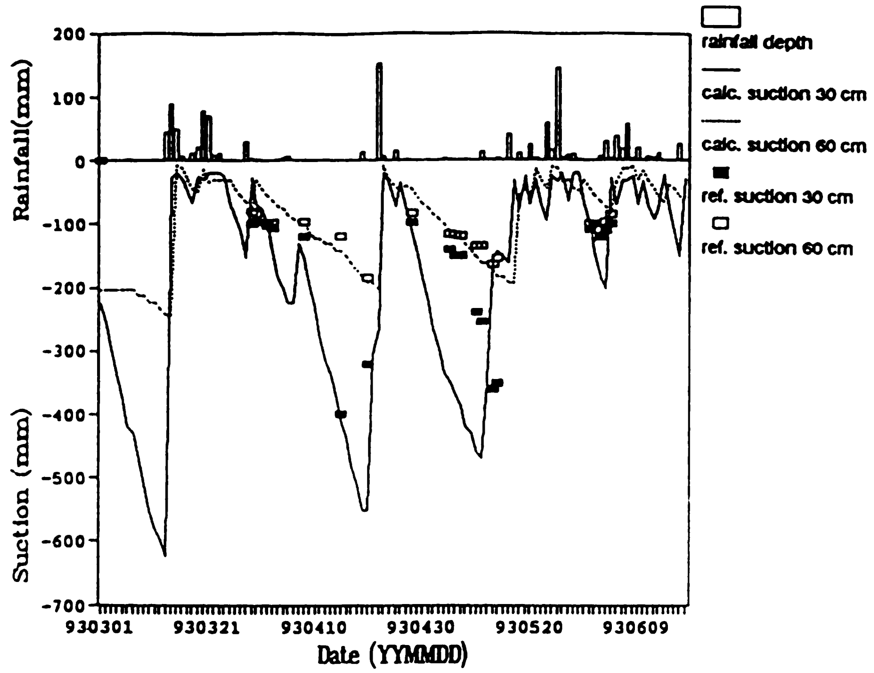


figure 4.2. LLA forest Model fit with measured parameters. Dots designate measured theta's, lines represent model results. The fit seems reasonable. Unfortunately, only three Forest datapoints are available.

figure 4.3. LLA Grassland Model fit with measured parameters. Dots designate measured theta's, lines represent model results. The fit seems reasonable as well. Unfortunately, only three Grassland datapoints are available.

figure 4.4. LLA Plantation Model fit with measured parameters. Dots designate measured theta's, lines represent model results. The fit is reasonable, and can be verified with the available data.



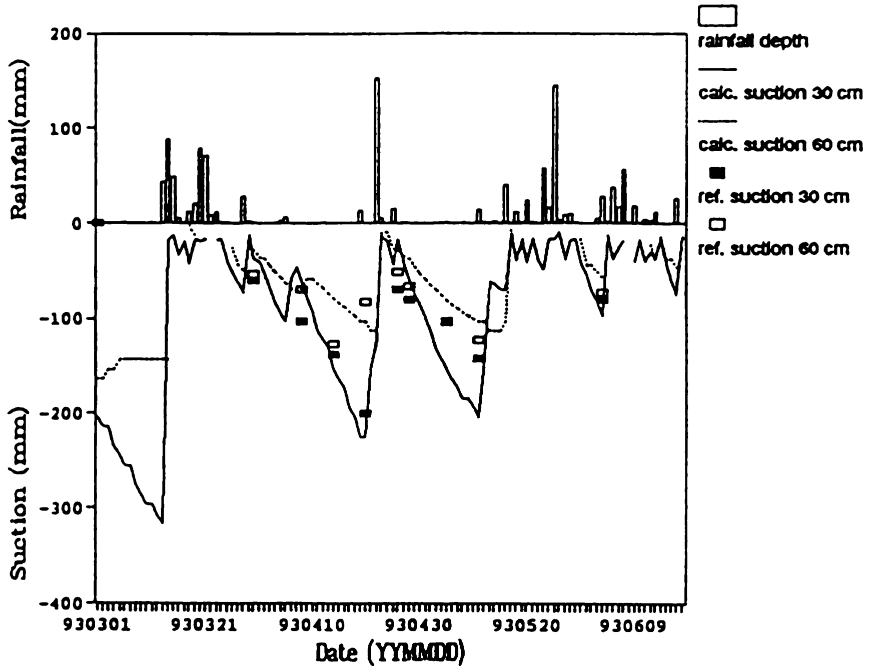
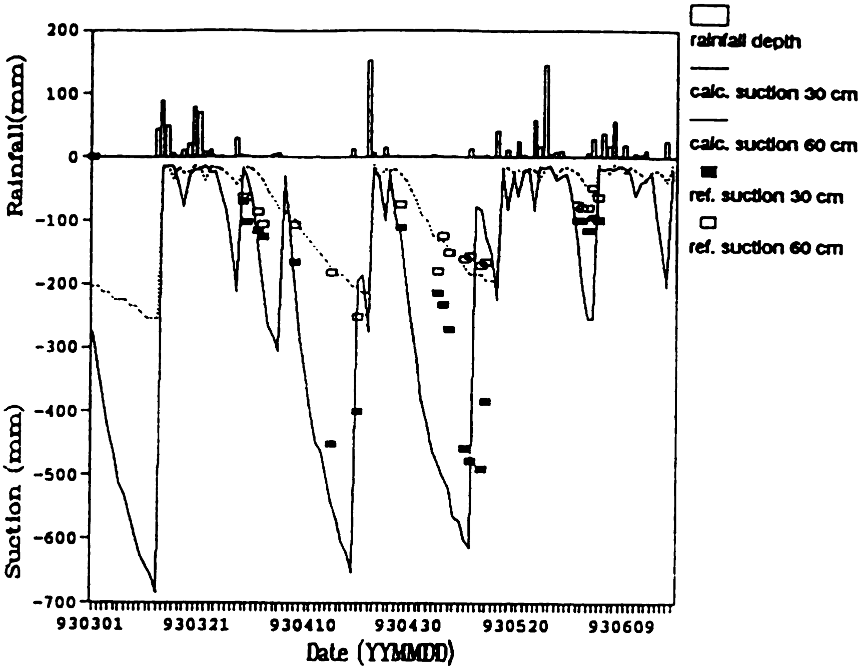


Figure 4.5. LMS forest model fit with measured parameters. Dots designate measured suctions, lines represent model results. Fits are good

Figure 4.6. LMS Grassland model fit with measured parameters. Dots designate measured suctions, lines represent model results. Fits are good.



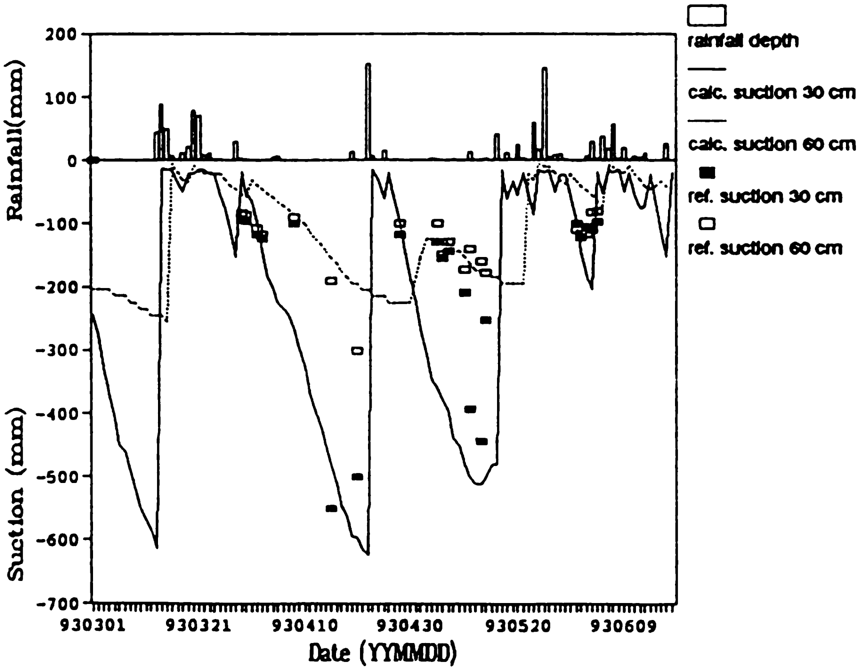


Figure 4.7. LMS Plantation (loamy) model fit with measured parameters. Dots designate measured suctions, lines represent model results. The fit is good.

Figure 4.8. LMS Plantation (sandy) model fit with measured parameters. Dots designate measured suctions, lines represent model results. The fit is good.

As a final checkup for modelling reliability, Cumulative water fluxes out of the profile where compared with rain, requiring for LMS that:

RAIN > CFW f > CFW g > CFW pl > CFW ps , and for LLA that

RAIN > CFW f > CFW g > CFW p

CFW = cumulative water flux
ps = sandy banana plantation soil
pl = loamy banana plantation soil
p = palmheart plantation soil
f = forest
g = grassland

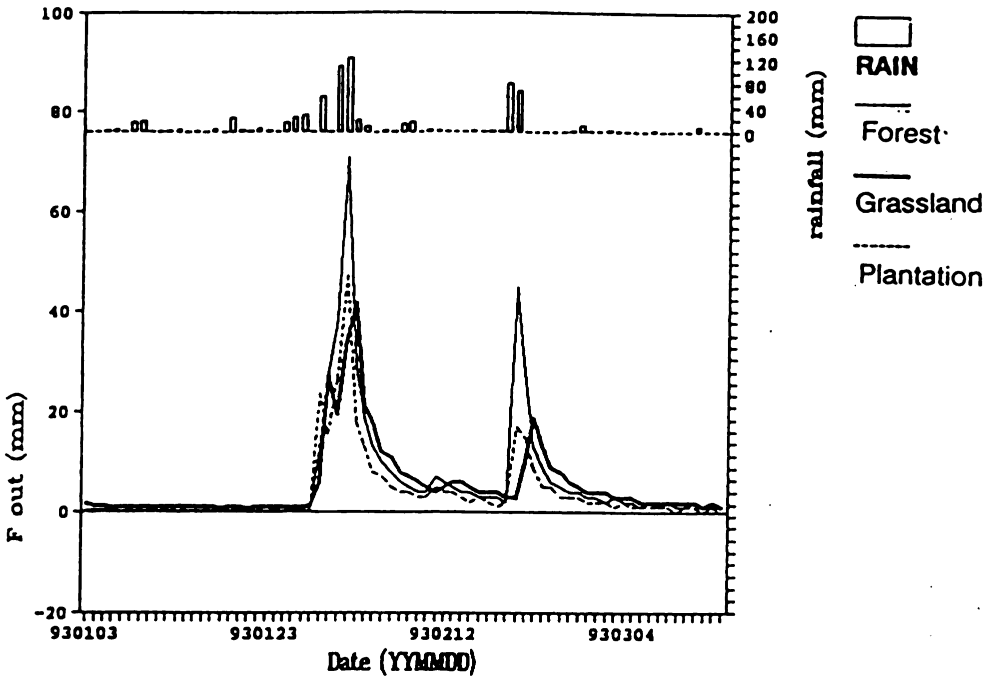
The requirements were based on the observation that, due to their various soil porosity and evapotranspiration properties, the water capacities of the three landuse types usually are in the order described by the above equations. See also annex 4.5.

This is due to the fact that after deforestation, K-sat of the surface soil decreases, and surface runoff losses of rainwater are greatly enhanced (a.o. Fritsch, 1993). Combined with this, the evapotranspiration of plantations is much larger than that of grassland (also, Fritsch, 1993). A combination of these factors results in the specific water capacities discussed above. The system with the highest capacity will retain most water. Next to infiltration capacity, evapotranspiration is another determining factor of the amount of water leaving the soil. Table 4.1 shows that the results of the CFW calculations indeed match the requirements.

Figure 4.9 and 4.10 show the LLA and LMS waterfluxes out of the profiles vs. time.

Table 4.1: Cumulative rainfall and calculated cumulative waterfluxes during the sampling periods:

LLA cumulative rainfall:		669 mm
	Calculated CFW (mm):	
	Forest	431
	Grassland	392
	Palmheart plantation	303
LMS cumulative rainfall:		1194 mm
	Calculated CFW (mm):	
	Forest	779
	Grassland	537
	Banana plantation - loamy	446
	Banana plantation - sandy	394



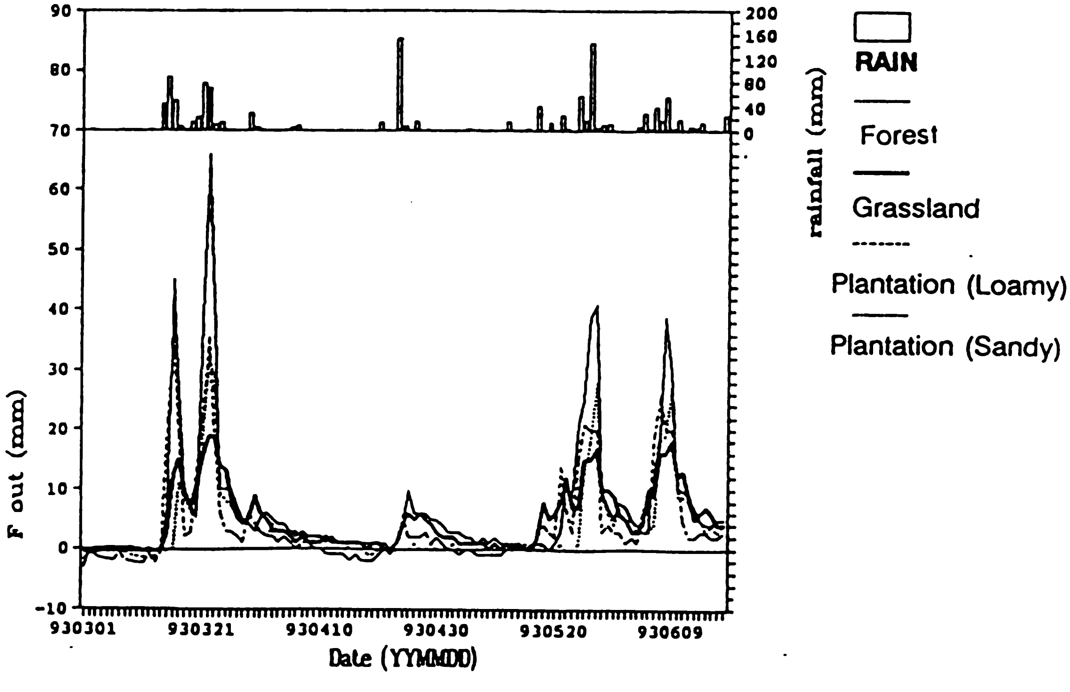


figure 4.9. LLA Calculated cumulative waterluxes (F out) versus time.

figure 4.10. LMS Calculated cumulative waterluxes (F out) versus time

5. Results, discussion

5.1. Data preparation, lab comparison

Sample yield, especially of the LLA sites, was lower than expected, due to various sampling and analysis drawbacks (see annex 5.2). Fortunately, the samples that were obtained gave useful results. A complete list of obtained analysis results is incorporated in Annex 5.1. Along with routine laboratory crosschecks of samples, analysis reliability was checked by comparing total basic cation concentrations with Ec. The ratio of these parameters should be constant. Deviating data were filtered out (fig. 5.1 a).

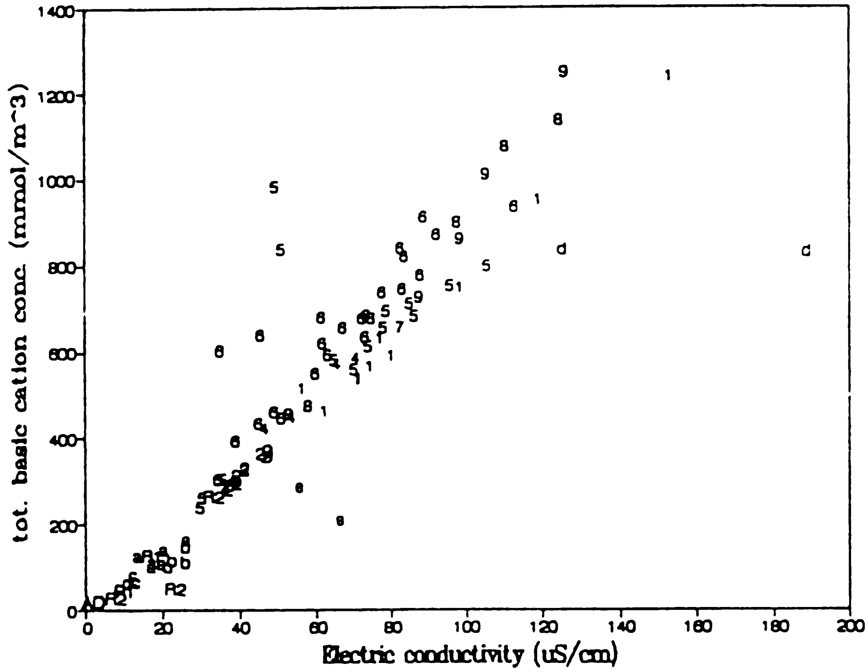


figure 5.1. a. Electric conductivity of water samples vs. total basic cation concentration. Data should fall on a straight line.

Fig. 5.1 b and 5.1 c show a comparison between the analysis results of the MAG, CATIE and BENG laboratories. The comparisons indicate that BENG and CATIE results are reliable and comparable, except for NH_4, NO_3 and pH. As indicated by figure 5.1 b, almost all BENG analyses show an increased NO_3 concentration and a decreased concentration of NH_4, when compared to the CATIE results. The large time interval between the two analyses (CATIE being in Costa Rica and BENG in the Netherlands) makes bacterial nitrification (compare eq. 5.2) a very probable source for this difference. Nitrification probably also accounts for the observed lower pH's in some of the BENG analyses. The observed rise in pH in some of the other samples is thought to be ascribable to CO_2 loss from the soil moisture samples. Soil PCO_2 is known to be several orders of magnitude higher than air CO_2 pressure, giving rise to a high PCO_2 in the moisture samples, that is not in equilibrium with soil moisture after sampling. As a result CO_2 will leak away, even if bottles are filled to the brim, (the polyethylene of the sampling bottles is permeable to CO_2). Loss of CO_2 will result in a pH rise (compare eq. 5.5 and section 5.8).

Comparing CATIE and MAG results, (fig. 5.1 c) a low accuracy in the MAG results, together with a large precision error for most elements is observed. Another conspicuous feature is the 'levelling' of Ec and basic cation analysis results (especially Na), that is due to the low resolution of the obtained data. The accuracy of the MAG apparatus is in the mol m^{-3} range, whereas most sample concentrations require a mmol m^{-3} accuracy. The low resolution becomes more serious at low concentrations. Many of the samples with a concentration lower than 10 mmol m^{-3} are wrongly analysed as having a zero concentration. MAG basic cation concentrations were, if possible (not zero), recalculated with the regression equations shown in fig. 5.1 c. The strongly deviating pH values are thought to be due to sampling the artifacts described for CATIE / BENG samples, combined with the low MAG accuracy. Since most of the LLA samples were analysed at the MAG lab (table 3.2), calculations derived from LLA data must be treated with caution.

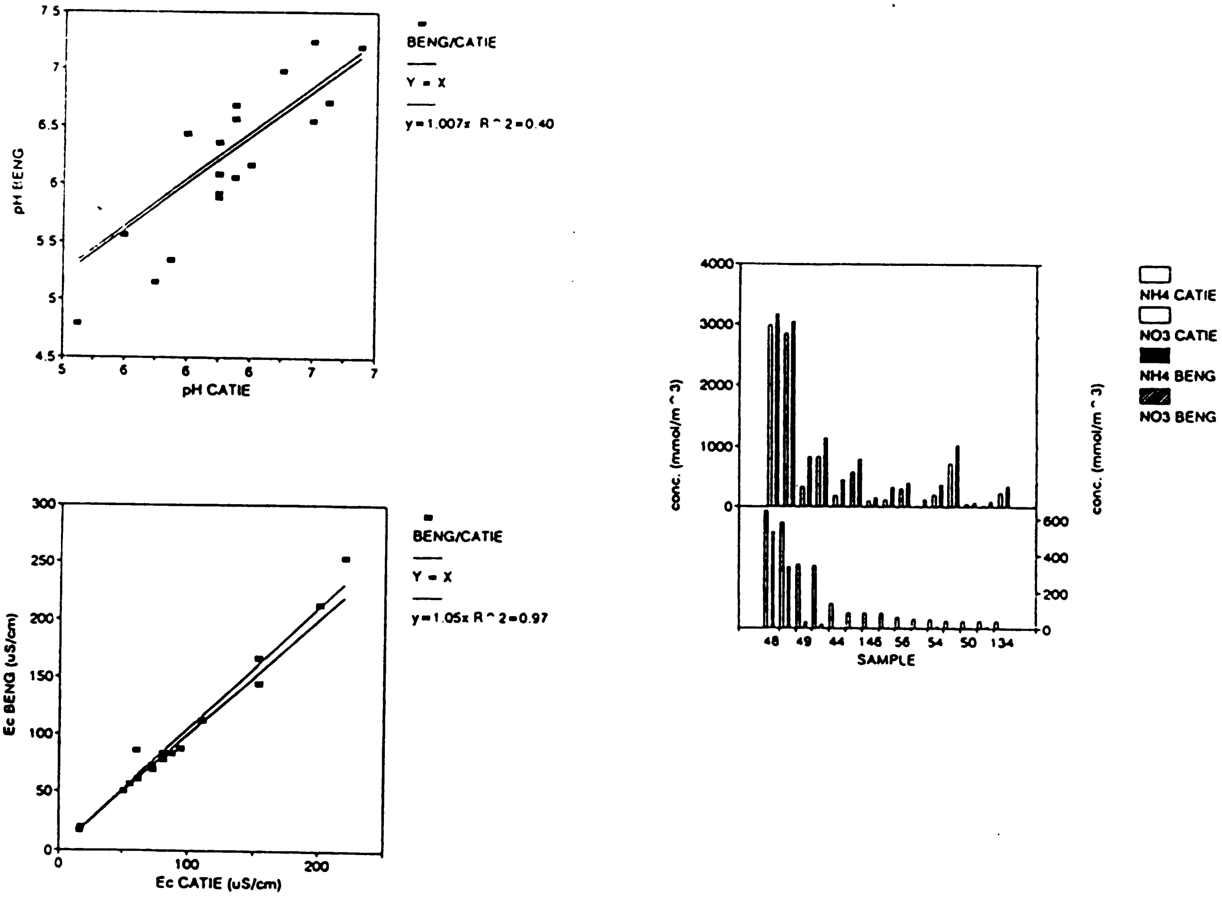


Figure 5.1. b. Comparison of the BENG and CATIE laboratory results. Ca, Mg, K, Na and Ec results fairly agree. NH_4, NO_3 and pH results strongly deviate.

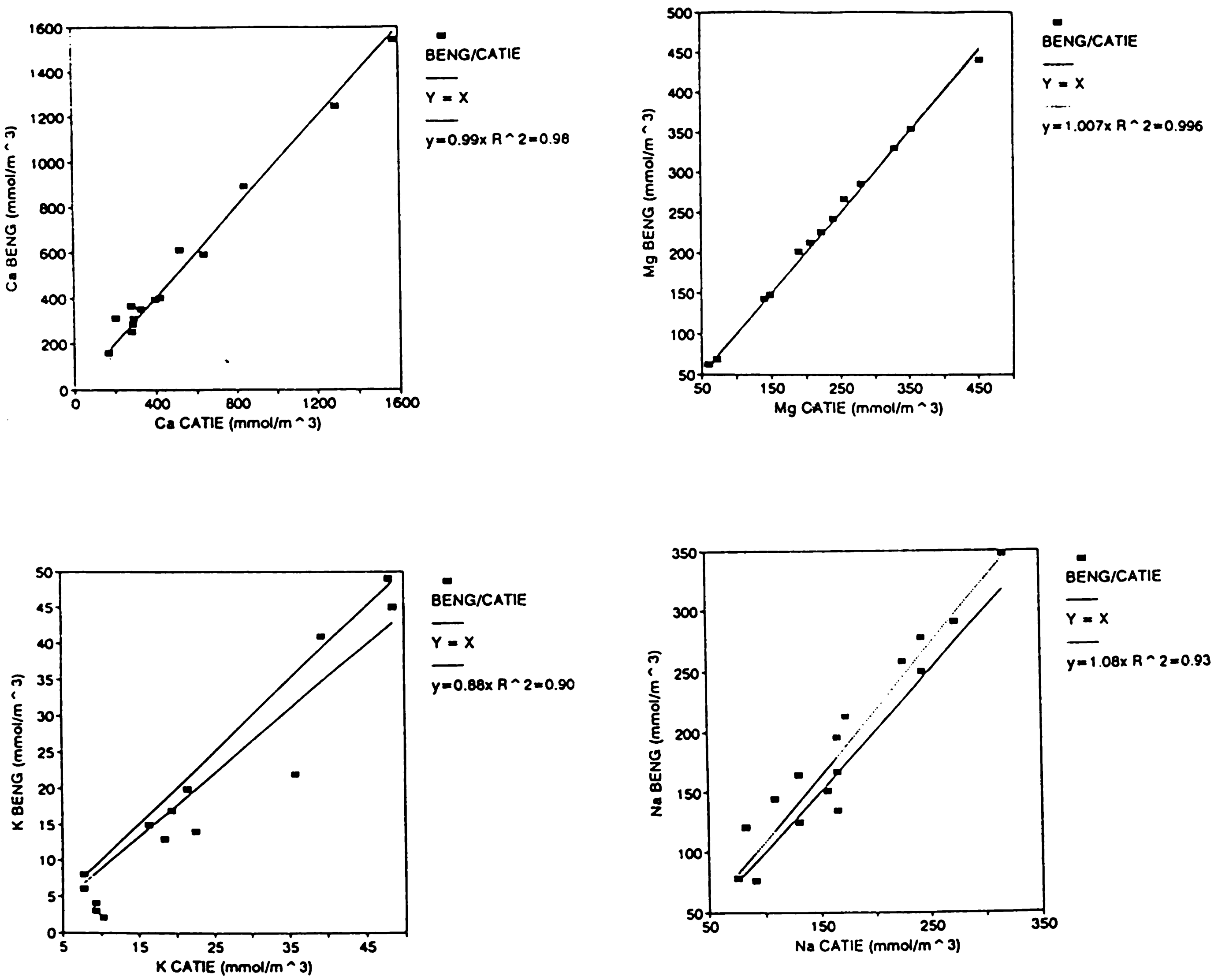


Figure 5.1-b continued. Comparison of the BENG and CATIE laboratory analysis results. Ca, Mg, K, Na and Ec results fairly agree. NH_4, NO_3 and pH results strongly deviate.

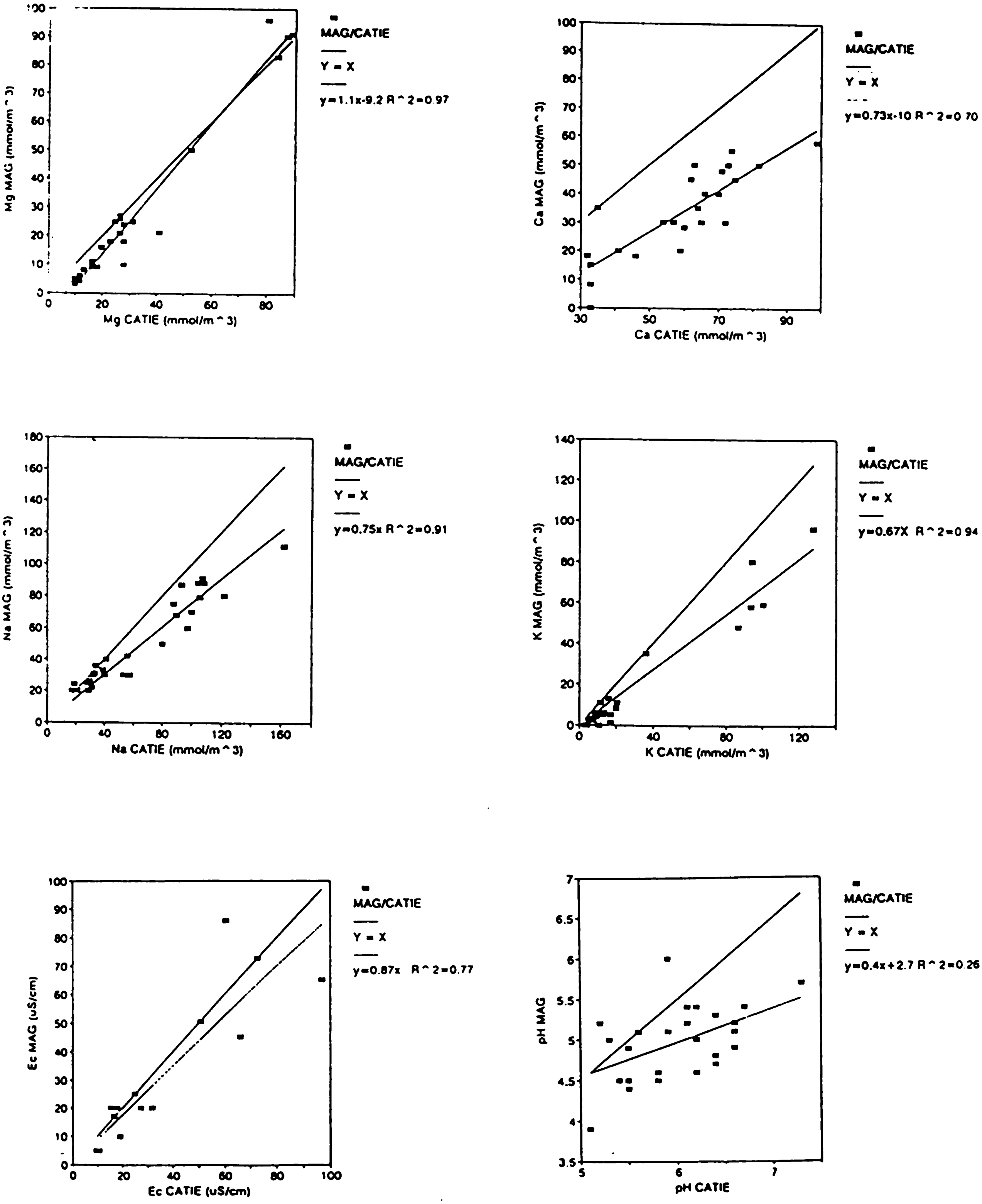


Figure 5.1. c. Comparison of the CATIE and MAG laboratory results. Ca, Mg, K, Na, Ec and pH results all strongly deviate.

Solute concentrations of fertilised sites were found to exceed background concentrations by up to two orders of magnitude, making them useless for a quantitative comparison. The in- and outputs of fertilizer completely override natural in- and outputs. For a general treatment of fertilizer loss of Atlantic Zone plantation soil the reader is referred to Rosales et. al. (1992). Samples of both the compared 'fertilized' and 'unfertiziled' sites (fig. **5.2**) yielded two types of samples: samples with concentrations clearly ascribable to fertilizer and samples with a 'background' concentration, comparable to that of the forest and grassland sites.

This 'mix up' is due to the fact that 'fertilized' and 'unfertilized' sites were too close to each other, in the same sampling pit. Fertilizer may have percolated to the 'unfertilized' site, and, due to preferential flow, may not always have reached the 'fertilized' site. Therefore data from both sites were pooled, and fertilizer contaminated values were filtered out applying the cumulative distribution of total basic cation concentrations as a criterium (fig. **5.3**). Average concentrations of the most heavily fertilized sampling depth are shown in table 5.2 b(depth 7), but will not be discussed, except for Si and NO_3, since all samples were contaminated.

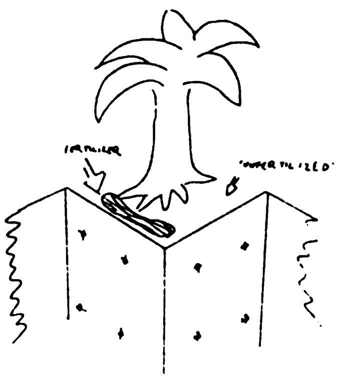


figure 5.2. Schematic representation of a LMS plantation sampling site. Fertilized and 'unfertilized' sites are indicated.

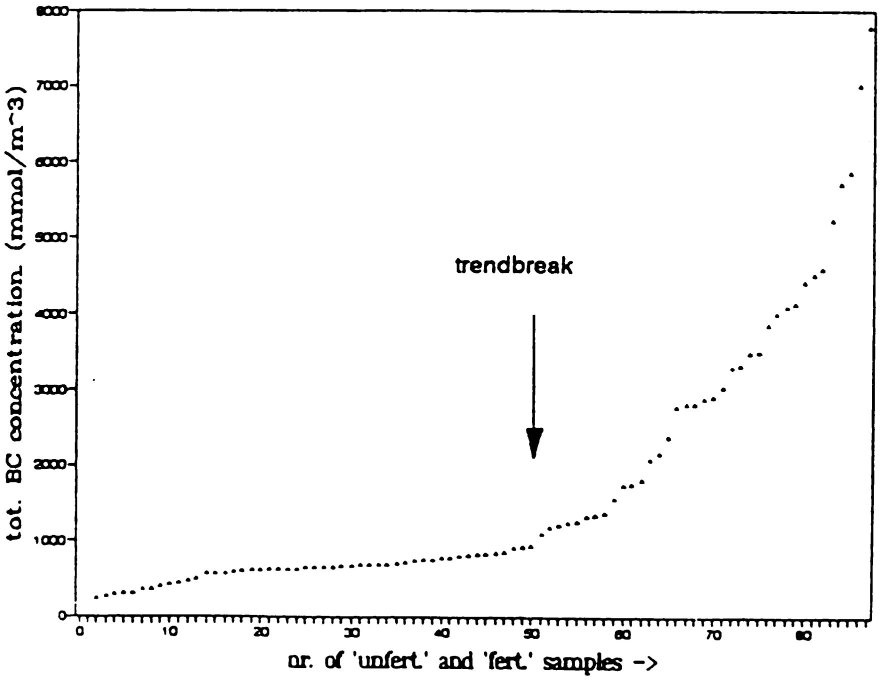


figure 5.3. Concentration distribution of LMS fertilized and 'unfertilized' samples. Samples with a concentration higher than 980 mmol m^{-3} were left out in most comparisons.

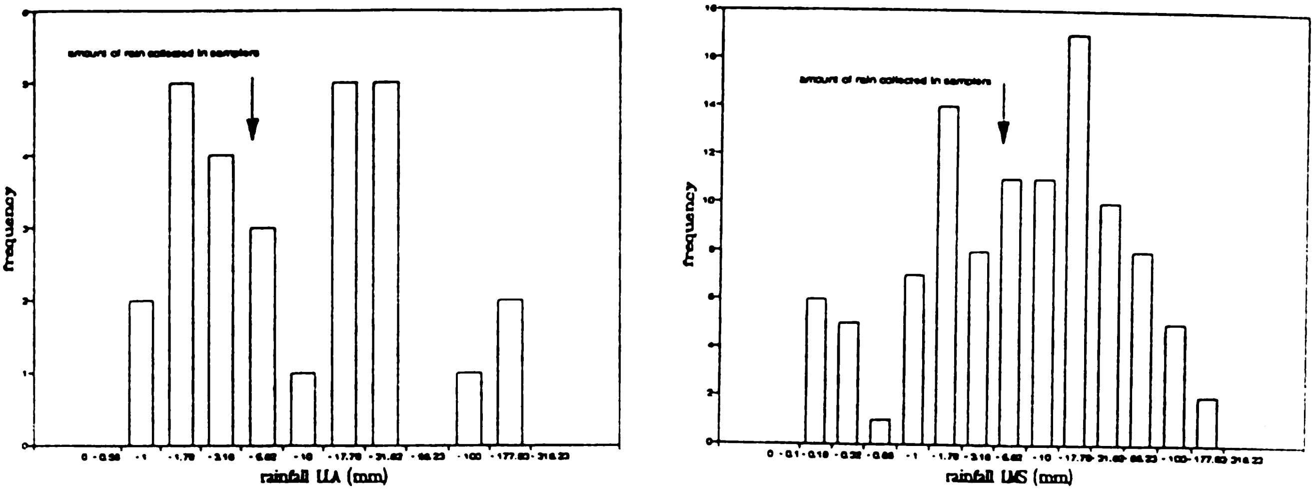
5.2 Rain water:

Obtained rainwater samples consisted of a usually completely filled 100 ml bottle, containing approximately 120 ml. With a gauge diameter of 20 cm, or 100π cm^2 per sample, this corresponds to a rainfall depth of 3,8 mm. This amount of water is in many cases only a minor part of the total rainfall, (fig. 5.4 a and b), but probably represents the bulk of the nutrients supplied to the system by precipitation, since dissolved elements in these samples are for the greater part associated with aerosols that are scavenged by the first amount of downcoming water (assuming that the showers are mainly convective). Early precipitation of the largest and most favoured nuclei produces high concentrations early in the shower and low concentrations in the heaviest rain (Gatz, 1971).

To confirm this assumption, a small experiment was done. Assuming that the aerosol nutrient scavenging by raindrops follows normal probability, so that the concentration of elements in rainfall decreases exponentially, an assesment was made as to which amount of rainfall still contains nutrients. At one of the rain events two immediately succeeding rainsamples were taken. Na, K and Cl content of these two samples were each taken to represent two points on an empirical concentration decay curve (a simple exponential curve). Approximating this curve by a straight line on the sample intervals, and assuming the concentrations to represent mean intercepted rainfall concentrations, the corresponding curve for each element was fitted. Figure 5.5. shows the results of this excercise. As n = 1, quantitative results are not reliable, but since Na, Cl and K show the same trend the small experiment probably gives a good indication of the real situation. Each of the two rain samples (one full bottle) was taken to correspond to ~ 4 mm of rain. Detection (or rather reliability) limits were derived from the concentration of the above mentioned elements in locally demineralized water.

The figure shows that the bulk of the nutrients is scavenged within the first ~ 15 mm of rain and that after 20 mm concentrations sink below the detection limit. Data collected at the Hubbard Brook experimental station (Likens et al., 1984) show a generally similar precipitation / concentration pattern, although the decrease shown in these data is not as pronounced.

The average input by rain at the Atlantic Zone sites was estimated as follows: of all the rain events with a rainfall depth exceeding 20 mm the 'surplus' rainfall was considered as 'non nutrient containing', and not incorporated in the rainfall nutrient input calculation. This is of course an oversimplification, because raindrop nuclei will always be present. However, compared to the fact that for the calculation the widely varying solute concentrations measured in rain were averaged, the error made by this assumption is thought to play a minor role.



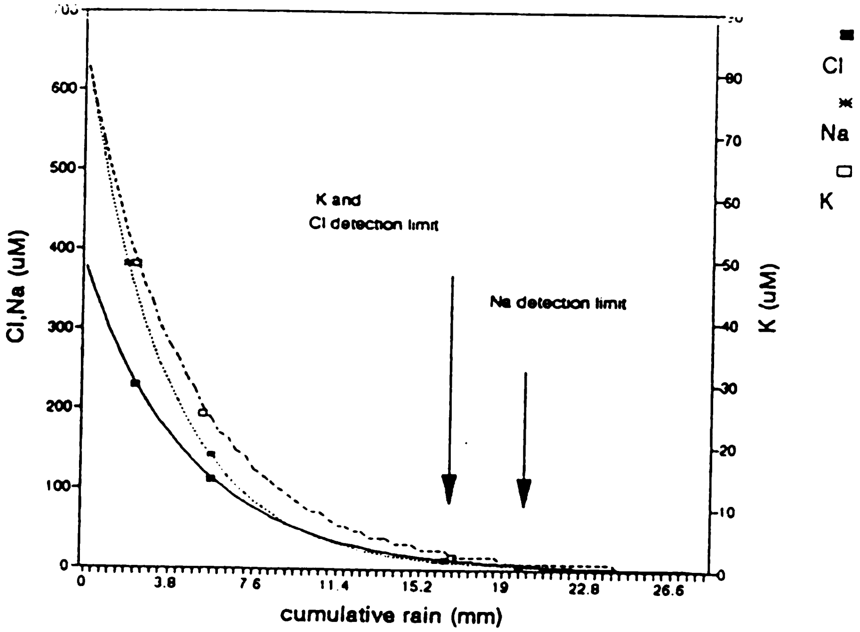


Figure 5.4. a. and. b.: Rainfall distribution histograms of LLA and LMS. The amount of rain collected in the rainfall samplers is indicated.

Figure 5.5. Normal probability curve used to asses the nutrient scavenging rate during a rain event

5.3. Pore water, introduction

At the LLA study area, three sites were selected, with two sampling depths for each site. Because LLA forest A-horizon sampling proved to be impossible, five depths were eventually sampled. Additionally, a well draining the LLA forest was sampled.

At the LMS study area, four sites were sampled at two depths, making a total of eight sampling depths. Also, grassland watersamples below the groundwater table were taken.

Table 5.1 shows the used codes for all sampling depths. LMS odd numbers (except 9) indicate A-horizons, and even numbers depths below the root zone.

Obtained soil moisture samples consisted of a quantity of water ranging from a few drops per bottle to a completely filled sampling device (containing approximately 120 ml). The obtained quantity of water limited the total number of solutes that could be analysed, since measuring methods were destructive. Due to the preparation of samples with chloroform, organic-C measurements were not reliable and thus not performed. Annex 5.1. gives a complete list of sample analysis data.

table 5.1. site sampling depth codes

	AD	Demineralized water
	R1	LLA rain
	R2	LMS rain
LLA sampling	'depths'*	
LLA	a	Forest site, below the root zone
LLA	b	Grassland site, A horizon
LLA	c	Grassland site, below root zone
LLA	d	Plantation site, A- horizon
LLA	e	Plantation site, below root zone
LLA	x	well draining Forest site
LMS sampling	'depths'*	
LMS	1	Forest site, sandy, A-horizon
LMS	2	Forest site, sandy, below root zone
LMS	3	Grassland site, sandy, A-horizon
LMS	4	Grassland site, sandy, below root zone
LMS	5	Plantation site, Loamy, A-horizon
LMS	6	Plantation site, Loamy, below root zone
LMS	7	Plantation site, Sandy, A-horizon*
LMS	8	Plantation site, Sandy, below root zone
LMS	9	Grassland site, sandy, waterlogged

* The used term 'depth' can be misleading, in stead of depth, 'subsampling site' can be read.

** All samples from this site were contaminated with fertilizer, and were not usable for calculations.

Table 5.2 gives average measured concentrations of the most important solutes for all sampling depths, and concentrations of rainwater and water demineralized in Costa Rica. The values must be viewed as a rough survey, since concentrations at each depth have a large range. Results will be discussed per measured solute in the following sections. The focus of the discussion will be on the LMS data, since these data are the most reliable.

table 5.2. a. analysis results per sampling depth, demineralized water, rain and LLA soil moisture

code	AD	R1	R2	a	b	c	e	x
pH	5.5	5.6	5.0	5.3	4.8	5.2	5.3	5.2
Ec (μS cm^{-1})	2.0	13.5	21.9	18.7	23.9	11.1		
Si (mmol m^{-3})		0.1	6.4	38	83	66	60	
Al "		1.0	0.1	13.7	8.0	0.4	2.0	
K "	2	41	14	19	20	12	56	27
Na "	3	138	85	164	77	32	73	132
Ca "	12	114	48	61	123	65	156	28
Mg "	2	63	41	32	37	19	46	38
NO$_3$ "	0	36	66	58	1	1	16	
IC "	117	157	86	112	38	79	54	
Cl "	14	93	53	116	118	38	29	
SO$_4$ "	0	49	43	5	47	42	40	
PO$_4$ "		9.30	0.21	0.11		0.11	1.40	

table 5.2. b. average analysis results per sampling depth, LMS soil moisture

code	1	2	3	4	5	6	7*	8	9
pH	5.9	6.1	6.7	6.9	6.1	6.7	5.3	6.3	6.9
Ec (μS cm^{-1})	88.7	46.8	88.1	58.5	80.1	69.7	437	81.9	104.1
Si (mmol m^{-3})	50	199	124	132	277	398	213	158	357
Al "	2.4	2.3	6.0	20.6	0.6	3.0	7.5	2.3	1.6
K "	72	10	7	130	10	7	494	60	107
Na "	112	85	149	102	118	180	621	155	241
Ca "	337	176	329	199	402	247	2139	396	312
Mg "	79	42	270	58	138	201	712	114	196
NO$_3$ "	482	181	3	24	391	163	2122	167	5
IC "	125	178	599	394	513	771		797	998
Cl "	129	66	348	165	152	103	913	224	158
SO$_4$ "	40	25	45	51	74	24	121	27	73
PO$_4$ "	0.05	0.05	0.11	0.05	0.17	0.34	0.37	0.37	0.53

* Site 7 values are shown for comparison, they have not been corrected for fertilizer contamination

5.4 LMS base cation behaviour, forest uptake

In fig. 5.30- 5.33 the concentrations of the four most important base cations vs. time of the investigated LMS sites are compared. A conspicuous feature of the data is the low and very constant K, Mg and Na concentration of depth 2 (forest subsoil). The low forest subsoil concentrations support the assumption that the forest has reached some steady state, in which weathering balances leaching. Ca seems, of all basic cations, to be released in the largest amounts in the A-horizon biomass, (as is expected from the biomass basic cation stoichiometry, table 5.7), whereas K, Na and Mg are released to a lesser degree. Subsequent uptake seems to strongly prefer K (table 5.3), with Ca lagging a factor 3-4 behind, and Mg as a close third. A somewhat more indifferent attitude toward Na (a ratio of approximately 1) is observed. However, the steady and low Na output suggests that indeed Na uptake by the forest is taking place, although no pronounced preference for Na is shown by the calculation of table 5.3.

Other conspicuous features (fig. 5.30- 5.33) are the high concentration of Mg at depths 3 and 6, and the extreme K concentrations at depth 4.

table 5.3 : The ratio of forest soil moisture nutrient concentrations in the A-horizon of the LMS forest (depth 1) to the nutrient concentration beneath the rootzone at the same site (depth 2) at various days during the sampling period. This ratio is a measure for the root nutrient uptake efficiency.

root uptake efficiency:(top rootzone conc./ bottom rootzone conc.)

K	Na	Ca	Mg	date
3.67	2.02	5.22	4.47	930322
3.44	1.78	2.84	2.74	930426
9.00	1.39	1.90	1.92	930427
6.60	1.02	1.36	1.39	930428
7.22	1.38	1.91	1.86	930505
10.0	1.25	1.56	1.76	930507
11.5	1.47	1.74	1.75	930510
8.67	0.74	1.05	1.12	930601
7.10	0.94	1.30	1.29	930603
7.28	1.29	2.05	1.96	average

(These figures assume that forest A-horizon nutrient release by weathering is neglegible, compare table 5.6)

In the following sections solutes will be discussed separately:

5.5 Calcium, Magnesium

Plotting Ca against Mg, (fig 5.6), data fall on distinct lines, indicating that sampling depths can be grouped by their similar, constant Ca/Mg ratio. This ratio is closely related to the Ca/Mg ratio of the exchange complex and to the base saturation of the profiles (table 5.4). Soils with a low base saturation show a high Ca/Mg ratio on their exchange complex and in soil moisture, and vice versa.

Assuming that the found Ca/Mg ratio's and base saturations of the sampling depths are related to a dominant soil process, sites were grouped according to their ratios. From the notion that a direct relationship exists between the amount of Ca and Mg on the exchange complex and the Ca/Mg ratio, a simple model was developed, to understand this relation.

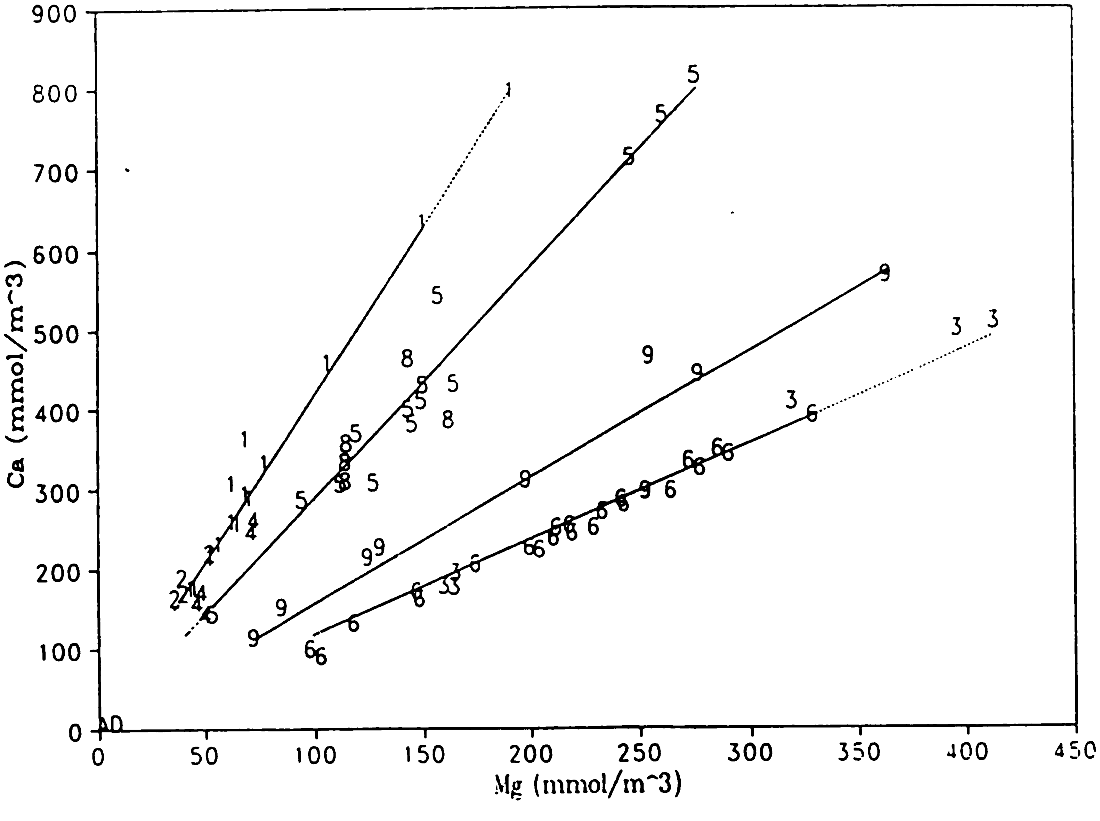


figure 5.6 Plot of Ca versus Mg of the collected LMS water samples. (Ca and Mg of the LLA sites are shown in figure 5.15)

table 5.4. Measured base saturation, Ca/Mg at the exchange complex and Ca/Mg in soil moisture of the LMS subsites

	%Base saturation	exchangeble Ca/Mg	porewater Ca/Mg
1	8	4.67	4.28
2	35	3.33	4.25
4	37	3.15	3.39
5	41	3.04	2.98
8	49	3.33	3.29
6	77	1.54	1.16
3	87	2 .4	1.19

table 5.5 litter Ca, Mg return and mineral soil Ca, Mg content.

Total litter Ca, Mg return from selected natural forests (kg $ha^{-1}yr^{-1}$)*

Ca	Mg	Ca/Mg	Location
154	27	5.7	Central Java
50	12	4.2	Puerto rico
115	26	4.4	Panama
69.5	18	3.9	Malaya
124	12	10.3	Colombia
159	33	4.8	Queensland
104	23	4.5	Tanzania

average (Colombia excepted): 4.58

Weathering stoichiometry and release of Ca/Mg from a number of Atlantic Zone profiles**

subs. age (ka)	calculated release of CaO/MgO	subs. age (ka)	Si/Si	Mg/Si	Ca/Si	Na/Si	K/Si	PROFILE
				calculated weathering stoichiometry from calculated cumulative loss				
2.5	0.79	2.5	1	0.42	0.33	0.12	0.03	AT5
3.5	0.83	3.5	1	0.11	0.09	0.08	0.03	AT7
5	0.74	'5'	1	0.11	0.08	0.07	0.01	YB
18	0.67	18	1	0.09	0.06	0.05	0.02	RPA
125	0.63	125	1	0.10	0.06	0.05	0.02	RF1
150	0.50	150	1	0.15	0.07	0.06	0.03	RF2
450	0.46	450	1	0.10	0.05	0.04	0.02	RCR
mean	0.66		100	15.3	10.6	6.9	2.2	= mean * 100

* Adapted from Bruynzeel, 1983.

** Adapted from Nieuwenhuyse, 1995, see also Annex 5.4

As indicated by table 5.5 , nutrient input from plants yields Ca and Mg in a high Ca/Mg ratio. Table 5.5 also shows that a high relative nutrient input from weathering yields Ca and Mg in a low ratio.
The mineral phase of many young soils in the Atlantic Zone contains about 2 times as much Mg as Ca. Under the prevailing weathering conditions, (Ca containing) Plagioclase is believed to weather more rapidly than (Mg containing) Augite. (Augite, although it is in itself more susceptible to weathering than plagioclase, upon weathering under the local conditions, forms iron oxide coatings that are thought to make it more resistant to acid attack (Nahon and Colin, 1982)). However, the data of Nieuwenhuyse (1995), as examined in annex 5.4, indicate that Mg is released about 1.7 times as fast as Ca during weathering. But, since the Mg mineral pool is larger, Ca will be dissapear first. Due to the higher release rate of Mg, the ratio of Ca and Mg released into the soil moisture is low.

As can be seen by comparison with table 5.6, in the forest the amounts of Ca and Mg released into the soil solution (compare table 5.2 b) are much higher than expected from a direct weathering release. The strong relation of the Ca/Mg ratio in soil moisture to the ratio on the exchange complex suggests that these nutrients have built up their current exchangable concentrations over a longer period. The discrepancy between expected weathering release based on Si concentrations and actual Ca and Mg release is thought to be due to a difference in source of soil moisture Si and soil moisture basic cations. The low correlation between Si and the basic cations is not a result of (very) incongruent weathering. Rather, Si finds its source in weathering, whereas the basic cations (though the bulk probably originally was released by weathering) are released from the exchange complex.

Depths 1,2 (forest A-horizon and subsoil) and 4 (grassland subsoil) plot in fig. 5.6 on a line with a slope of about 4.2. This suggests the Ca/Mg ratio of the complex reflects a high biogenic input. (The high Ca/Mg ratio indicates that the most important source has a high Ca/Mg ratio). - However, the fact that depth 4 (a buried A-horizon) also has a high Ca/Mg ratio, indicates a different thing is happening. A thought that comes to mind is that the main determinant of the Ca/Mg ratio is A-horizon maturity: The more mature the (buried) A-horizon, the higher its C-org, the higher its Ca/Mg ratio. This idea is contradicted by the low C-org content of depth 2.

A more probable cause lies in the low base saturation of sampling depths 1,2 and 4 (The small differences with depth 5 and 8 are ignored here for a moment, since their Ca/Mg ratio is thought to be ascribable mostly to fertilizer contamination).

As found in numerous studies (a.o. Barber, 1984), Ca has a stronger affinity for the exchange complex than Mg. Thus, if the exchange complex is offered a (relative) low supply of Ca and Mg, more Ca will be absorbed than Mg, resulting in a high Ca/Mg ratio.

The low base saturation in the forest, compared to the other sites, is thought to be due to the fact that the root uptake of nutrients, especially from the A-horizon, is stronger than the nutrient release from roots. The nutrients follow different pathways from and to the soil moisture, due to the plants' evapotranspiration moisture 'pump'. Large amounts of basic cations are pumped up through the vegetation, and returned as litterfall or washed down from leaf surfaces by throughfall (a.o. Nye, 1961). These different pathways in the nutrient cycle are thought to result in larger residence times for the nutrients in the biomass than in the available nutrient pool, keeping the base saturation of the exchange complex low. Of course, this assumption is only valid if the amount of nutrients in the forest soil moisture pool is much larger than the amount released by weathering. This seems to be the case, especially for the A-horizon, but also for the root zone (table 5.6, compare table 5.2 b).

table 5.6 expected concentrations of nutrients released from the mineral soil underneath LMS forest, calculated from the weathering stoichiometry found in annex 5.4.

code	a	b	c	d	e
Si	100	50	199	50	199
Mg	27	79	42	13	51
Ca	21	337	176	11	42
Na	10	112	85	5	21
K	3	72	10	2	6

a	Weathering stoichiometry as derived from Nieuwenhuyse (1995)
b	Measured concentration at A-horizon (mmol m^{-3})
c	Measured concentration at rootzone (mmol m^{-3})
d	Expected concentration relative to A-horizon Si release (mmol m^{-3})
e	Expected concentration relative to rootzone Si release (mmol m^{-3})

The low base saturation of depth 4 (beneath grassland) is due to its large C-org content. A large amount of nutrients has accumulated on this buried A-horizon over the years, but, due to its large capacity, it is still undersaturated.

Depth LLA-a (LLA forest subsoil, not shown in fig 5.6) is expected to have a high Ca/Mg ratio, due to its extremely low base saturation, but has a lower Ca/Mg ratio, for reasons that will be discussed later (section 5.9).

Samples from the LMS 3 and LMS 6 depths (grassland topsoil and plantation subsoil) all plot on a line with a slope of approximately 1.2. This low Ca/Mg ratio is thought to be due to their high base saturation, finding its source in Ca and Mg released in large amounts sometime ~~during~~ after the conversion from forest to grassland.
Ca and Mg seem to have been offered to the exchange complex in a much lower ratio, causing a relative flooding of the exchange complex with Mg, replacing enough Ca to decrease the Ca/Mg ratio to approximately 1:1. The low ratio of the Ca and Mg offered in the past makes weathering the most probable source for this Ca and Mg input (compare table 5.5). Further proof for this is the fact that grassland groundwater (depth 9) has a Ca/Mg ratio similar to that of depths 3 and 6. Since the grassland is aproximately ten years old, the bulk of the nutrients released by the logging is supposed to have left the system by now, and the solutes found in groundwater represent leaching losses from the establishing grassland vegetation.

The relatively high Ca/Mg ratio's found in samples from the LMS 5 and LMS 8 subsites (Loamy plantation A-horizon and sandy plantation subsoil) are thought to be due to a mix of weathering background values and fertilizer contamination. Samples obviously contaminated with fertilizer have a Ca/Mg of up to 20. Fertilizer contamination will probably have affected depth 6 (plantation loamy subsoil) less, due to the lower permeability of the loamy substrate. This indicates that the method for filtering out contaminated samples is not reliable and that most of the samples from depth 5 and 8, and possibly also from depth 6, are contaminated.

The LMS 9 sampling depth (waterlogged grassland) plots on a line with a slope that lies close to that of subsites 3 and 6, but not quite on it. This depth represents groundwater composition, since samples were taken below the groundwatertable.

During the sampling period the water level was constantly lowered due to the construction of new drainage canals for the plantation. Thus the flow of water was mainly from the grassland and forest sites towards the plantation, and not vice versa. The situation being so, it is very unlikely that the relatively higher Ca content in these waters is due to fertilizer contamination from plantation canals.

Thus the conclusion can be drawn, that the composition of the depth 9 water represents groundwater composition beneath LMS sandy grassland soils. The fact that the slope of the line is close to the slope of the 3,6 line, but not quite on it, is probably caused by the high contents of other cations (K,Na) in the groundwater, that affect the Ca/Mg ratio on the exchange complex.

Without their various sources of contamination, that distort the background value, subsites 4, 5 and 8 (grassland and plantation sampling depths) are thought to have a Ca/Mg ratio comparable to that of grassland and plantation sampling depths 3 and 6.

Thus, the Ca/Mg ratio gives an indication of the processes that take place or have taken place in the soil. Even though the approach is an oversimplification, in that it fails to solidly quantify the weathering released amounts of Ca and Mg, it indicates that the release of nutrients onto the exchange complex has been greatly enhanced after the forest was cut down, and that the most probable source for this enhanced release is the mineral soil.

The relatively low base saturation in the forest soil indicates that forest vegetation, although probably approaching steady state, in which uptake is close to zero, maintains a situation in which the bulk of the cycling nutrients at any time resides in the biomass.

5.6. Silica, Aluminium

Figure 5.7. shows measured pore water silica concentrations of the LMS sampling depths in sandy soil, vs. time. These concentrations are thought to give information about the in situ weathering rate. Silica concentrations in pore water from loamy subsites are not shown in the graph. They are approximately twice as high (table 5.2 b), due to the fact that the finer loamy material is more susceptible to weathering. At the loamy subsites the difference in substrate overrules vegetation influence, and therefore only the three landuse types on sandy soil will be discussed in relation to silica.

As illustrated in fig 5.7, Si in most profiles (except the LMS sandy plantation A-horizon, depth 7) remains remarkably constant throughout the measuring period, in contrast with concentrations of the other measured solutes (compare fig. 5.30 - 5.40).

The small Si variances indicate that the processes giving rise to the measured concentrations of most other solutes have little effect on the Si concentration. Si concentratons are subject to different boundary conditions, more rigid than for the other solutes (fig. 5.30-5.40). These boundary conditions are are probably more strongly related to the dissolution of the soil mineral phase and the formation of secondary minerals, than to processes on the exchange complex (compare also previous section).

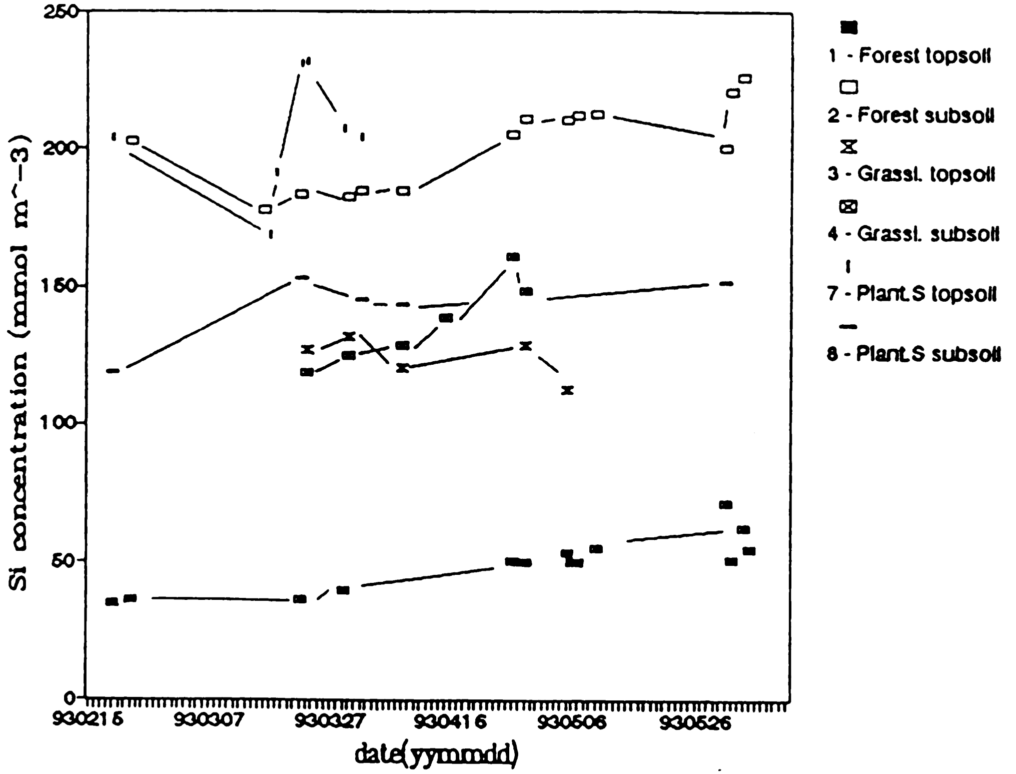


Figure 5.7. Plot of LMS Si concentrations versus time. (Only sandy soils)

Predominant boundary conditions may be:

- the maximum amount of Si that can be released from primary minerals at the prevailing proton donor concentration
- some secondary mineral Si phase, determining the release rate of Si, such as opal
- a steady state (biocontrolled) addition and removal proces.

The greatest differentiation between A-horizon and underlying soil Si concentrations is found within the Forest (depths 1,2). A-horizon (depth 1) concentrations are relatively low, while Si concentrations below the root zone (depth 2) are high.

Grassland (depths 3 and 4) shows a more or less equal concentration of Si at the A-horizon and below the root zone. Concentrations are higher than in the Forest A-horizon, but remain lower than those below the forest root zone.

Depth 7, the plantation A-horizon, shows a high and varying Si concentration and the concentration below the root zone (depth 8) is comparable to that of grassland.

From figure 5.7., the conclusion can be drawn that A-horizon Si concentrations rise after alteration of forest to grassland or plantation. This implies that, relative to grassland and plantation A-horizons, Si release must in some way be inhibited within the forest A-horizon. The low A-horizon Si concentrations are thought to be due to a number of reasons. Firstly, as indicated by section 5.4, the ratio of weathering released nutrients to nutrients present on the exchange complex is very low in the forest A-horizon. The greater part of the solutes in the topsoil are biocycling products. A high concentration of biomass derived solutes keeps the demand for weathering released nutrients in the forest topsoil low.

A second reason is thought to be vegetation Si uptake. Table 5.7 shows data compiled by Bruynzeel (1983) on forest (leaf) litter nutrient content, compared to nutrient concentrations in the LMS forest A-horizon. These data show that leaf litter contains Si in amounts even exceeding Ca. Decomposing litter, mostly leaves, should release Si into the forest A-horizon in relatively large amounts. The fact that the ratio of Si to basic cations in the forest A-horizon is small compared to that of leaf litter is evidence for A-horizon Si uptake. Extraction of Si from the soil by the vegetation is somewhat unusual, but not unexpected. Tropical vegetation is known to contain large amounts of Si. Under conditions of tropical agriculture on highly leached soils, (Sanchez, 1976) rice and sugarcane show poor growth characteristics and low pest resistance, due to silica deficiency. Also, certain trees in the Atantic zone contain Si up to amounts that prevent logging, so called 'petrified' stems (Nieuwenhuyse, personal communication).

Si in forest trees,(in contrast with grass, that quite rapidly recycles its opal), has a long residence time. Large amounts of Si are stored in the woody parts, and, on the short term, practically not released. The low Si concentrations in depth 1 are therefore exclusive to forest vegetation.
It might be argued that high below - rootzone and low A-horizon Si concentrations are just representing evidence for a very quick removal of Si down the soil, but as forests are known for their high water retention capacity, and the overall solute pattern is inverse, this does not seem reasonable.

table 5.7. Annual return of nutrients via leaf litterfall in selected natural tropical forests and plantations, as compared to Forest A-horizon concentrations

Ca	Mg	Na	K	P	SiO_2	(Kg ha^{-1})
128	22.5	2..5	27.5	3	219	Central Java
90.5	8.5	2	22	2.7	165.5	Colombia
82	15	2	19	2	159	Java (Plantation)

Ca	Mg	Na	K	P	SiO_2	(mmol m^{-3})
337	79	112	72	0.05	50	LMS Forest A-horizon

upper data set adapted from Bruynzeel. 1983

The high rootzone Si concentrations (depth 2) of the forest are best explained by the optimal weathering conditions created in the forest subsoil by the constant, slow percolation of organic acid, CO_2 and HNO_3 holding water. These acids find their source in the decomposition of litter (equation 5.1) and subsequent nitrification (eq. 5.2), (that are strongly related to the forest moisture regime, compare figure. 5.35, 5.36 and 5.37)

$$C_aN_{(b+k)}P_cS_d...M_gH_{2x}O_x\text{(fresh litter)} + (a+2b+2d)O_2 \dashrightarrow$$
$$aCO_2 + bNO_3 + cH_2PO_4^- + dSO_4^{2-} + gM^+ + kNH_4^+ + xH_2O + (b+c+2d-g-k)H^+ \qquad 5.1$$

Measured Si concentrations below the forest root zone (table 5.2 b, 200 mmoles m^{-3}) represent the cumulative amount of all Si leached out over the total profile depth, excepting the A-horizon. The low base concentrations and high (biogenic) acid flux will encourage a rapid weathering.

Judging from their very similar Si concentrations, depths 3 and 4 (grassland) are supposed to have a similar weathering regime. Also, Inorganic Carbon concentrations (fig. 5.12) indicate a similar weathering regime for both horizons. (NO_3 concentrations are very low and therefore nitric and other biodecomposition derived acids are thought to make a small contribution to weathering).

A-horizon Si concentrations (depth 3) are, as expected, somewhat lower than those below the root zone, due to Si transport down the soil. But the difference remains small. The fact that down the grassland profile no pronounced increase in Si is seen, indicates that grass biocycles Si in the A-horizon. Plants biocycle Si by storing and releasing it as plant opal. According to Dahlgren, Shoji and Nanzio (1991), most of the plant opal found in general is derived from grass species, thus stressing the importance of these vegetation types in

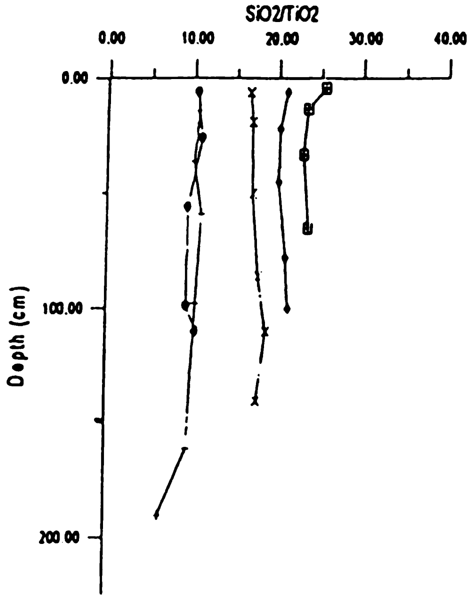


figure 5.8. SiO_2/TiO_2 content of various soil profiles under grassland in the Atlantic Zone (N. Walraven, B.v. Oonen, unpublished data)

biocycling of Si. Shoji takes japanese Pampas grass as an example. This grass biocycles large amounts of Si and contributes to high Si concentrations in the surface horizons of ash soils. As an indication: this grass produces litter with up to 40 g/Kg SiO_2.

Biocycled Si is released into the soil as opaline phytoliths. These phytoliths have been observed to be present in large amounts in Atlantic Zone grassland soils (N. Walraven, personal communication). Grassland soil Si measurements by B.v. Ooijen and N. Walraven further confirm biocycling. Instead of the expected decrease of SiO_2/TiO_2, Some of their profiles even show a marked increase in Si in the A-horizon(figure **5.8**).

High and varying Si concentrations in plantation A-horizon (7) are thought to be due to a rapid weathering of primary minerals, induced by the contact of excess fertilizer derived acid with the relatively fresh mineral material. The acid is produced by bacterial nitrification of NH_3. The most well described in vivo nitrification reactions are the transformations of NH_3 performed by Nitrosomonas and Nitrobacter (a.o Schlesinger, 1991, equations 5.2. a and b). A comparable set of reactions is thought to give rise tp the N-transformations observed in tropical soil.)

$2NH_4^+ + 3O_2 \text{-->} 2NO_2^- + 2H_2O + 4H^+$ (Nitrosomonas) 5.2 a
$2NO_2^- + O_2 \text{-->} 2NO_3^-$ (Nitrobacter) 5.2 b

Proof for this bacterial nitrification are the very large NO_3 concentrations of depth 7 (table 5.2 b) and the fact that the pH of depth 7 is generally the lowest LMS pH measured. (except for the rain related nitrification events in the Forest A-horizon (fig. 5.35, 5.36)). The plantation A-horizons represent reworked, but humus holding former grassland A-horizons, they will therefore also, at the prevailing pH's, exhibit CO_2 weathering, in the same order of magnitude as the grassland site (depth 3 and 4). But since this can't explain the high Si concentration of depth 7, (compare with depths 3, 4 and 8) the conribution of CO_2 weathering to the high Si conc. of depth 7 is thought to be minor (similarly to that of depth 5, the loamy plantation A-horizon, although at depth 5 it is not as pronounced, see fig. **5.12**)

Below the plantation root zone (depth 8) silica concentrations are comparable to those of the grassland subsoil (depth 3,4). This implies a weathering regime comparable to that of the grassland, as can be expected, since the plantation was only 5 months old at the time of sampling. The CO_2 concentrations in the grassland are thought to find their source in the decomposition of humus built up by the forest, and are not likely to have changed very much in the subsoil in this short period. Nitrification (fertilizer) derived acid has in most cases not reached this depth, though figure **5.12.** suggests in some cases it does play a role.

Si levels of the LLA soils are in the range expected for oxisols (figure **5.9**) The Si concentrations, averaging around 70 mmol m^{-3}, suggest that there is still weatherable material left in these soils (possibly, Halloysite or Kaolinite degrading to Gibbsite). The somewhat lower value for LLA-a (forest subsoil) than the value found for grassland (LLA-b,c), as well as the high values of LLA-d (plantation A-horizon) suggest the influence of the low moisture content of the samples, raising the concentration. Another reason for this concentration sequence, that is inverse to the LMS forest - grassland Si concentration sequence, might be that the soil Si minerals are degrading faster after removal of the forest vegetation, but since n =< 3 for these measurements, no definite conclusions can be drawn.

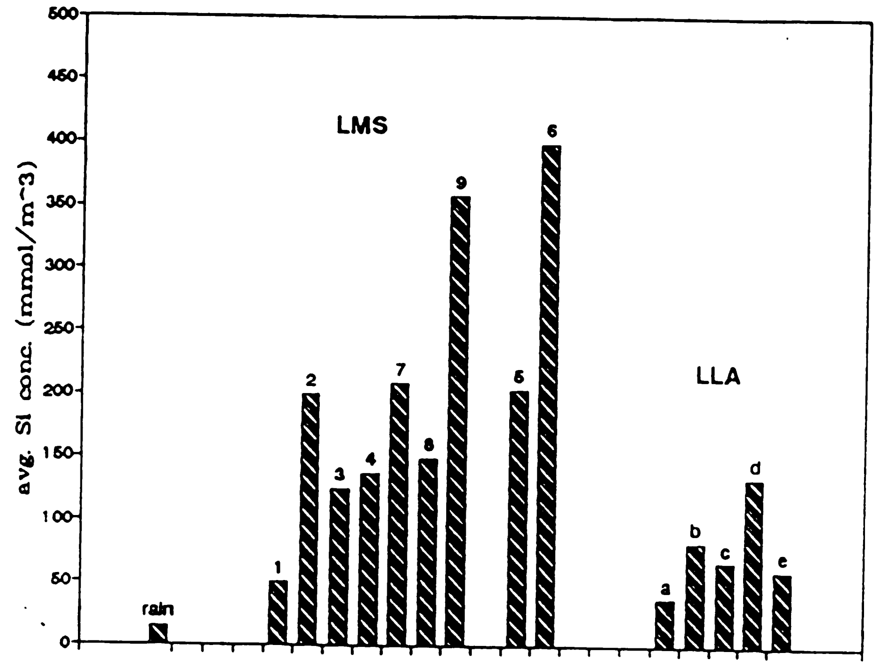


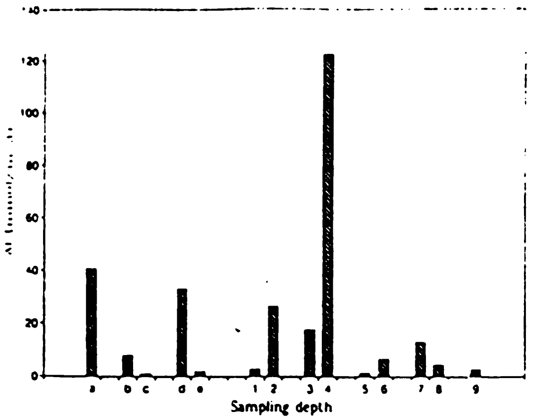
figure 5.9. Average Si concentrations of soil moisture samples of both the LLA and LMS sites.

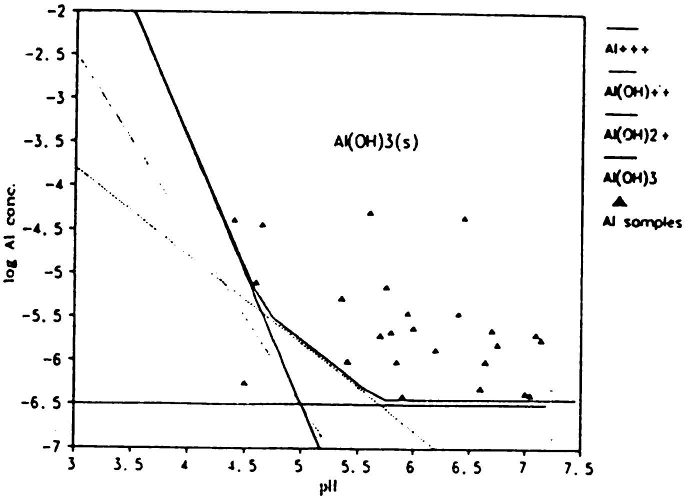
As expected, Al concentrations at most LMS sampling depths (except depth 4, fig. **5.10 a**) are low , due to the fact that the LMS soils have pH's typical for andisols (table 5.2 b, table 5.20). Al level's for LLA soils seem somewhat higher, in accordance with their lower pH regime, but as very few LLA samples were analysed on Al, this is not a very established fact.

As shown in figure 5.10 b, all samples (excepting a LLA sample) lie in the stability field of precipitated $Al(OH)_3$, indicating that free Al^{3+} cannot account for the Al concentrations found at the measured pH's. The fact that still, Al was measured, might be attributable to incorrect pH measurements (compare section 5.1). Another, more plausible reason for the LMS samples, is that mobilization of Al has occured by complexation with organic matter. Al was determined by colorimetry. The used method is based on complexing free Al with the complexing agent pyrocathecholviolet. This complexing agent may very well complexate Al that was previously bound to a less strongly complexing agent, a low molecular weight organic acid. The Al results must be viewed as total dissolved Al, rather than as free Al^{3+}.

Figure 5.11 shows, that ammoniumoxalate extractable Al and exchangable Al increase with C-org. content. A clear division between low Al /low C-org subsoil and high Al/high C-org A-horizons can be seen (with depth 3 and 4, the grassland A-horizon and buried A-horizon as an exception). In the soil, Al bound to organic matter is thought to be mostly retained within the C-org rich layer by high molecular weight organic material (compare fig. 5.11). A small part of the organic material is mobile and travels down the soil. It can be decomposed on its way down the root zone, or washed out. The measured LMS Al probably comes from these dissolved organic acids.

The C-org rich grassland subsoil (depth 4) has, of all LMS subsoils, highest exchangable Al and ammoniumoxalate extractable Al concentrations (table 5.20). Exchangable Al concentrations are about twice as high as in the forest. It is interesting to see that though about 2000 years passed since the catastrophic burial of the former forest A-horizon, total acidity is quite similar to that of present day forest (compare table 5.20, depth 1). Only, Al has replaced H^+ on the exchange complex, as can be expected. The high Al concentration on the exchange complex is reflected in high total dissolved Al concentrations.





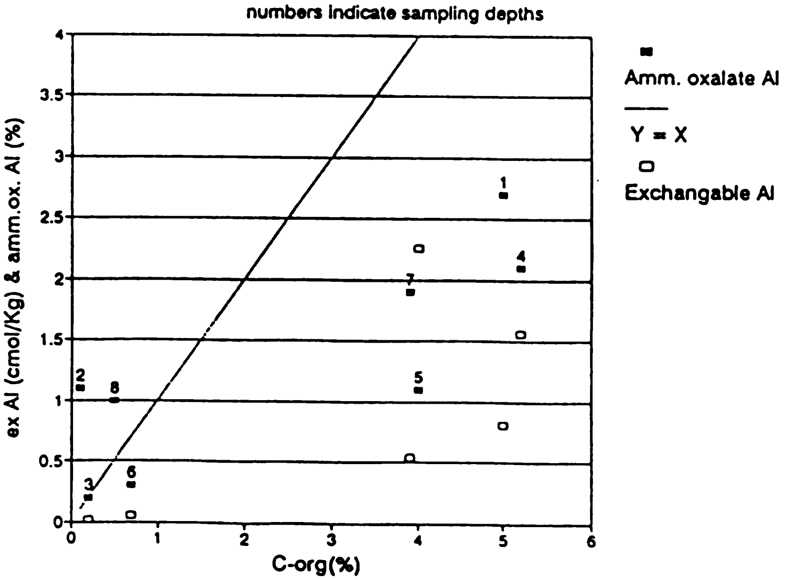


figure 5.10 a. Average Al concentration of the LLA and LMS sampling depths.

figure 5.10. b. Al Concentrations of the water samples plotted in the Al-hydroxide stability diagram (298.15° K, 1 atm., adapted from Morel, 1983)

figure 5.11 Ammoniumoxalate extractable and Exchangable Al versus organic Carbon content of LMS soil samples.

5.7 Potassium, Nitrogen, Phosphorus

The LMS forest A-horizon (depth 1) shows, of all A-horizons, highest releases of NO_3 and K vs. time(table 5.2 b, figure **5.30.** and **figure 5.36.**).

The strong covariation of NO_3 with rain (figure **5.36**) suggests that nutrients in the forest soil are subject to flushing. This flushing of nutrients is thought to occur in the following way:

The turnover rate of solutes from dead to living biomass in the forest A-horizon is higher than their percolation rate. Large amounts of NH_3 and other biodegradation products are released from decomposing litter into the soil solution (eq. 5.1.) and are rapidly reassimilated again by plant roots (see also section 5.4).

During periods of relative drought, degradation of organic material continues, but reassimilation slows down, leaving degradation products to accumulate in the A-horizon. A subsequent heavy shower triggers bioactivity to a higher level and flushes accumulated nutrients down the soil. This can be seen in Ca, Mg and Na concentrations vs, time, and in the pH vs. time plot of the various A-horizons

(fig. **5.30 a - 5.35 a**, compare also SO_4, fig **5.37 b**). After the two largest rainfall events, in the forest A-horizon a sharp pH drop is seen, together with an NO_3 peak (fig. **5.36 a**), due to bacterial nitrification of the released NH_3 (eq. 5.2.). The extreme differences within one day are a tribute to the high efficiency of the tropical soil biota. SO_4 represents a litter degradation product (eq. 5.1), and therefore the sulphate peaks in the forest subsoil following rain are further proof to the suggested flushing events.

The weak covariation of K with rain suggests that K does not build up higher concentrations during periods of relative drought. This is consistent with the fact that the forest has a high K demand, and a relative low supply, encouraging uptake.

Depth 2 (forest subsoil) K concentrations are very much independent of rainfall and very low. It is likely that this pattern arises from rigorous nutrient uptake of the forest, leaving only residual amounts of nutrients behind. The forest seems to be less economical with NO_3.(fig 5.36). However, this is due to the effect of the large forest biomass N-inventory, compared to the small N- inventories of the grassland and plantation. Average forest A-horizon concentrations (depth 1) are about 480 mmoles m^{-3}, and subsoil concentrations average about 180 mmoles m^{-3}. This suggests an uptake factor of 2,7. As can be seen by comparing with table 5.3, this is higher than the forest uptake preference of Ca, Mg and Na.

Depths 3, 5 and 8, (grassland, loamy plantation and sandy plantation) generally show lower K values than in the forest, as expected from their smaller biomass K pool. Depth 4 and 9 (grassland below the root zone and waterlogged grassland) K values are exceptionally high. Since the sampling site of depth 4 was located only several meters from the site of depth 9, in the same grassland, it is probable that it has been subject to frequent waterlogging. This brought the buried C-org layer in contact with groundwater, having the composition measured at depth 9. Exchange processes with this groundwater are thought to have given the exchange complex at depth 4 the composition it currently has. It is interesting to see that compared to depth 9, K is enriched by the exchange process, relative to Ca and Mg. The former forest A-horizon organic matter of depth 4 seems in itself to have a preference for K, even without living biomass.

The K concentration at depth 6 is extremely low. Since at depth 8 this low concentration is not found, it can not be due to the high K demand of banana plants. Therefore some other sink must be found, since the weathering release of K must, like that of Ca and Mg, also have been large at this depth (see section 5.4.) The first thing that comes to mind is that K is incorporated in some (illitelike) mineral phase. This has not been observed in the field yet, although some researchers have found a mineral association similar to illite in andesitic ashsoils.(Wada and Kakuto, 1985) The topic needs further research.

NO_3 concentrations at depth 3 and 4 and 9 (grassland) are extremely low, as expected. The grassland biomass is much smaller, and probably symbiotic nitrogen fixation is not as effective as in the forest at this site. Therefore, the demand for nitrogen in the grassland will be high and the supply low, giving the above mentioned result.

NO_3 values of depth 5 and 8 are higher than those of the grassland, probably due to fertilizer contamination.

Phosphorus is in most of the cases low, and close to the detection limit (0.01 mmol m^{-3}, see annex 5.1), The general low concentration of P is in accordance with it's being a biolimiting element within tropical plant-soil systems. The demand for P by the forest and grassland biota is high enough to keep its concentrations low at all sites. Rain P concentrations are generally higher than soil moisture P concentrations (annex 5.1). It is interesting that P concentrations of the LMS grassland are higher than P concentrations of the LMS forest. Because N concentrations of the grassland are lower, the grassland higher P concentrations must be the result of the higher forest efficiency in recycling P. The LMS plantation P concentrations are so high that contamination is suspected.

5.8 Inorganic Carbon, pH

As mentioned before, the LMS forest rapidly decomposes it's litter, producing large amounts of nitric and organic acids in the process. These acids are thought to be important proton donors , along with CO_2, explaining why in the forest soil overall pH values are low and weathering is high, but also, Inorganic Carbon (IC) concentrations (figure **5.12 a**) are relatively low.

LMS soil pH's are above 5 (table 5.20), therefore, H_2CO_3 is supposed to be the main proton donor for weathering at all LMS sites. Contrary to this expectation, depths 1 (A-horizon of the forest) and 5 (A-horizon of the loamy plantation site), and part of depth 8 (subsoil sandy plantation site) , in contrast with depths 3, 6 and 9, show a low total IC vs. **total** basic cation trend (fig **5.12 a**), that indicates a high input of NO_3 as extra proton donor (fig **5.12 c**). Total IC concentrations of figure 5.12 a. were calculated from the excess negative charge. Figure **5.12 b** shows measured Inorganic Carbon concentrations. These indicate that the difference is even more extreme than suggested by figure 5.12 a.

In the plantation depths 5, 7 and 8 the NO_3 source is artificial (fertilizer), but for the forest it is natural. The high forest organic acid input is thought to make a strong contribution to weathering in the forest soil, as can also be inferred from the fact that (fig 5.12 a and 5.12 b) IC at depth 2 shows a weak correlation with basic cation cation concentrations.

Total Inorganic Carbon is related to the pH and PCO_2 of soil moisture in the following way (Morel, 1983):

At pH's lower than 6.3, the $H_2CO_3{}^*$ complex does not dissociate, and IC can be taken to be equal to $H_2CO_3{}^*$, (H_2CO_3 together with dissolved CO_2, hence the * sign) that is independently of pH related to PCO_2 in the following way (brackets designate 'concentration' in moles/l, PCO_2 is in vol.%):

$(H_2CO_3^*) = 10^{-1.5} \cdot PCO_2$ 5.3

or in it's logarithmic form: $\log (IC) = -1,5 + \log (PCO_2)$ 5.4

Above pH 6.3 (until pH=10,3), the dominant CO_3 form is HCO_3^-. IC can be taken to approximately equal to HCO_3^-. HCO_3^- is related to pH and PCO_2 in the following way:

$(HCO_3^-) = 10^{-7.8} \cdot PCO_2 \; /(H^+)$ 5.5

or in it's logarithmic form: $\log (IC) = -7,8 + \log(PCO_2) + pH$ 5.6

Using equation's 5.4 and 5.6, PCO_2 was calculated for a number of pH and TIC data from different subsampling sites. The results are shown in figure **5.13**. The figure indicates that data neatly follow the 'main CO_3 phase' rules as set up o.a. by Morel (1983). PCO_2 is relatively evenly distributed among the LMS depths.

The average $\log(PCO_2)$ for the samples is -2.39. The atmospheric $\log(PCO_2)$ being ≈ -3.5, this value indicates CO_2 concentration in soil moisture is at least ten times as high as in the atmosphere. This is probably even a low estimation, due to the atmosphere equilibration discussed in section 5.1.

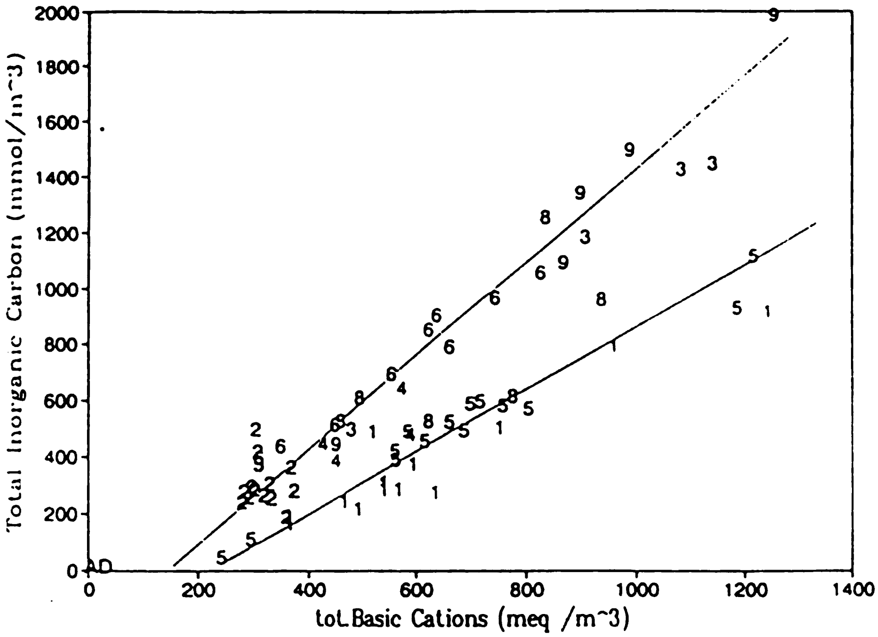
PCO_2 is higher at depth 3 (grassland topsoil) than at depths 1 and 2 (forest). Also, it seems to be lower at depth 1 (A-horizon) than at depth 2 (below the rootzone). This is surprising, since pH's are lowest at depth 1, increasing for depth 2, and are highest (for these three) at depth 3. IC concentrations also follow this pH inverse PCO_2 pattern.

The 'reverse' IC - pH pattern is evidence of the fact that along the whole forest profile extra proton donors are active; the organically derived acids mentioned earlier. (judging from the strong nitrification effects, predominantly HNO_3). The acids play their most active role in the upper soil and IC plays a bigger role as the forest root zone is left (see fig. 5.12).

Generally, a conversion of forest vegetation to grassland leads to a rise in pH, due to the lessened release of organic acids. The role of NO_3 and organic acids is almost completely taken over by CO_2. Weathering, as measured by the amount of Si released, seems to be lower.

Lowered vegetation activity after forest removal can be seen clearly when grassland NO_3 (5.12 c) and %C-org (table 5.20) are examined. These values are very low, NO_3 values being almost all below detection limit (fig. **5.36**). The reason for this is that grassland contains a biomass that is about a factor 20 lower than standing tropical forest (Nye and Greenland, 1960). The grassland is about ten years old, so the source of enhanced NO_3 release so often observed after deforestation is probably already depleted.

Although the absolute validity of the LMS pH values (5.35) is somewhat questionable (see section 5.1), relative values show that for the A-horizons, grassland pH's are highest, followed by forest, and are lowest for the plantation (due to fertilizer nitrification). Soil moisture pH values below the root zone are lowest for the forest vegetation, suggesting that the amount of acid released into the subsoil is greatest in the forest, as can be expected from it's high biomass. Summing up, forest vegetation affects the soil more thoroughly than grassland or plantation.



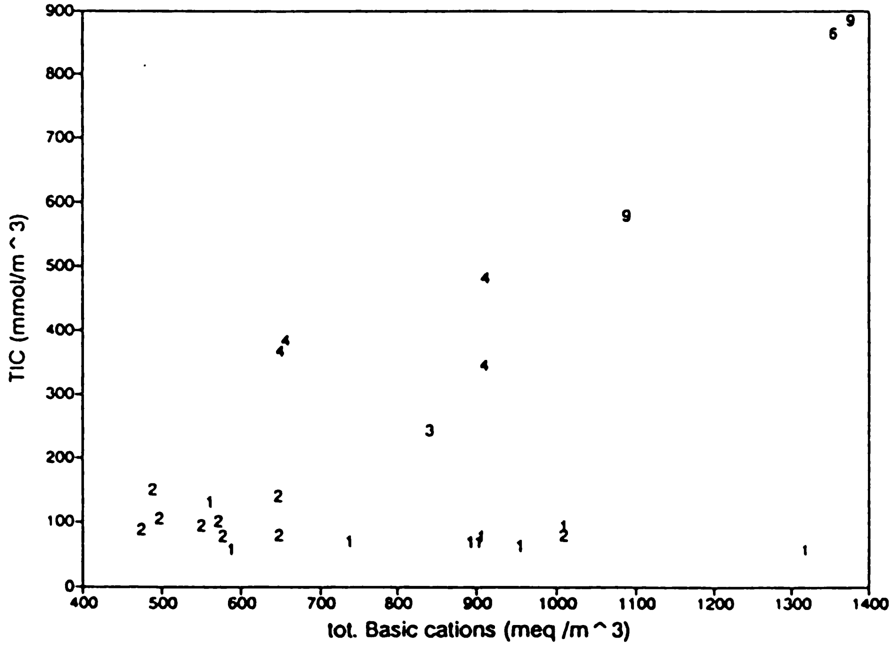
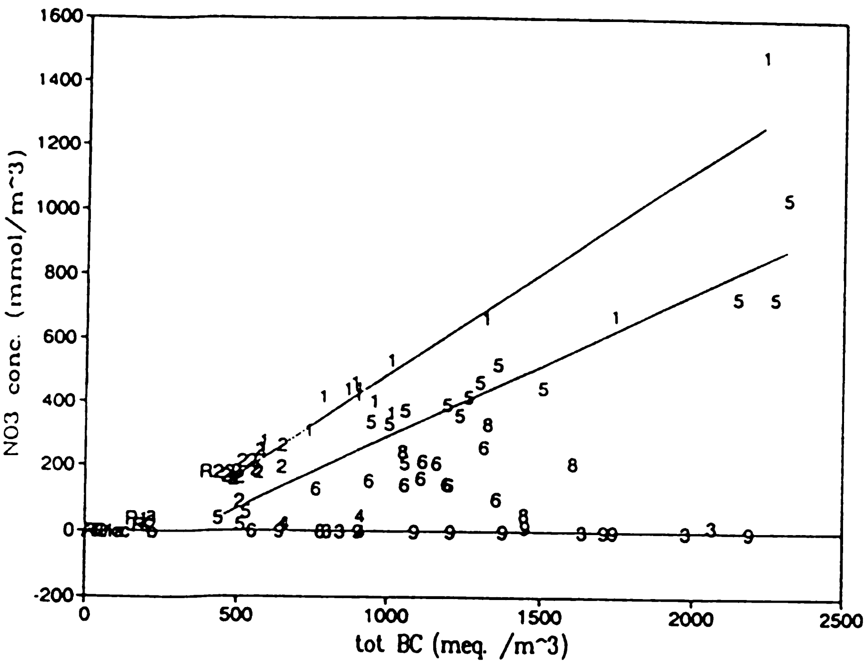


Figure 5.12 a. Total Inorganic Carbon (as calculated from charge balance) versus total basic cation content of LMS water samples

Figure 5.12 b. Tota Inorganic Carbon (as measured) versus total basic cation content of LMS water samples



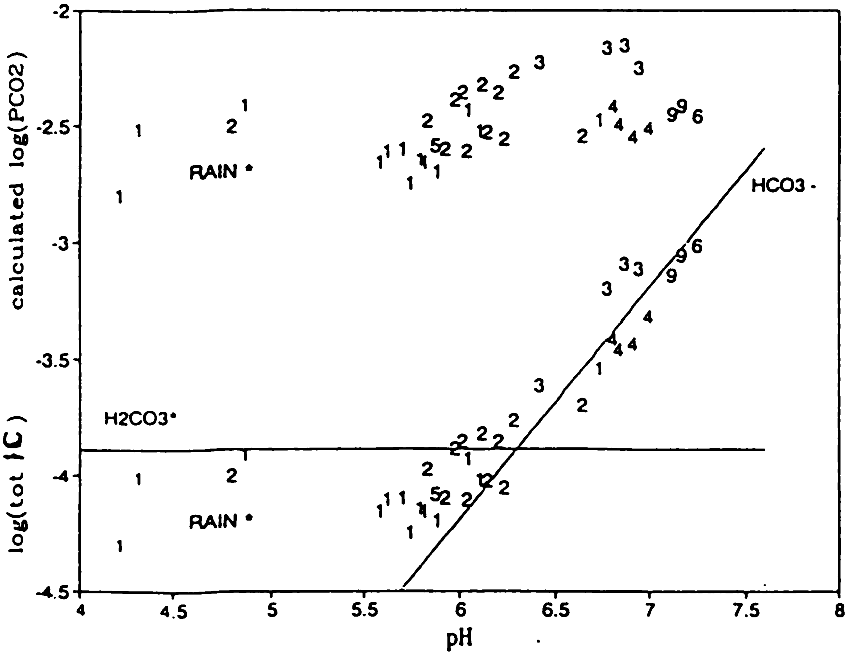


Figure 5.12 c. NO_3 concentration versus total basic cation content of LMS samples.

Figure 5.13. Total inorganic Carbon and calculated $\log(PCO_2)$. Solid lines were drawn for $\log(PCO_2) = -2.39$

Na concentrations are higher in the LLA forest root zone (LLAa)(fig. 5.14) and in the well draining the LLA forest (LLA x) than at the other LLA sites. The reason for the Na anomaly is sought in the degree of maturity of the forest-soil system and it's position close to the sea.

LLA soils are all depleted so strongly in basic cations, that in a rough approximation they can be thought of as (H^+ bearing) ion-exchange material for the vegetation. Water leaving this soil should have a basic cation composition that is the resultant of the average composition of vegetation and rain (vegetation approaches steady state, but never quite reaches it). Samples taken from a well draining the area show a clear anomaly in Na and Mg. Table 5.8 shows the average basic cation composition of in and outcoming water fluxes from both the soils and the average composition of sea water.

Supposing that aerosol carried drops of seaspray are frequently mixed with terrestrial dust, supplying nutrients that are subsequently scavenged by rain and keeping in mind the preference of plants for Ca and K, draining water (LLAout) holding anomalously high Na and having a somewhat raised, but still very low Ca/Mg ratio is to be expected. Therefore, assuming the weathering base to be below the well, the composition of the well water is proof to the fact that the forest actively utilizes seaspray derived nutrients. This effect is also noticable for the LMS forest. even though concentrations of nutrients are still relatively high within the soil. As can be seen in table 5.7, if the main input of nutrients in the forest A-horizon is from plant decomposition, Na is anomalously high.

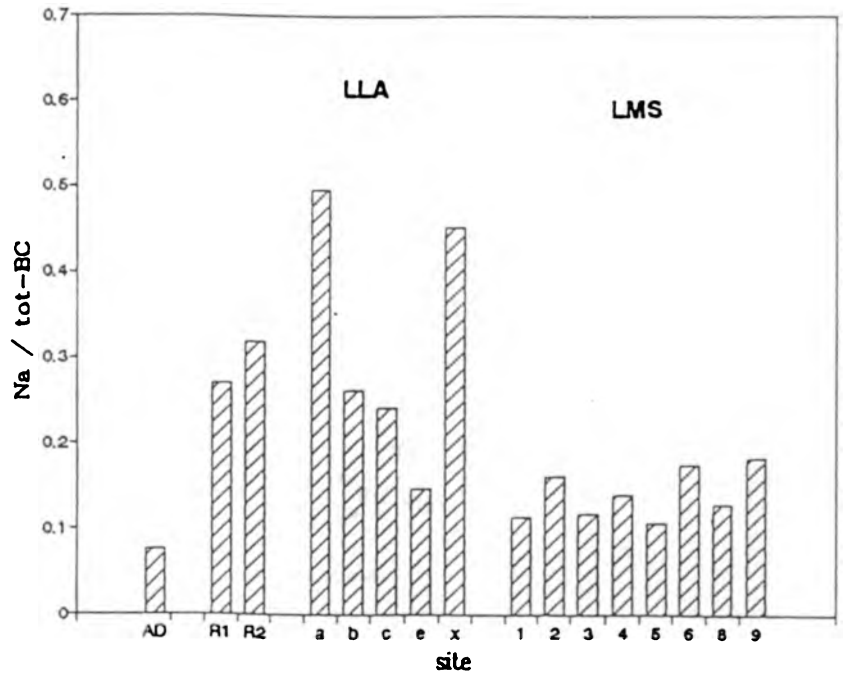


figure 5.14. average Na/(Na + K + Ca + Mg) for both the LLA and LMS sites. Rainfall, site LLA a (forest subsoil) and site LLA x(a well draining the forest) show positive anomalies.

table 5.8 average conc. of basic cations (mmoles m^{-3}) in seawater, rain and water leaving the soil (out)

solute	LLArain	LLAout	LMSrain	LMSout	Seawater[a]
Ca	114	28	35	424	10500
Mg	63	38	38	256	54300
K	41	27	12	33	10400
Na	138	132	85	241	479000
Ca/Mg	2.24	0.74	1.21	1.68	0.19

a: Adapted from Broecker and Peng (1983)
Values are averaged, compare annex 5.1,

corresponding codes:
LLArain - R1
LMSrain - R2
LLAout - LLA x
LMSout - LMS 9

Further proof for LLAa Na enrichment is found in the fact that this forest subsoil is the only depth that has a Ca/Mg ratio corresponding to that of LLA rain(fig. 5.15.)

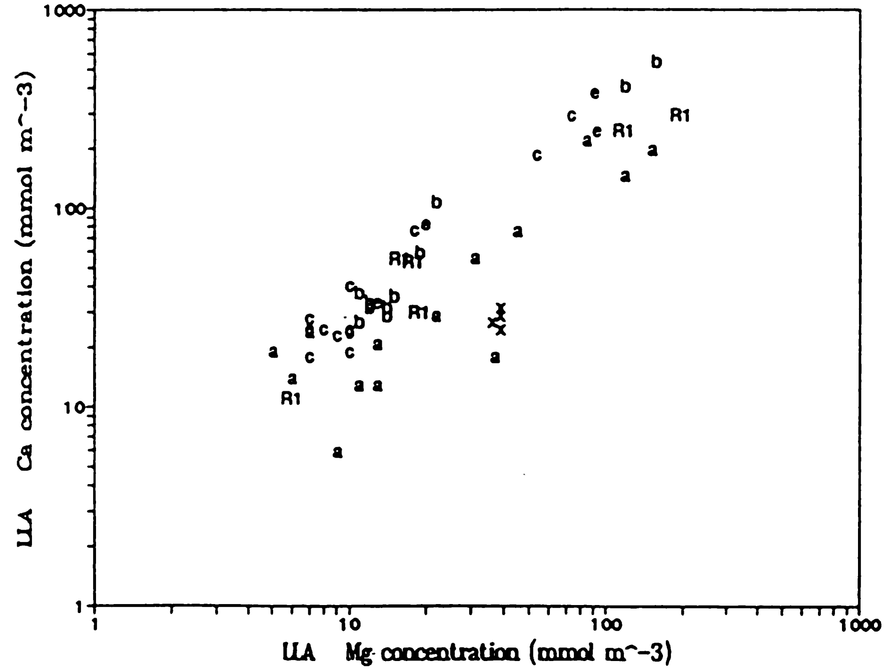


figure 5.15 log(Ca) versus log(Mg) of LLA water samples. LLA a, LLA x and rainfall plot slightly beneath the normal trend.

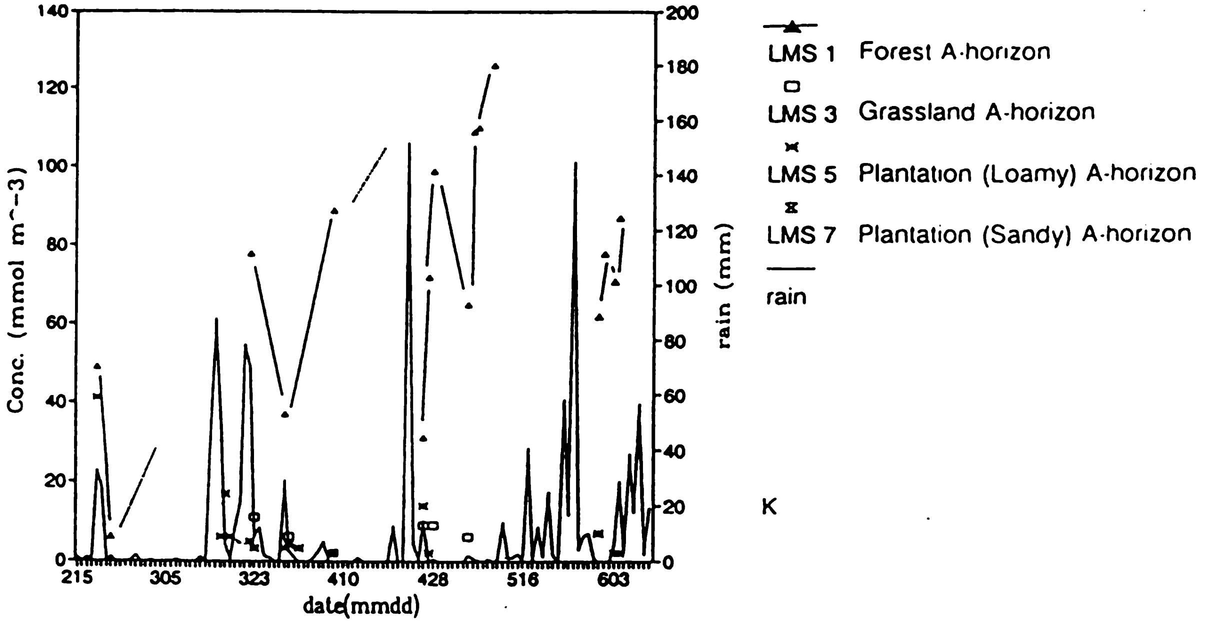
5.10 major anions

The behaviour of Cl and SO_4 generally falls in the line of expectation. They are thought to be mainly excess positive charge compensators. Except for two 'flushing' events, following extreme rainfall (fig. 5.37 b), than can be expected from the fact that it is needed for the formation of organic tisue, SO_4 shows no conspicuous features. With this it is similar to Chlorine, that has as only conspicuous feature a somewhat lowered concentration in the forest A-horizon as well as below the root zone, compared to the other depths. Generally, Cl and SO_4 are supposed to play no active role in soil processes, and are thought to find their main source in precipitation. This explains the low, rain related concentrations, that have a low correlation with basic cations. Unfortunately, LLA data contain very few Cl and SO_4 analyses.

table 5.20 soil sample analyses of LMS and LLA soils. Two LLA forest sites were analyzed. Depths are in centimeters. The sites referred to by the codes are listed in table 5.1

CODE	DEPTH	theta	pH KCl	total.ac (cmol/kg)	ex. Al (cmol/kg)	ex.H (cmol/kg)	% org. C	CEC	% BASE SATUR.
LMS 1	0-10	0.936	4.52	2.08	0.81	1.27	5	24.6	8
	30-40	0.741	5.01				3.1	10.4	15
LMS 2	180-190	0.344	5.2				0.1	4	35
LMS 3	0-10	0.336	4.5	0.01	0.02	0.00	0.2	14.6	87
	30-40	0.431	4.81	0.00	0.01	0.00	0.3	18.6	80
LMS 4	100-110	0.962	4.47	1.90	1.56	0.34	5.2	20.4	37
LMS 5	0-10	0.795	4.24	3.90	2.26	1.64	4	23.7	41
	30-40	0.589	4.54	0.60	0.25	0.35	1.1	21.9	73
LMS 6	70-80	0.554	4.59	0.11	0.05	0.06	0.7	22.8	77
LMS 7	0-10	0.476	4.56	0.78	0.54	0.23	3.9	13.4	31
	30-40	0.327	5.3				1.2	6.9	36
LMS 8	90-100	0.229	5.18				0.5	5.7	49
	0-10	0.607	3.88	7.36	6.24	1.12	3.7	17	3
	30-40	0.615	4.03	5.02	3.30	1.71	0.7	8.4	2
LLA a1	100-110	0.872	4.03	5.42	4.09	1.34	0.7	10.3	3
	0-10	(H2O->)	4.4	5.10			8.5		
	30-40	(H2O->)	5	4.80			0.3		
LLA a2	115-125	(H2O->)	5.3	4.60			0.8		
LLA d	0-10	0.556			5.20	0.00		14.1	
LLA e	140-150	0.59			3.10	0.00		8.7	

		ammoniumoxalate extractable				<- cmol+/kg ->			
CODE	DEPTH	% Fe	% Si	% Al	ex. Ca	ex. Mg	ex. Na	ex. K	(Ca/Mg)
LMS 1	0-10	0.8	0.8	2.7	1.4	0.3	0	0.2	4.67
	30-40	0.9	1.1	3.2	1	0.3	0.1	0.2	3.33
LMS 2	180-190	0.5	0.5	1.1	1	0.3	0	0.1	3.33
LMS 3	0-10	0.6	0.1	0.2	8.4	3.5	0.3	0.5	2.40
	30-40	0.8	0.1	0.4	9.6	4.2	0.4	0.6	2.29
LMS 4	100-110	1.4	0.5	2.1	4.1	1.3	0.3	1.8	3.15
LMS 5	0-10	1.4	0.2	1.1	7	2.3	0.2	0.2	3.04
	30-40	1.2	0.2	0.7	9.3	5.9	0.6	0.2	1.58
LMS 6	70-80	0.6	0.1	0.3	10.3	6.7	0.5	0.1	1.54
LMS 7	0-10	0.8	0.6	1.9	3.3	0.6	0.1	0.2	5.50
	30-40	0.7	0.6	1.7	1.6	0.7	0.1	0.1	2.29
LMS 8	90-100	0.6	0.4	1	2	0.6	0	0.2	3.33
	0-10	0.9	0	0.5	0	0.3	0	0.2	
	30-40	0.3	0.1	0.5	0	0	0	0.2	
LLA a1	100-110	0.3	0	0.5	0	0	0.3	0	
	0-10	0.5		0.6	0.86	0.15	0.28	1.03	5.73
	30-40	0.7		0.7	0.87	0.04	0.12	0.11	21.75
LLA a2	115-125	0.5		0.7	1.03	0.09	0.14	0.15	11.44
LLA d	0-10				0.2	0.1	0	0.4	2.00
LLA e	140-150				0.2	0.1	0	0.1	2.00



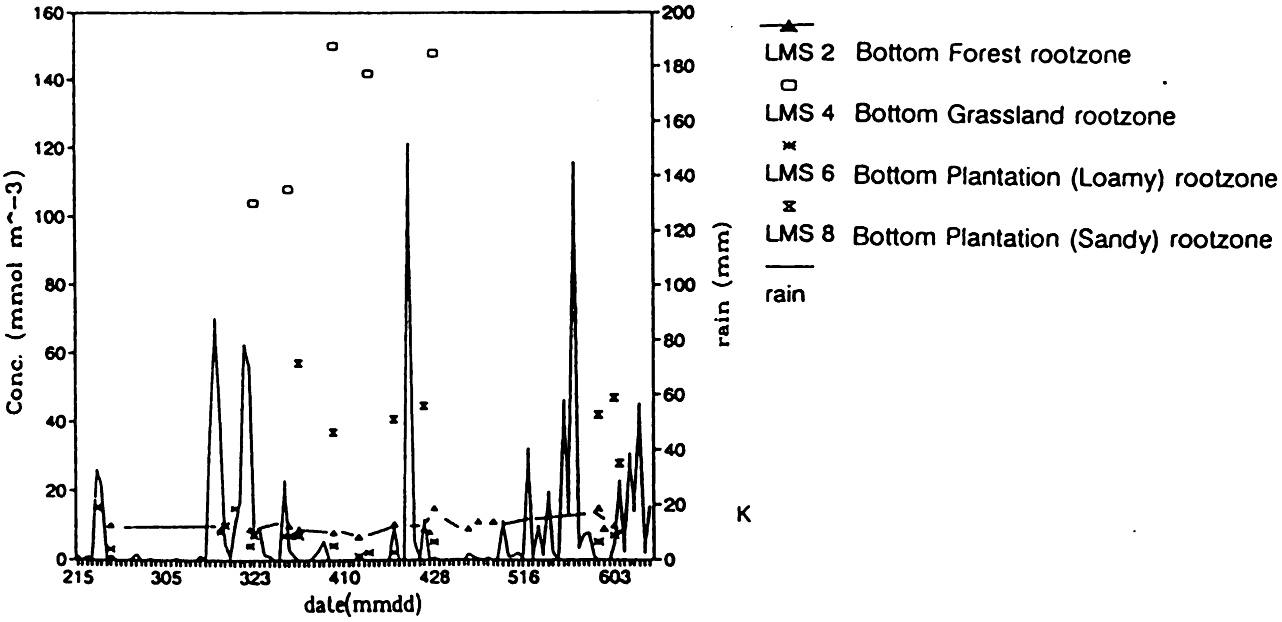
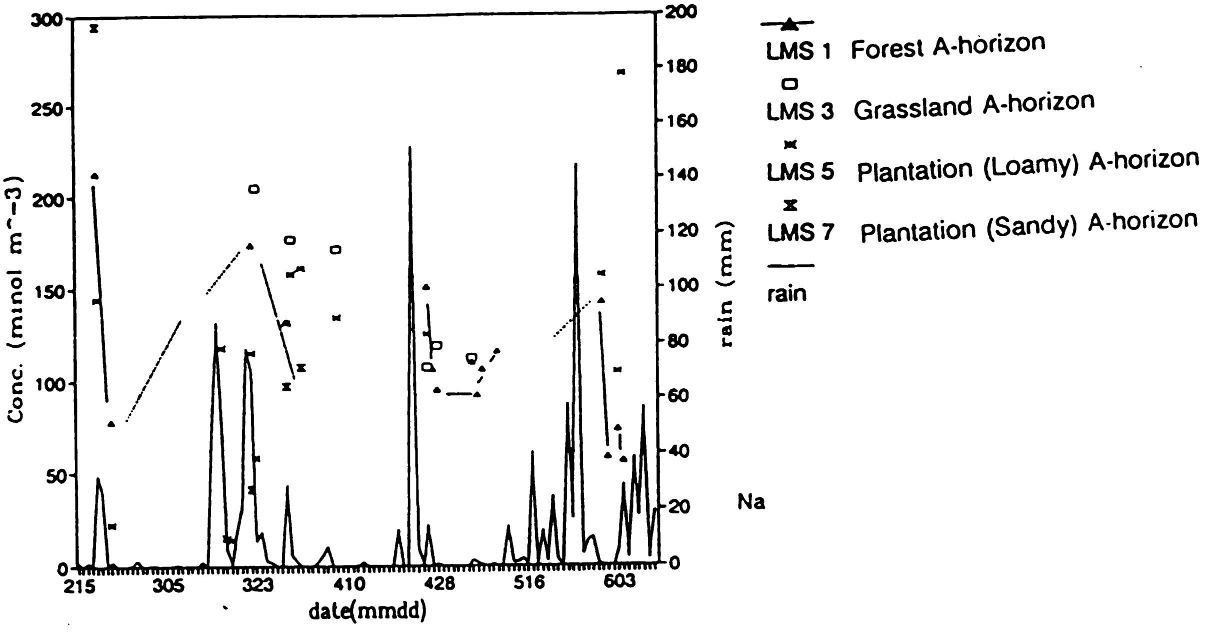


Figure 5.30. a. K concentrations vs. time of the LMS subsampling sites: A-horizons. LMS forest concentrations are interpolated.

Figure 5.30. b. K concentrations vs. time of the LMS subsampling sites: below the rootzone. LMS forest concentrations are interpolated.



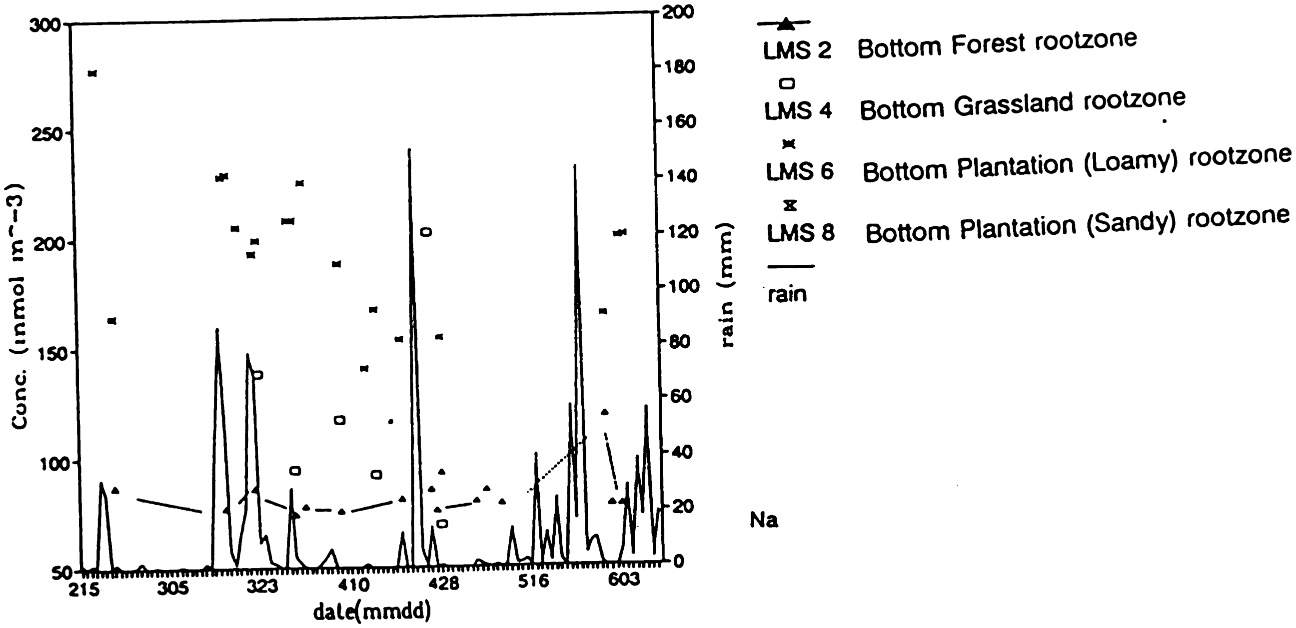
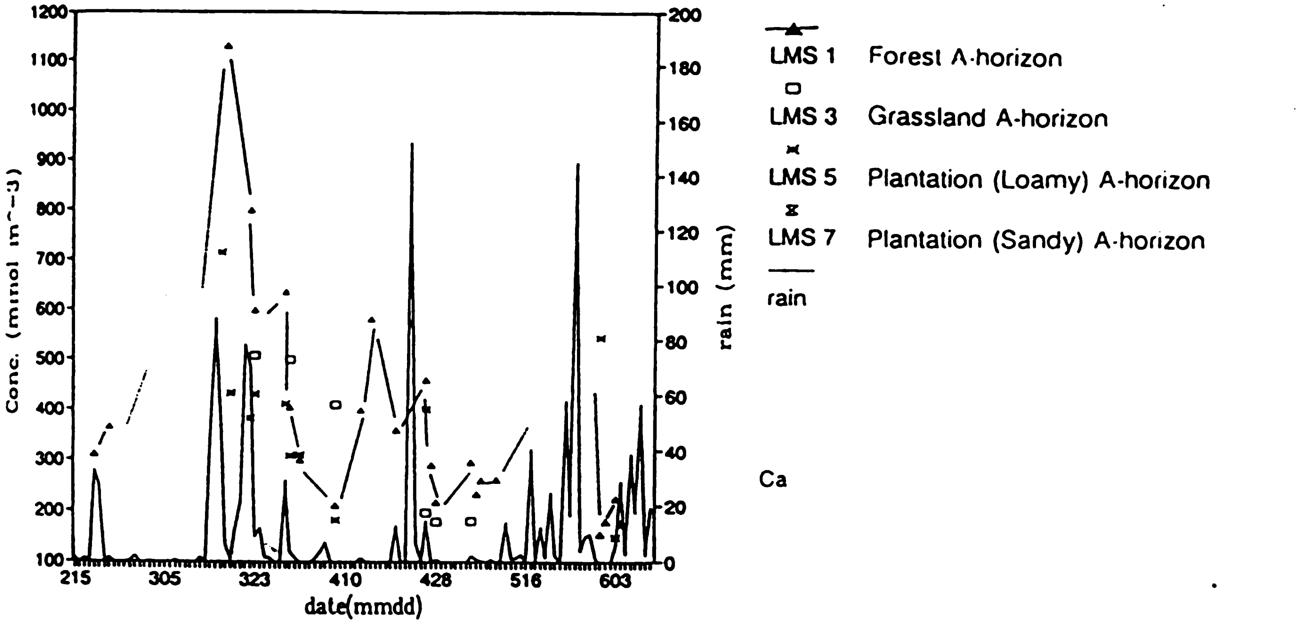


Figure 5.31. a. Na concentrations vs. time of the LMS subsampling sites: A-horizons. LMS forest concentrations are interpolated.

Figure 5.31. b. Na concentrations vs. time of the LMS subsampling sites: below the rootzone. LMS forest concentrations are interpolated.



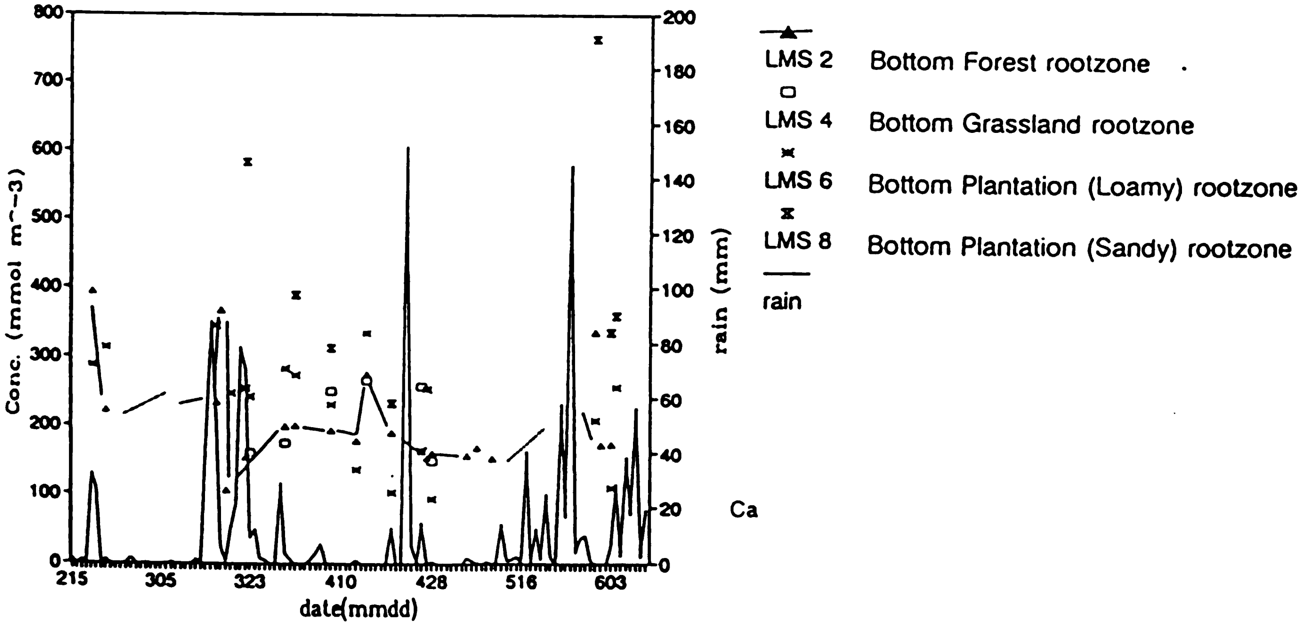
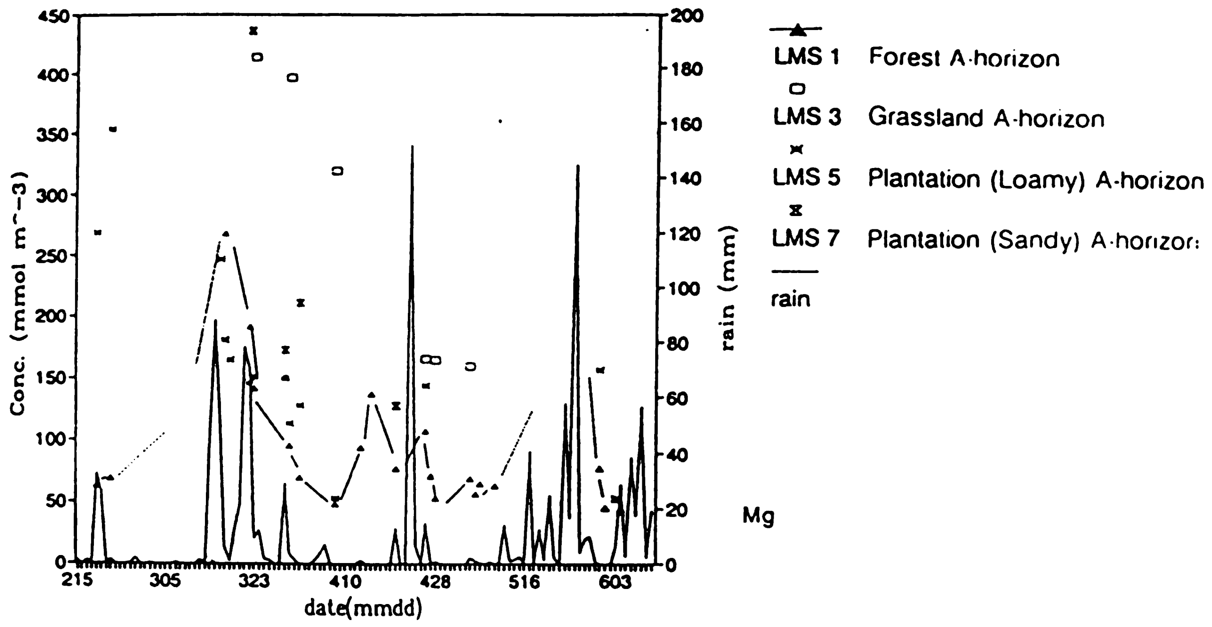


Figure 5.32. a. Ca concentrations vs. time of the LMS subsampling sites: A-horizons. LMS forest concentrations are interpolated.

Figure 5.32. b. Ca concentrations vs. time of the LMS subsampling sites: below the rootzone. LMS forest concentrations are interpolated.



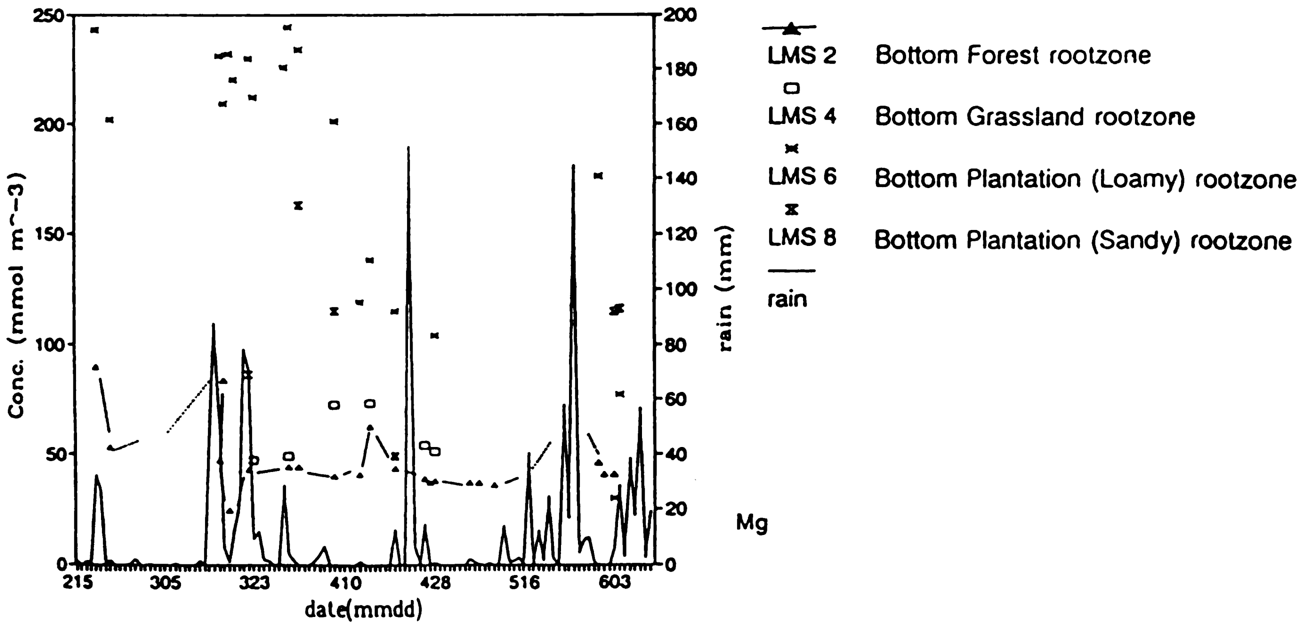
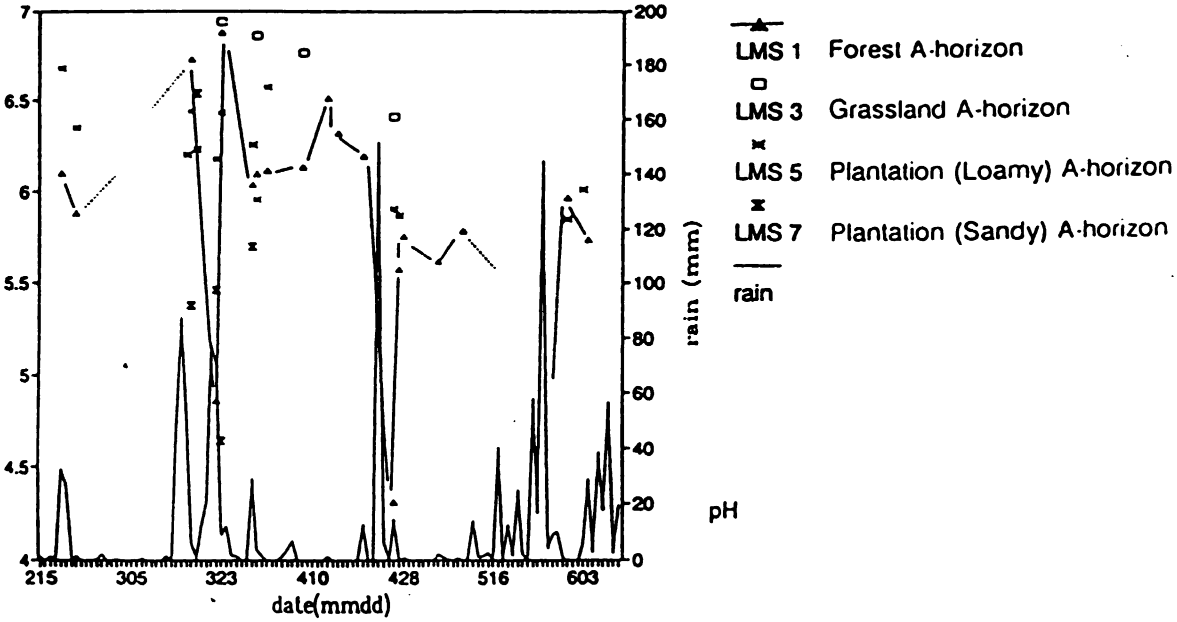


Figure 5.33. a. Mg concentrations vs. time of the LMS subsampling sites: A-horizons. LMS forest concentrations are interpolated.

Figure 5.33. b. Mg concentrations vs. time of the LMS subsampling sites: below the rootzone. LMS forest concentrations are interpolated.



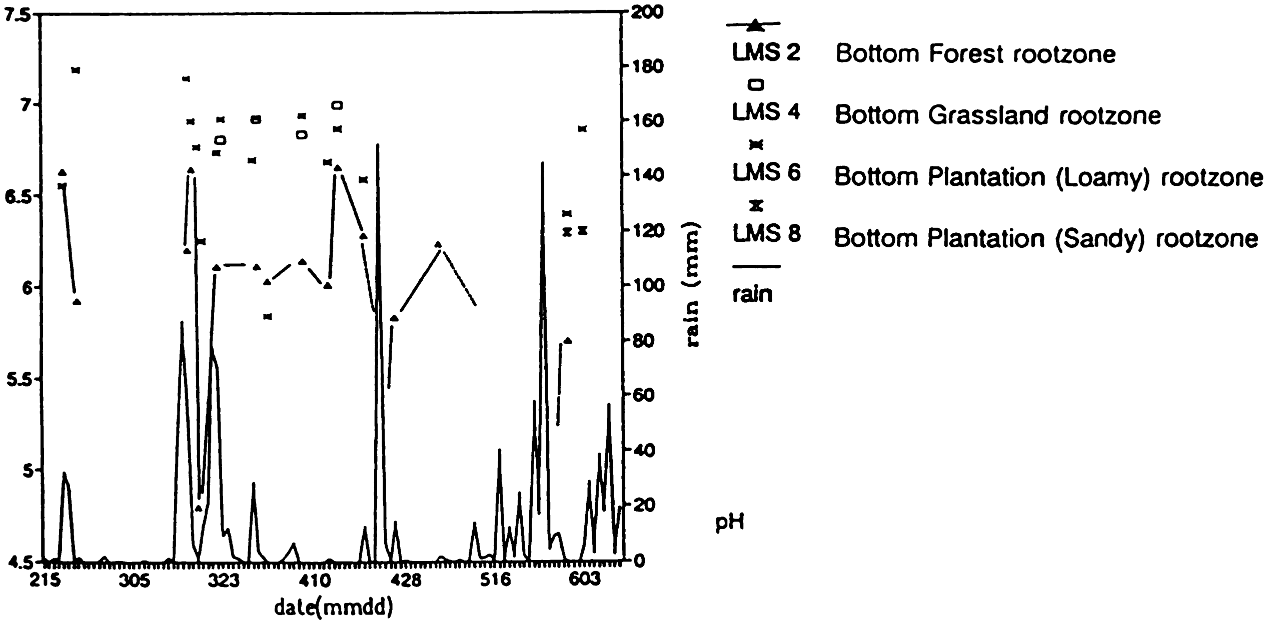
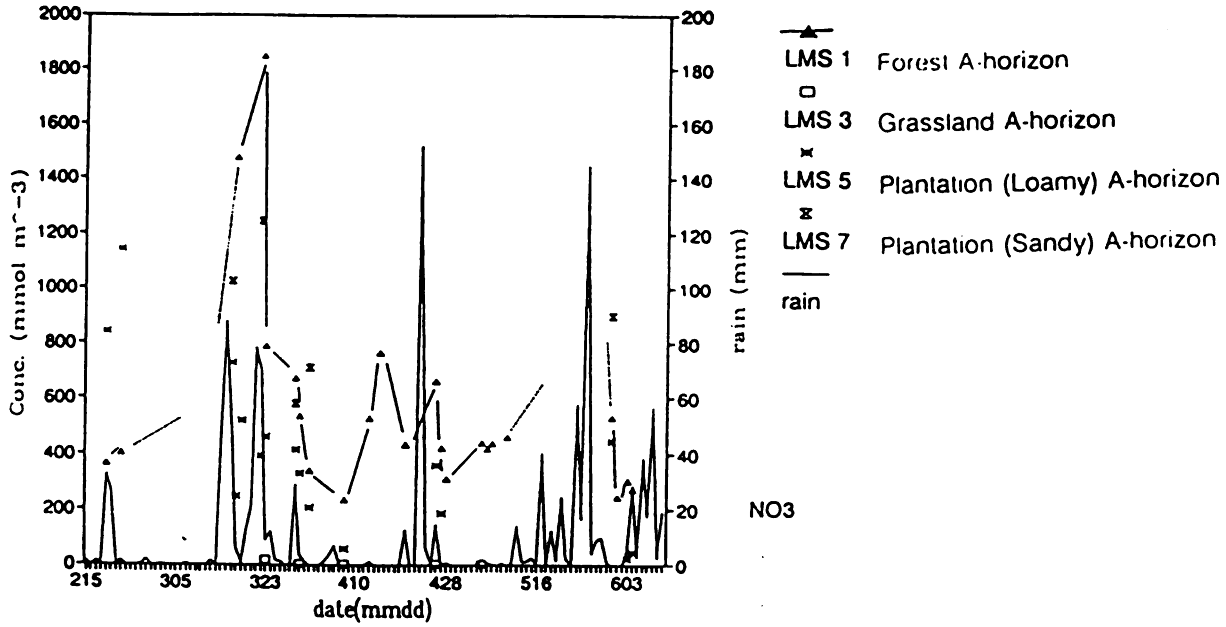


Figure 5.35. a. pH's vs. time of the LMS subsampling sites: A-horizons.
LMS forest values are interpolated.

Figure 5.35. b. pH's vs. time of the LMS subsampling sites: below the rootzone.
LMS forest values are interpolated.



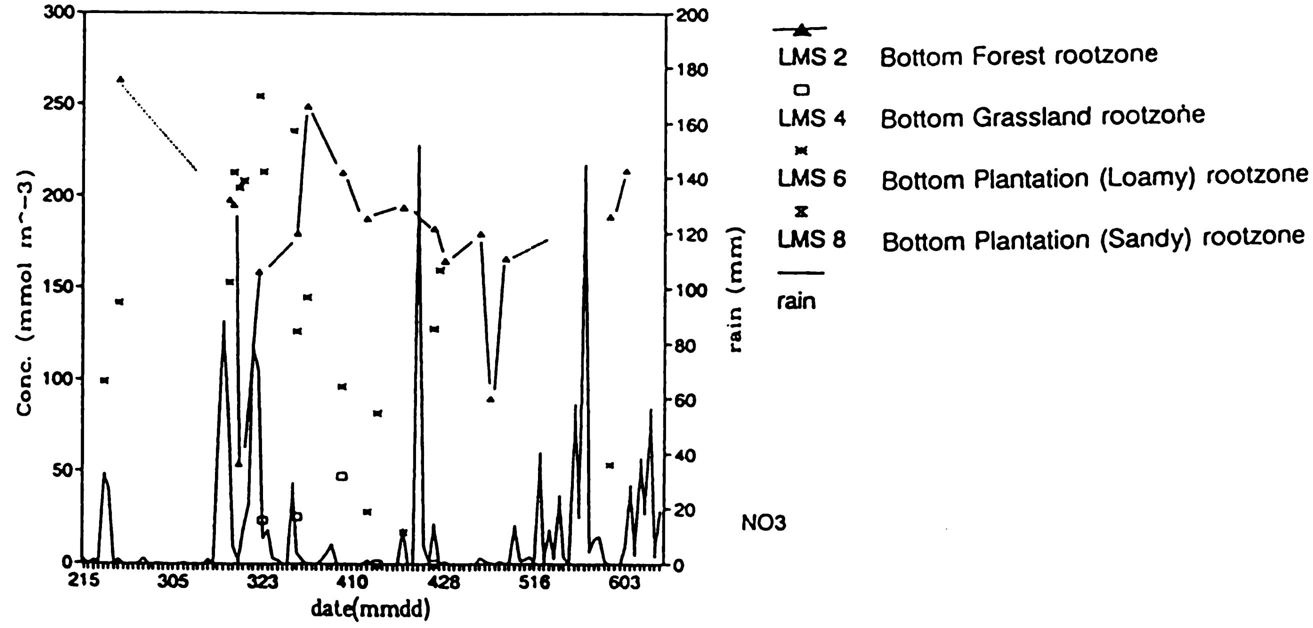
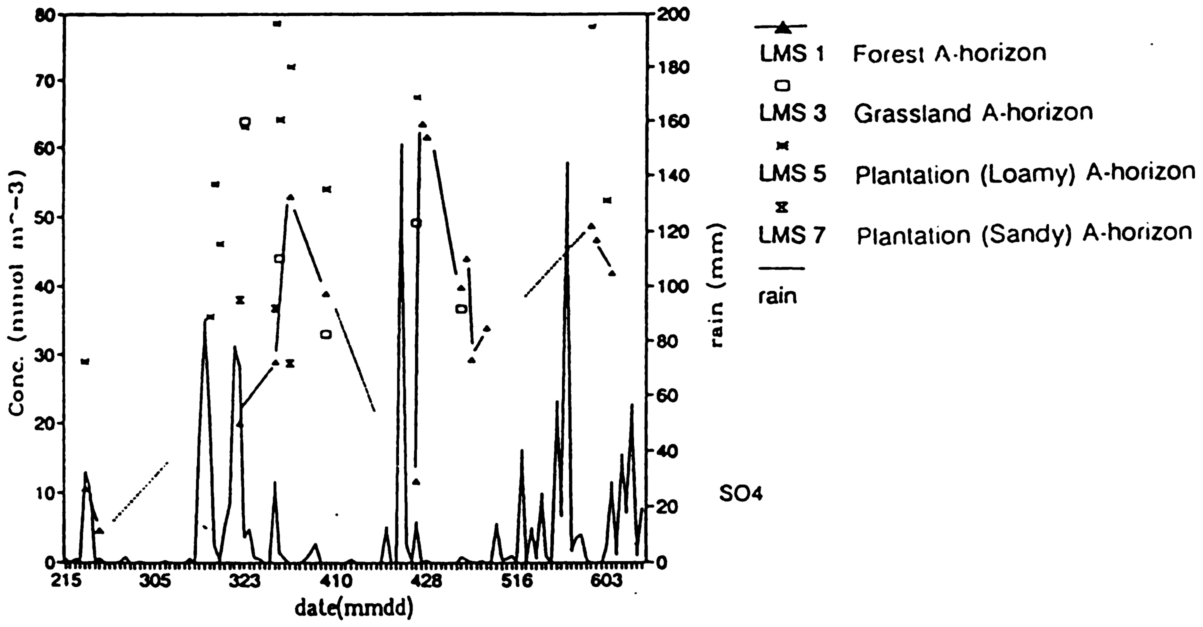


Figure 5.36. a. NO_3 concentrations vs. time of the LMS subsampling sites: A-horizons. LMS forest concentrations are interpolated.

Figure 5.36. b. NO_3 concentrations vs. time of the LMS subsampling sites: below the rootzone. LMS forest concentrations are interpolated.



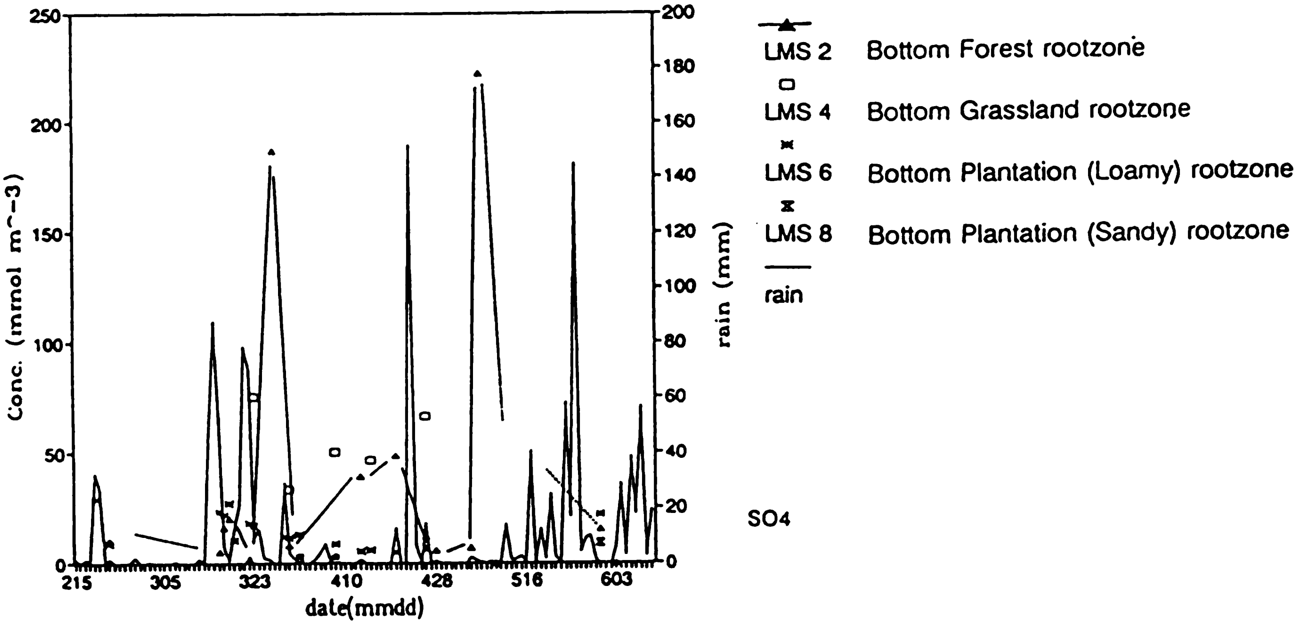


Figure 5.37. a. SO_4 concentrations vs. time of the LMS subsampling sites: A-horizons. LMS forest concentrations are interpolated.

Figure 5.37. b. SO_4 concentrations vs. time of the LMS subsampling sites: below the rootzone. LMS forest concentrations are interpolated.

6. Nutrient budgets

6.1 Rainfall nutrient inputs:

Annual rainfall nutrient inputs (**FSin**) were calculated with equation 3.1. Using the excess rainfall correction of section 5.2, about 41% of the total rainfall was estimated to be nutrient carrying. This amount of water was taken to represent the nutrient carrying water influx (**Fin**). Since average element concentrations of LLA and LMS rainfall collectors differ widely, separate calculations were performed for each location. The following inputs were calculated (table 6.1):

table 6.1: Rain nutrient inputs

LLA year factor: (365 /interval of sampling period): 4.93
LMS year factor: (365 /interval of sampling period): 3.31

LLA Cumulative rainfall during the sampling period: 669.2 mm
LLA amount of nutrient carrying water (Fin): 275.8 mm
LMS Cumulative rainfall during the sampling period: 1193.8 mm
LMS amount of nutrient carrying water (Fin): 494.6 mm

m	molar weight of nutrient
Crain	measured nutrient concentration in rainwater
FSin	calculated annual nutrient influx

		LLA		LMS	
	m (g/mole)	Crain (mmol m^{-3})	FSin (kg ha^{-1} yr^{-1})	Crain (mmol m^{-3})	FSin (kg ha^{-1} yr^{-1})
K	39.1	41.0	21.8	14.3	9.1
Na	23.0	138.3	43.3	85.3	32.2
Ca	40.1	114.3	62.4	48.3	31.8
Mg	24.3	62.8	20.8	40.5	16.2
NO_3*	62.0	35.5	30.0	66.0	67.1
SiO_2	60.1	0.1	0.1	6.4	6.3
PO_4	95.0	0.1	0.1	0.1	0.2

The following published concentrations of elements in rainwater (in mmol m^{-3}) are given for comparison:

	Crain a	Crain b	Crain c
K	40	5.2	1.52
Na	390	12	4.79
Ca	525	5.3	3.36
Mg	230	3.7	1.51
NO_3			23.5
SiO_2	150	3.8	
PO_4			0.10

a - Average North America, adapted from Morel, 1983
b - Average Java, adapted from Bruynzeel, 1983
c- Average Hubbard Brook, adapted from Likens et. al., 1984
* NH_4^+ data are not available for most samples. Keeping in mind the nitrification of the samples described in section 5.1, NO_3 concentrations are takento represent the bulk N input.

Concentrations from literature inserted here apear to be one order of magnitude bigger to one order of magnitude smaller than the values measured at LLA and LMS. This is indication to the fact that rainfall measurements, especially of the LLA sites, may be an overestimation, due to (roaddust) contamination. It is a fact that measured solute contents are heavily dependant on how careful sampling and measurement procedures are executed.
However, solute contents of rain may also differ widely on grounds of geological substrate, climate and landuse, and It is beyond the scope of this paper to quantitatively evaluate measurement and sampling techniques of both the references and this study, so found values will, with some caution, be used as such.

6.2. Nutrient outputs by leaching

Annual leaching nutrient outputs (FSout) were also calculated using equation 3.1. The cumulative flux of leaching out water during the sampling period at each site (Fout) was assessed using the model described in section 4. The calculated LLA and LMS outputs are shown in Table 6.2.

Table 6.2 a: Calculated annual nutrient outputs of the various LLA sites:

LLA year factor: (365 /interval of sampling period): 4.932

Calculated outflux of water (Fout) during the sampling period (930103 - 930315) :

Forest (mm)	Grassland (mm)	Plantation (mm)
431	392	303

Concentrations of nutrients in water beneath the root zone (mmol m^{-3}):

	Forest	Grassland	Plantation
K	19.1	11.7	56.0
Na	164.1	32.3	72.8
Ca	61.2	65.3	155.8
Mg	32.1	18.7	45.8
NO_3	57.6	0.7	16.0
SiO_2	38.0	66.0	60.0
PO_4	5.4	0.1	1.4

Calculated annual outflux of nutrients FSout (kg ha^{-1} yr^{-1}):

	Forest	Grassland	Plantation
K	15.9	8.8	32.7
Na	80.3	14.3	25.0
Ca	52.2	50.6	93.4
Mg	16.6	8.8	16.6
NO_3	75.9	0.8	14.8
SiO_2	48.6	76.7	53.9
PO_4	10.8	0.2	2.0

Table 6.2 b: Calculated annual nutrient outputs of the various LMS sites:

LMS year factor: (365 /interval of sampling period): 3.318

Calculated outflux of water (Fout) during the sampling period (930301 - 930618) :

Forest (mm)	Grassland (mm)	Plantation L. (mm)	Plantation S. (mm)
779	537	446	394

Concentrations of nutrients in water beneath the root zone (mmol m^{-3}):

	Forest	Grassland	Plantation L.	Plantation S
K	10.1	33.2	6.6	59.9
Na	84.9	102.0	180.2	155.3
Ca	176.4	311.7	247.1	395.5
Mg	41.5	196.2	201.3	114.0
NO_3	181.1	10.7	163.4	167.4
SiO_2	199.0	147.8	397.6	157.6
PO_4	0.1	0.1	0.3	0.4

Calculated outflux of nutrients FSout (kg ha^{-1} yr^{-1}):

	Forest	Grassland	Plantation L.	Plantation S
K	10.2	23.1	3.8	30.6
Na	50.5	41.8	61.3	46.7
Ca	182.8	222.7	146.7	207.3
Mg	26.1	85.0	72.4	36.2
NO_3	290.3	11.8	149.9	135.7
SiO_2	309.1	158.3	353.7	123.9
PO_4	0.1	0.1	0.5	0.5

Using equation 1.2 on the FS values listed in table 6.1 and 6.2, a budget was calculated, as shown in Table 6.3.

Table 6.3 Calculated annual nutrient budget of the various LLA and LMS sites:

Calculated LLA net annual nutrient budget (kg ha^{-1} yr^{-1}):

	Forest	Grassland	Plantation
K	5.9	13.0	-10.9
Na	-37.0	28.9	18.3
Ca	10.2	11.8	-31.0
Mg	4.2	12.0	4.1
NO$_3$	-45.9	29.2	15.1
SiO$_2$	-48.5	-76.6	-53.8
PO$_4$	-10.69	-0.05	-1.85

Calculated LMS net annual nutrient budget (kg ha^{-1} yr^{-1}):

	Forest	Grassland	Plantation . S	Plantation L
K	-1.1	-14.0	-21.5	5.3
Na	-18.3	-9.6	-14.5	-29.2
Ca	-151.1	-190.9	-175.6	-114.9
Mg	-9.9	-68.8	-20.1	-56.2
NO$_3$	-223.2	55.3	-68.6	-82.8
SiO$_2$	-302.8	-152.0	-117.5	-347.3
PO$_4$	0.04	0.10	-0.30	-0.32

The absolute results shown in table 6.3 must be treated with caution, since sampling, analysis methods and flux calculations are not wholly reliable (see section 5.1 and section 4.4). Most modelling parameters come from literature or were estimated, possibly leading to an over- or underestimation of the importance of various factors. Also, very few samples were analysed in duplicate. Another disturbing factor is that LLA **FSin** is probably over estimated, due to road dust contamination (section 3.3.) The resulting LLA budgets are therefore probably a bit optimistic.

In spite of the somewhat doubtfull absolute reliability, the desired comparison can be made with little restraint, since the type of error is the same for all sites.

The figures in table 6.3 are equal to **FSin** - **FSout** , and therefore:

$$\mathbf{FSwe} + (\mathbf{FSin} - \mathbf{FSout}) = (\mathbf{FSgu} + \mathbf{FSad}) \tag{6.1}$$

The LMS forest, primary forest on a relatively young, fertile soil, might be thought of as an 'initial' situation. The forest, about 2 Ka old, is supposed to have reached a steady state, in which it the bulk of the biomass nutrients are recycled. This nutrient cycle is supposedly not very tight, since the soil is still relatively base rich.

The LMS forest budget shows that Na, Si and seemingly also NO$_3$ and Ca are quite uneconomically used by the forest. K, Mg and PO$_4$ losses are small. P even up to a degree that leaching is more than compensated for by rainfall. The seeming carelesness towards Ca and NO$_3$ is thought to be related to the large Ca and NO_3 pool of the forest biomass. The forest's preferent uptake of Ca and NO_3 (as approximated in section 5.4 and section 5.7) is higher than that of Mg and Na.

The high Ca/Mg ratio of the forest nutrient losses and the high NO_3 content indicate that (section 5.5) a large part of the nutrients lost represents 'leaks' from the exchange complex and the vegetation, rather than direct weathering and leaching losses (compare table 6.4). As such a situation must eventually lead to a complete drainage of the vegetation and exchange complex reservoir, the stoiciometric weathering assumption is probably a gross oversimplification, and recharge by weathering of basic cations occurs much faster, as it must. Compare also Annex 5.4.

Table 6.4: Calculated annual weathering output (from expected weathering concentrations as calculated in table 5.6) and inferred total nutrient uptake for forest and grassland. Negative figures designate loss. The figures were obtained assuming a stoichiometric weathering.

	Forest	Grassland	Forest	Grassland	Forest	Grassland
	FSin-FSout	FSin-FSout	FSwe calc	FSwecalc	FS(gu+ad)calc	FS(gu+ad)calc
K	-1.1	-14.0	3.0	2.1	1.9	-11.9
Na	-18.3	-9.6	4.1	2.8	-14.2	-6.8
Ca	-151.1	-190.9	7.9	5.4	-143.2	-185.5
Mg	-9.9	-68.8	10.4	7.1	0.4	-61.7
NO_3	-223.2	55.3			-223.2	55.3
Si	-302.8	-152.0	309.1	158.1	6.4	6.4
PO_4	0.0	0.1	0.7	0.5	0.8	0.6

The LMS forest uptake of silica, relative to the large amounts released, must of course be small. The fact that silica loss is large, indicates, as already discussed, that forest **FSwe** is quite large. In order to aproach **FSin** - **FSout** $\approx$ 0, by necesity the forest basic cations and phosphorus must satisfy : **FSgu** + **FSad** $\approx$ **FSwe**. This condition seems to be satisfied for K and P, and to a lesser degree by Mg and Na. **FSgu** + **FSad** are close to zero for these solutes, indicating no net uptake and thus steady state. **FSgu** + **FSad** are negative and quite large for Ca and NO_3, as could be expected. The large pools of these solute distort the result. For NO_3, another thing is also influencing the result: The fact that the forest has a more or less 'unlimited' supply of organic N, due to symbiotic N fixation. This can be inferred from the fact that in the LLA forest on depleted soil, N losses are still high. Natural tropical forest seems to accumulate enough N to ensure N 'surplus ' over long time periods. N accumulates in the forest by micro-organism fixation in root nodules and in the phyllosphere on leaves (Proctor, 1987), rather than by weathering. This makes N supply independant of soil weathering inputs. Rather, a correlation of N output with the amount of standing biomass is expected.

Change of landuse on fertile soils enhances nutrient loss. In grassland, the most pronounced loss is of K, Mg and Ca. P losses are also increased. Si, NO_3, and Na losses seem to have been diminished, after conversion to grassland. Vegetation uptake of NO_3 in the grassland is pronounced. The smaller loss of Si is due the diminished weathering, whereas the smaller Na loss is thought to be due to the fact that grassland does not receive as much seaspray as the forest. The NO_3 uptake is ascribable to the much smaller N pool of the grassland, and the related smaller N fixation capacities. N and P losses are much smaller than in the forest, up to a degree that even N is 'oversupplied' by rainfall. This is due to the smaller biomass inventory of N and P, and it's subsequent higher economy. Thus, the NO_3, P and Na budget are directly determined by the amount of standing biomass (the standing biomass serves as a scavenger for seaspray).

On converting LMS forest to grassland and plantation, the large biomass nutrient reservoir is removed. As discussed before, CO_2, mostly released from decaying forest remains in the soil and humic material, becomes the main proton donor. The soil, that still contains large amounts of organic material, has a high exchange capacity, and absorbs most of the nutrients released by weathering. As the grass has a much smaller nutrient uptake capacity (having a much smaller biomass), vegetation nutrient budgets become less economical, and direct losses of basic cations as leaching and losses to the exchange complex are enhanced. This can be seen in the lowered ratio of Ca/Mg.

LMS Plantation losses of N,P K and Na are largest. Because Ca and Mg losses indicate that loss of nutrients is smaller than in the grassland, these higher losses must be ascribed to fertilizer contamination, indicating that the used technique for filtering data was not correct. Probably all samples of sandy plantation sites are contaminated, due to the high permeability of the substrate and the large quantities of fertilizer applied. The subsoil weathering regime largely remains similar (unchanged) to that of the grassland. (see also section 5.5)

A similar story can be told for the loamy plantation site. (Of course Si loss from the loamy material is much higher than from the sandy material). An exceptional fact is that the K loss from this soil is so small the sites appear to be gaining K. Since the sandy plantation site does not show this exceptional property, it can't be due to an extreme K uptake by the growing banana plants. It is the more exceptional keeping in mind the fact that the loamy sites have also received K fertilizer, and that not even the LMS forest shows such an economy with K. The most obvious reason that comes to mind is K fixation in some mineral (illite like) phase. Although the loamy sites seem to be gaining K, this K is probably not plant available.

As a tropical soil plant ecosystem, the LLA forest represents a 'final' situation, in which most of the weatherable material has been removed. The soil, and presumably also the forest, is over 10 Ka old, and a large part of the nutrients that were formerly stored in the mineral soil are now stored in the biomass. Almost all nutient loss must come from 'vegetation leaks'; - (FS**gu** + FS**ad**) > FS**we**. The nutrient cycle is tight, so the only basic cation that shows a negative budget is Na. As Na is abundantly supplied by forest scavenged seaspray, this is no real problem.

As indicated before, high LLA forest N-losses are due to the large N-pool of forest biomass. The Si loss from LLA forest is about six times lower than from the LMS forest. The source of this Si might lie in the vegetation as well, but since Si losses rise after alteration to grassland and plantation, it is more probable that there is still weatherable material left in the soil (kaolinite degrading to gibbsite?) Phosphorus loss is so high that an analysis or notation fault is almost certainly the source, (especially since $n = 2$ for phosphorus analysis.) The real value is expected to more positive than that of the LMS forest.

Converting the LLA forest to grassland, most of the biomass nutrient inventory is removed, and subsequently, 'leaks', -(FS**gu**+ FS**ad**) from the vegetation, that are by now the main nutrient source left, must become smaller. The grassland is about ten years old, and direct logging nutrient losses are not supposed to play and active role. The smaller losses result in more positive budgets for all nutrients, except Si. The allready poor soil is deprived of it's only left nutrient supplying reservoir, the forest. P figures are also not reliable ($n = 2$).

For the LLA plantation, the same processes are at work as in the LMS plantation. Application of fertilizer enhances seeming losses of N, K and P(?) (no material for comparison), also, a conspicuous loss of Ca can be seen, that is due to liming in these acidic soils.

7. Discussion, conclusion

7.1 Suggested method improvements

As indicated by section 5.1, analysis and sampling techniques can be improved. The NO_3 and NH_4 concentration differences shown in fig. 5.1 b prove that adding chloroform to the water samples does not completely supress microbial conversion of solutes. This microbial conversion gives rise to large changes in pH and NO_3 concentration. Also, loss of CO_2 will contribute to a shift in pH. As a result, the obtained pH laboratory values are unreliable. Future field workers are therefore strongly advised to measure pH at the moment of sampling, using an in situ pH meter. After measuring pH, samples can be safeguarded against micobial conversion by adding a few drops of strong acid (HCl) to the sample.

As discussed in Annex 5.2, RHIZON soil moisture samplers often become leaky. Users of the samplers are advised to perform an airtightness check, as described in annex 5.2, every time a new sampler is introduced into the soil. A close monitoring of sampler quality will dramatically enhance sampler efficiency.

7.2 evolution of the soils under different landuse types.

As indicated by Moss (1971), the tropical forest differs from man made landuse systems in many ways. It typically has a microclimate that is very different from the surrounding macroclimate, and its high rate of energy use is expressed in a very high rate of litter production and rapid mineralization rates.

Sampling over a period of three years in African tropical forest, Moss showed that there was available water present in the soil at all levels throughout the year, and that the soil was permanently wet below six feet. Even in areas with a pronounced dry season, wilting point was never reached. Outside the forest catchment, in a similar location with comparable soil characteristics and almost identical atmospheric water regime, runoff was much greater, and the upper soil layers dried out rapidly at the onset of the dry season.

Organic matter and nutrient cycles within the forest were almost closed, and small scale disturbances easily restored. The plant-soil system of the forest thus prestents a stable ecologic entity, strongly buffered against change induced by environmental effects, notably seasonal and diurnal changes, and possibly secular changes as well.

Grassland is characterised by a much smaller bulk vegetation. Work by a.o. Nye and Greenland (1960) indicates that bulk forest organic material may be up to twenty times the grassland bulk. Grasslands have been shown to dry out very easily during periods of rain deficiency, and grass contains relatively much lower amounts of Ca and K than trees.

Plantations are notorious for their strong influence on local ecology. Often, they can be considered as ecological deserts (Bruynzeel, 1983).

As discussed by Mohr et al (1978), weathering in andisols usually leads to the formation of secondary minerals that contain almost no basic cations. It is therefore permitted to assume that these elements, if they are not taken up by the exchange complex or the vegetation, on weathering dissapear out of the profile, together with most of the Si ('desilication', Mohr et al.1978).

In the current study, tropical forest on young soil appears to create an environment in which nutrients contained within the biomass are optimally used and recycled. The high moisture retention of the forest continuously provides water for evapotranspiration and nutrient uptake. As discussed before, the low base saturation relative to other sites indicates that residence times of nutrients are larger in the forest vegetation than in the forest soil. This condition, together with the high (organic) acid production of the forest, encourages weathering of minerals.

As a result of a high organic matter degradation rate and high moisture capacity, the proton donor concentration in forest soil moisture is high. Consequently, the nutrient release by weathering (in the subsoil) is high. This high nutrient release is favourable for agradating forests, but of little use to the mature forest.

The role of CO_2 in forest weathering is relatively small, and NO_3 and organic acids are major proton donors, as indicated by figure **5.12 a,b, and c** and fig. **5.36**. Si release in the young forests' A-horizon is relatively small, due to a high concentration of solutes, that keeps the demand for weathering release low. The Si release increases down the profile, acompanying a decreasing nutrient concentration. The study shows that even though sufficient weatherable material is still present, organic proton donors beneath the forest floor play an important role in weathering. These donors are supplied in large enough quantities to play a major role in the weathering in the subsoil. Furthermore, the high moisture retention of the forest renders the acids relatively less mobile than in the grassland and plantation, giving them maximal time to influence the mineral soil.

The normally held view that forests on nutrient rich soils are not very economical in their nutrient use, as opposed to forests on nutrient poor soils, can be partly confirmed by the current study. However, a slightly different angle of perception is added here. The large nutrient loss of the studied young forest is mainly due to its efficient release of nutrients by bio-acid weathering, and therefore an implicit result of the presence of the forest.

The investigated LLA forest, on its nutrient poor soil, has not stopped its release of bio-acids, as can be inferred from its still high loss of NO_3. (allthough the loss of NO_3 has gone down to about 20% of the NO_3 loss of young forest, table 6.3). The lessened release of bio-acid is consistent with earlier observations that plants on poor soils produce more refractory secondary products such as lignin and polyphenols, that yield less N and are more difficult to break down. The smaller loss of nutrients of the forest on nutrient poor soil can be partly ascribed to the lessened release of proton donors, but for a large part the lessened loss of nutrients is due to the fact that there is simply very little weatherable material left. (Unfortunately, no data are available on LLA forest A-horizon nutrient contents, so no relative uptake, as for the LMS forest, could be determined.). Further research is bound to give more insight in these matters. Since the activity of soil organisms (that break down the organic material and fix Nitrogen, and are therefore a main determinant of the weathering potential) is determined by o.a. soil pH, a simple negative feedback system could be a possible explanation for the lesened weathering potential of the forest on nutrient poor soil. It would be very interesting to find out more about the role and activity of nitrogen fixing and other soil organisms in both the young and the old forest.

The LMS grassland is ± 10 years old, therefore, primary effects of logging (enhanced nutrient losses to streamwater due to the primary degradation of dead organic material) are supposed to have disappeared, and long term effects become visible. As indicated by the net grassland NO_3 gain (LMS), the release of bio-acid is immensely lowered . CO_2 weathering, due of the degradation of humus and decaying of more refractory forest remains (large roots and trunks), is enhanced. Grassland vegetation can not maintain a high - vegetation derived - basic cation concentration in the topsoil, and as a result weathering in the A-horizon increases. Since the bio-uptake of the agradating grassland vegetation cover is much lower than that of growing forest (aproximately by a factor 20), and nutrients are continuously released by CO_2 weathering in both the topsoil and the lower horizons, the base saturation (table 5.20) dramatically rises (not considering the the interfering effects of the buried A-horizon).

While in the forest the weathering regime seems to be differentiated, for grassland the situation is not so. Weathering seems to be in the same order of magnitude in the topsoil as in the subsoil. This is further indication to the fact that the main proton donor source are forest leftovers. CO_2 has taken the main proton donor role, and organic acids are marginal. The low Ca/Mg ratio found at the soil exchange complex for (uncontaminated by fertilizer) grassland and plantation makes it improbable that these nutients find their source in the nutrient release 'peak' found just after logging (these would have a high Ca/Mg ratio). The nutrients are thought to have built up their concentration at the exchange complex due to the enhanced weathering and small uptake of the grass during the establishing of the grassland vegetation described above. The saturated exchange complex will result in enhanced losses of nutrients, since the new vegetation is not capable of using the stored nutrients.

Another extreme situation is created when grassland is replaced by plantation. Due to a.o. nitrification of NH_3 supplied by fertilization, A-horizon weathering is enhanced to a level higher than that of the forest subsoil, but this weathering concentrates itself at the surface, leaving the bulk of the soil unaffected. The greater part of the nutrients released in this way leave the soil with preferentially channeled water, along with excess fertilizer. This is shown by the fact that while the nutrient concentration in the soil moisture in some cases increases up to two orders of magnitude at fertilised sites (annex 5.1), the nutient content of the exchange complex is lowered (table 5.20), compared to that of the grassland exchange complex. Most of the fertilizer is washed away, and wasted. In other words, plantation plant-soil systems receive a discontinous nutrient supply in space and time, leading to a surplus-starvation situation, in which great wastes and losses, especially of micronutrients, are expected. (It is therefore highly advisable to keep some soil cover.)

The low Si losses of the LMS sandy plantation subsoil (sampling depth 8), similar to those of the grassland, indicate that the role of CO_2 in weathering is similar at this horizon to its role in the grassland.

The very low K concentrations in the loamy plantation subsoil suggest uptake in a mineral phase (this requires further research).

The LLA forest, on degraded soil, has reached a 'terminal' situation. The biomass has become the main nutrient reservoir. Seaspray enriched precipitation plays an important role in the natural supply of nutrients. The forest scavenges aerosols and has enough waterbuffering capacity to use them, whereas grassland and plantation vegetations are much less effective in this. (Such scavenging differences were among others found by Minderman and Leeflang (1968)). The LLA forest system highly depends on external nutrient inputs to compensate for its (small) losses. As inferred from the budget calculations, the nutrient supply by rain seems to more than compensate for nutrient losses. The fact that Na supply by rain does not seem to match the high Na output has no straightforward explanation. Possibly, during the measuring period, mixing of seaspray with other aerosols was lower than in other seasons of the year (the measuring period was during the dry season).

On changing to another cultivation type on the LLA soils, the main nutrient compartment: biomass, and it's external nutrient uptake capabilities, are removed. A depletion of soil basic cations is expected. Table 6.2 shows that indeed the grassland subsoil losses of base cations and other nutrients are smaller than for the forest. Unfortunately, general data obtained of the LLA soils are somewhat unreliable.

For the LLA plantation, generally, the same story goes as for the LMS plantation. Liming and fertilizing are conspicuous external nutrient sources on the depleted soil. However, caution must be taken with the interpretation of the calculations. The high element concentrations found in the plantation are partly attributable to its pronounced dryness, and calculated moisture fluxes might not sufficiently compensate for this effect.

The anomalously high Al, organic matter, K etc. values found for the sampling depth beneath the rootzone in the LMS grassland indicate that this horizon represents a buried A-horizon. It may be noted that these buried A-horizons are additional buffers to soil depletion. Due to their high CEC and relatively high pH and base saturation, they act as cation traps, delaying basic cation leaching. The organic carbon rich layer seems to have a high preference for K.

Data collected by Nieuwenhuyse (1995) and B. v. Ooien and N. Walraven suggest that the mineral nutrient reservoir of fresh volcanic material is biggest for Mg, followed by Ca and Na, and is lowest for K. On weathering, Ca seems to be depleted most rapidly, followed by Na (fig. 7.1). This is consistent with the average mineral composition of volcanic ash. Ca and Na from plagioclases seem to be released more rapidly than Mg from the pyroxenes, but this is due to the larger Mg reservoir (See Annex 5.4). The suggested inhibited weathering due to iron oxide coating must therefore be discarded. K from the K-feldspar is, as expected, the slowest process (Annex 5.4).

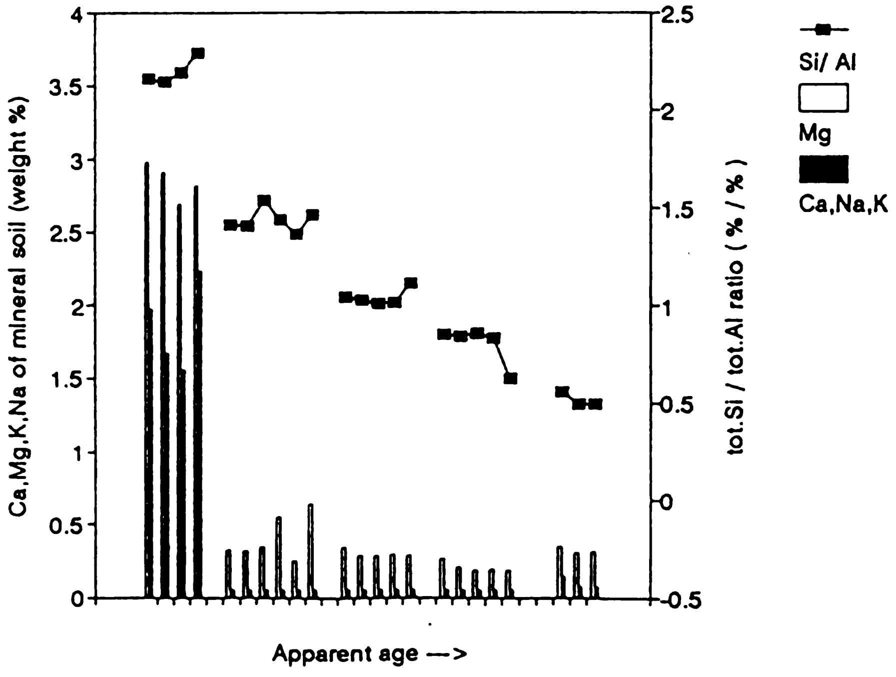


Figure 7.1. Content of Mg and Ca+Na+K (%) vs relative age. Si/Al ratio's indicate age. Clusters designate complete soil horizons.

Over the profile time series, an enrichment of Al relative to Si and basic cations can be seen. This is consistent with Mohr et al's (1978) earlier formulation of andisol weathering as the leaching of basic cations and Si.

The rate of release and subsequent disappearance of Si and basic cations is determined by the proton donor type and concentration and other vegetation related factors such as the size of the exchange complex, the soil structure and the root influence zone. The landuse type turns out to be a main determinant of the fate of nutrients held within the mother material. The rate of release of nutrients and their transfer from the local system (to other systems and eventually the sea) is strongly infuenced by the vegetation and mans impact on this vegetation.

Moss (1971) states that any land-use pattern is an expression of its agricultural system, stressing the interaction between economic and ecological factors in which the vital link is the decision maker, the farmer. Any understanding of tropical land use must thus be obtained by concentrating on the factors which affect, and the phenomena which are immediately affected by, the actual decisions of the farmer. The focus of attention must be the ecological implications of economy driven agriculture and forestry practice, not only the description of particular ecological systems and their distribution. What this simply implicates is that ultimately the fate of the systems studied and any ecological system is in the hands of man. Better understanding will only help sustain culture and nature if man realizes the full length of the implications of his activities.

8. BIBLIOGRAPHY

Barber, S.A., 1984. Soil nutrient bioavailability, a mechanistic approach. Wiley and Sons, New York.

Bartlett, A.S., and E.S. Barghoorn. 1973. Phytogeographic history of the isthmus of Panama during thepast 12 000 years (a history of vegetation, climate, and sea-level change). p.203-299. In: A. Graham (ed.) Vegetation and vegetation history of nrth. Ltn. Am., a symposium. Elsevier, New York.

Broecker, W.S. and Peng, T.H., 1982 Tracers in the sea. Lamont Doherty Geological Observatory, Columbia University, New York

Bruynzeel, L.A. 1990 hydrology of tropical rainforests; a closer look. DHV (etc.) , 22 pp. Project working series, Konto river project ATA 206, no. 27

Bruynzeel, L.A. 1983, Hydrological and biogeochemical aspects of man-made forests in south-central Java, Indonesia. Dissertation VU Amsterdam, Final report, vol. 9, Nuffic Serayu Valley project, ITC/GUA/VU/1, The hague, The Netherlands.

Buurman, P., Van Breemen, N., Brinkman, R., 1992. Processes in soils. Text for course J050-202. Dept. Soil Science and Geology, Agricultural University Wageningen.

Dahlgren, R., Shoji S. and Nanzyo, M, (1991), 1993. Volcanic ash soils: Genesis, properties and utilisation. Elsevier, Amsterdam, 288 pp. - Developments in soil science; no. 21

Driessen, P.M. and Dudal, R. 1989. Lecture notes on geography, formation, properties and use of the major soils of the world. Agricultural University, and Katholieke Universiteit Leuven, 296 pp.

Fritsch, M.J. 1993, The hydrological effect of clearing tropical rainforest and of the implementation of alternative landuses. in: Hydrology of warm humid regions, (proceedings of the Yokohama Symposium, July 1993)

Gatz, D.F. and Dingle, A.N., 1971, Trace substances in rainwater: Concentration variations during convective rains, and their interpretation. Tellus vol. 23, pp. 16 - 27

Golley, Mc Ginnis et al. 1975. Mineral cycling in a Darien tropical moist forest ecosystem. University press, Athens, Georgia, USA

Hemond, H.F. 1980 Biogeochemistry of Thoreau's bog, Concord, Massachusetts. Ecological monographs 50(4),pp 507. The Ecol. soc. of Am.

Jansen, A.I. BINAS informatieboek VWO - HAVO voor het onderwijs in de natuurwetenschappen, tabel 38: "De elementen; symbool, atoomnummer en relatieve atoommassa". Wolters Noordhoff, Groningen, the Netherlands

Likens G.E. et al., 1984, Long term trends in precipitation chemistry at Hubbard Brook, New Hampshire. Atmospheric Environment vol. 18, no. 12 pp. 2641 - 2647

Loch, J.P.G, 1992, Reader bij het college bodemchemie. Instituut voor Aardwetenschappen, RU Utrecht, The Netherlands

Morel, F.M., 1983. Principles of aquatic chemistry. Wiley and Sons, New York.

Moss, R.P. 1971 The ecological background to landuse studies in tropical Africa p.193-235 in: Thomas M.F. and Willington G.W., 1971 Environment and landuse in Africa, Methuen & Co ,London

Nahon, D.B. and Colin, F., 1982. Chemical weathering of orthopyroxenes under lateritic conditions. Am.J.Sci. 282: 1232-1243

Nieuwenhuyse, A. and Van Breemen, N., 1995. Quantitative aspects of weathering and neoformation in volcanic ash soils in perhumid tropical Costa Rica., Department of Soil Science and Geology, P.O. Box 37 6700 AA, Wageningen, The Netherlands.

Nye, P.H. and Greenland, D.J. 1960 The soil under shifting cultivation, Tech. Commun. Commonw. Bur. Soil. Sci. 51, Farnham Royal, Bucks, USA

Nye, P.H., 1961 Organic matter and nutrient cycles under moist tropical forest. Plant and soil 13:333-346

Poels, R.L.H., 1987. Soils, water and nutrients in a forest ecosystem in Suriname. Doctoral thesis, Agricultural University, Wageningen.

Proctor, J. 1987 Nutrient cycling in primary and old secondary rainforests. Applied Geography 7, 135-152.

Rosales, A, Maebe, P. Sevenhuysen, R., 1992 Determination of losses of nutrients and nematicides on a banana plantation in the Atlantic Zone. The Atlantic Zone programme, Phase 2, report no. 33, Turialba.

Rodin, L.E. and Basilevich, N.I., 1967. Production and mineral cycling in terrestrial vegetation. Oliver & Boyd, Edinburgh, 288 pp.

Sanchez, P.A. 1976 Properties and management of soil in the tropics, John Wiley, New York.

Seuss, dr. G.T., 1960. Green eggs and ham. Beginner books, Distributed by random house, New York, 62. pp. illus. 24 cm.

Shone, M.G.T., 1967. Factors involved in the uptake of potassium and magnesium from the soil solution. In: Soil potassium and magnesium technical bulletin no. 14 Her majesty's stationary office, London, 1967, pp. 9 - 38

Simonson, R.W. 1970. Loss of nutrient elements during soil formation. p.21-33. In Engelstad, O.P. (ed.) Nutrient mobility in soil, accumulation and losses. Soil science society of america inc.

Stover, R.H. and Simmonds, N.W., 1987. Bananas, (tropical agricultural series), 3rd ed. Longman Scientific and technical, Burnt Mill, Harlow

Trudgill, S.T., 1977. Soil and vegetation systems. (Contemporary problems in geography) Clarendon Press, oxford.

Van Breemen, N., Driscoll, C.T. and Mulder, S., 1984. Acidic deposition and internal proton sources in acidification of soils and water. In: Nature 307 (1984) pp. 599 - 604.

Vriend, S.P. Practicum Handleiding analyse III, o.a. XRF methodiek. Instituut voor Aardwetenschappen, RU Utrecht, the Netherlands.

Wada, K. 1980. Mineralogical characteristics of andisols. In: B.K.G Thenf(ed), soils with variable charge, 87- 108. New Zealand Society of Soil Science, Lower Hutt.

Wada, K. and Kakuto, Y., 1985. Embryonic halloysites in Ecuadorian soils derived from volcanic ash. Soil. Sci. Soc. Amer.J. 49:1309-1318

Weyl, R. 1980. Geology of Central America, second, completely revised edition. Beitrage zur regionalen geologie der erde band 15. Gebr. Borntraeger, Berlin, Stuttgart.

Annex 2.1

PROFILE DESCRIPTION OF THE NEGUEV SOIL TYPE

classification:
FAO (1988): Dystric Cambisol (???, Ultisol - Oxisol)
USDA Soil Taxonomy: Andic humitropept
Date of observation:24/11/89
Authors of description: Desiree Janssen, Luis Guillermo Quiros, Gwen Zuring
Location: La Lucha, Guacimo district, province of Limon, Costa Rica (aproximately 10°15'N 83°33'E)
Altitude: aproximately 30 m a.s.l.
Terrain form: Strongly undulating
Slope at profile site: 0%
Land Use: Altered primary forest

general information on the soil type
Parent material: Sand of volcanic origin
Drainage: class 4: well drained
Humidity conditions of the soil:moist throughout the profile
Depth of the freatic surface: more than 2.5 m
Risk of inundation: none
soil fauna: worms, ants and nematodes were observed

No stones were observed at the soil surface and no evidence of erosion, nor of compaction was found.

description of the soil horizons
Horizon colours were described according to 'the revised standard soil colour carts'(Japan, 1970).

A	0- 10 cm	Dark brown (7.5 YR 3/4) when moist; clayey;structured, very fine subangular blocky (50%), strong; lightly adherent and slightly plastic when moist; very friable when moist; no pores were observed; abundant roots of every size; clear sharp boundary.
Bw	10- 70 cm	Brown (7.5 YR 4/4) when moist; clayey; structured, very fine subangular blocky (50%) and very fine granules, moderately weak; lightly adherent and slightly plastic when moist; very friable to friable when moist; many medium to very fine pores were observed; normal rooting of every size; clear diffuse boundary.
Bw2	70- 120 cm	Brown (7.5 YR 4/6) when moist; clayey; structured, very fine subangular blocky; weak; lightly adherent and slightly plastic when moist; friable when moist; many medium to very fine pores; few fine roots.

Micromorphological characteristics 'neguev' profile La Lucha (old alluvial terrace).

No single and compound mineral grains are present in the profile deeper than 15 cm, except for some quartz (200 µm) and many opaque minerals up to 50 µm. In the 15 cm top layer however, pellicular, linear and complex altered pyroxene and plagioclase grains, and pellicular altered hypocrystalline andesite fragments up to 150 µm occasionally were observed.

The fine material (c/f limit <5 µm) consists of anisotropic reddish brown (Pol. light) material with many red iron droplets.

The microstructure is a mixture of fine subangular blocky and granular with many channels, interconnected with wedge shaped cracks. In the topsoil a crumb structure is present.

b-Fabrics occur throughout the profile and consists of granostriated b-fabrics around gibbsite nodules, mosaic b-fabrics concentrated in excremental infillings, and mono-striated b-fabrics randomly distributed in the groundmass.

The following pedofeatures are present throughout the profile:

- Gibbsite features frequently as:
1). Euhedral and subhedral strongly birefringent coarse crystalline gibbsite crystals and intercalations (10-100 µm) randomly distributed.
2). Smooth, rounded and subrounded, weak, moderate and strong birefringent anisotropic and (an)isotropic gibbsite bodies (fragmented gibbsite coatings and infillings) with a stipple-speckeled b-fabric; Textures vary from dusty to impure as a result of the presence of opaque minerals. The sizes of the gibbsite bodies vary from 30 µm to 1 mm.
3). Gibbsite nodules as mentioned under 2, but with a destroyed saprolite internal fabric, up to 1mm in diameter.

- Anisotropic orange-yellow crystalline iron (goethite) pieces, up to 200 µm, randomly distributed.
The large gibbsite bodies and iron pieces decrease in amount towards the soil surface.

- Yellow-green, anisotropic, smooth and rounded to subrounded clay-bodies, with a stipple-speckled b-fabric and sometimes a partially continuous b-fabric.

- Abundant, loose (dis)continuous, mineral excremental infillings with sizes ranging from 200 µm to 1/2 cm. In addition dense complete infillings occur in the topsoil.

- Few weakly impregnated ferric nodules with diffuse boundaries are present.

DISCUSSION

Parent material homogeneity

Field observations indicate that the original sediment consisted of a coarse sandy and gravelly andesitic deposit. Optical observations of the current soil did not show different sediment layers. Up to 2m the sediment is totally homogenized.

Biological homogenization

The granular and subangular blocky structure and the presence of numerous mineral excremental infillings gave evidence of occurrence of strong biological activity throughout the soil. As a result, the upper 2m of the soil examined has been completely homogenized.

Weathering of primary minerals

Absence of primary minerals except for quartz and opaque minerals evidenced that the single and compound mineral grains are completely dissolved as a result of strong weathering processes., so the current sand and silt fraction entirely consists of the neoformed minerals gibbsite and iron (goethite).

Formation of secondary minerals

Micromorphological observations demonstrate that different kinds of neoformed minerals occur throughout the soil:
1) Fragmented iron (goethite) pieces. Optical examination of the saprolite the rio Costa Rica profile (an andesitic lava flow) show that the iron pieces originally were parts of porous iron pseudomorphs after pyroxene phenocrysts (boxwork structures)
2) Gibbsite phenomena;
Coarse gibbsite crystals and intercalations are found in the whole profile, but the sizes appears to decrease towards the soil surface. The studied lava saprolite (see 1) reveal that these coarse crystalline gibbsite features originally were part of gibbsite pseudomorphs after plagioclase, and were formed in dissolution voids of altered plagioclase. They were also present in the dissolution voids in iron boxwork pseudomorphs, but the Al must be allochtonous because the original pyroxene does not contain large amounts of Al.
The fine gibbsite stipple-speckled oriented rounded gibbsite bodies originally were parts of coating and infillings in voids present in the saprolite, as examination of the isovolumetric lava saprolite reveal. Upon physical break down the isovolumetric character of the saprolite disappears, whereas coatings and infillings were fragmented and deformed. Absence of gibbsite features and occurrence of isotropic pale-yellow fine material in the youngest alluvial soil indicate that formation of allophane is the first step in formation of neoformed minerals. The difference in birefringence of the gibbsite nodules suggest a differen chemical/mineralogical composition. low birefringence suggest a beginning

transformation of isotropic pale-yellow allophane into randomly distributed fine gibbsite crystals. strong birefringence may suggest a complete transformation of allophane into gibbsite.

The iron boxwork pseudomorphs, the gibbsite coatings and infillings, and the gibbsite pseudomorphs were broken up into smaller pieces by the physical break down of the isovolumetric weathered saprolite, and these fragmented pieces are distributed within the profile as a result of the intensive faunal activity to a great depth. As a result ,the amount of larger pieces decrease towards the soil surface

The yellow-green stipple speckled clay-bodies consist of 2:1 and 1:1 clay minerals (Jongmans et al., 1992), and are probably the source of the measured 2:1 clay minerals by X-ray diffraction.

The anisotropic character of the fine material suggest that it consists of crystalline clay minerals mixed with fine red iron droplets, probably hematite. Occurrence of gibbsite in the fine material cannot be excluded, but is not observed.

Rejuvenation

The small amount of plagioclase, pyroxene and andesite fragments and their sizes demonstrate that few ash addition has been taken place in the upper 15 cm of the soil. The alteration patterns observed indicated that those minerals are affected by weathering processes. Sporadically, anisotropic, non-laminated, continuous oriented, limpid, yellow coatings occur in voids. These coatings resulted from precipitation of dissolved Si and Al derived from the ash particles, and following recrystallization of the formed allophane into crystalline clay-minerals.

2.2.3

Annex 3.1: Description of the RHIZON soil moisture sampler

Root Ecology and its Practical Application. Int. Symp. Vienna, 2-6 Sept 1991

RHIZON SOIL SOLUTION SAMPLERS AS ARTIFICIAL ROOTS

Frits Meijboom and Meine van Noordwijk

SUMMARY: A brief description is given of a new cylindrical microporous device for extracting soil solution samples.

INTRODUCTION: Frequent sampling of soil solution is often required to evaluate solute transport in soils, e.g. due to nutrient uptake by root systems. Prequisites for an adequate sampling system are that it does not disturb soil structure, has no ion-exchange properties, that its internal, 'dead', volume is small and that it can function for at least one growing season. BRIGGS and McCALL (1904) proposed the use of ceramic cups as 'artificial roots' to extract soil solution. As reviewed by GROSSMAN and UDLUFT (1991), this technique is now widely used, but ceramic cups have some disadvantages (Table 1). The RHIZON SSS, Soil Solution Sampler, provides a new option for such studies.

MATERIAL AND METHODS: Figure 1 shows the design of the sampler. A hydrophylic polymer with a typical pore diameter of 0.1 μm is used to extract the samples. A stainless steel wire gives support while inserting the sampler into the soil in a pre-drilled hole. The samplers should be installed into wet soil, after preparing a hole with a 2 mm rod. A good tube-soil contact can be obtained when samplers are inserted horizontally into cylinders of soil. Horizontal installation in the field is possible from trenches or cylindrical holes ('inverted lysimeter'). Vertically placed samplers may have less satisfatory tube-soil contact. A simple stainless steel wire positioning system is available for use in very soft soil, e.g. rice fields. The samplers are directly suited to sample water saturated materials.

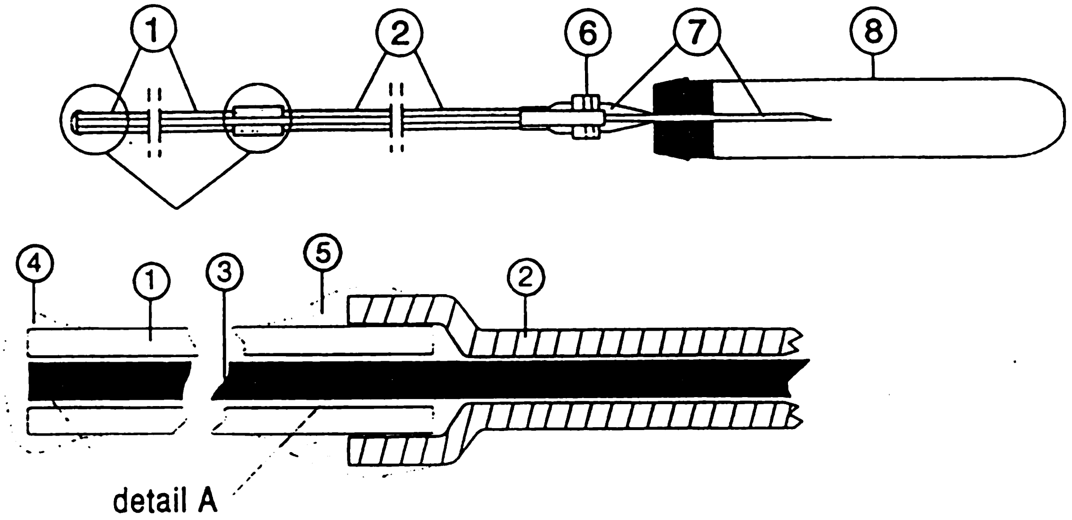


Fig. 1. Construction of RHIZON SSS soil solution sampler. 1. Porous hydrophylic hollow fibre of 2.5 mm outer and 1.4 mm inner diameter, 100 mm long; 2. PVC tubing of 2.7 mm outer and 1.0 mm inner diameter; 3. Stainless steel wire of 0.8 mm diameter; 4. & 5. Adhesives; 6. Luer-lock connector; 7. Injection needle; 8. Vacuum tube.

Samples can be extracted by connecting a syringe to the sampler (using the Luer-Lock connection), or - as shown in Fig. 1 - by the use of a vacuum bottle (as used for collecting blood samples). In water a 10 ml sample can be extracted in less than 5 minutes. In soil 7 ml of sample can be obtained per 10 ml vacuum tube, in 1 - 16 hours (overnight), depending on soil water content. Below a hydrostatic soil water potential of -200 to - 500 cm (depending on soil physical characteristics), no satisfactory sampling is possible.

RESULTS AND DISCUSSION: In Table 1 a tentative comparison of ceramic cups and the new samplers is made, based on experience obtained in a range of field and pot experiments. Quantitative measurements of the water extraction rate as a function of soil water content are currently performed in our Institute. In this work the samplers are used to check model calculations of soil water uptake by roots. In further applications of this kind, effects of partial root-soil contact on uptake rates can be investigated by making half of the tube diameter impermeable to water. The tubes can

Table 1. Tentative evaluation of ceramic cups and Rhizon soil solution samplers.

Criterion	Ceramic cups	Rhizon SSS
Soil disturbance	Minimally 6 mm diameter	2.5 mm diameter
Dead volume	Usually high	0.5 ml
Mechanical strength	High	Low
Ion-exchange	Yes, varies with age	Inert
Longevity	Ageing depends on soil	No ageing; samplers fragile in cracking soils
pH-measurements	Unreliable, CO_2 loss	Correct, no CO_2 loss

also be used to inject solutes into the soil, e.g. to simulate exudates and subsequently extract soil solution. The tube diameter is within the range normally encountered for roots.

REFERENCES

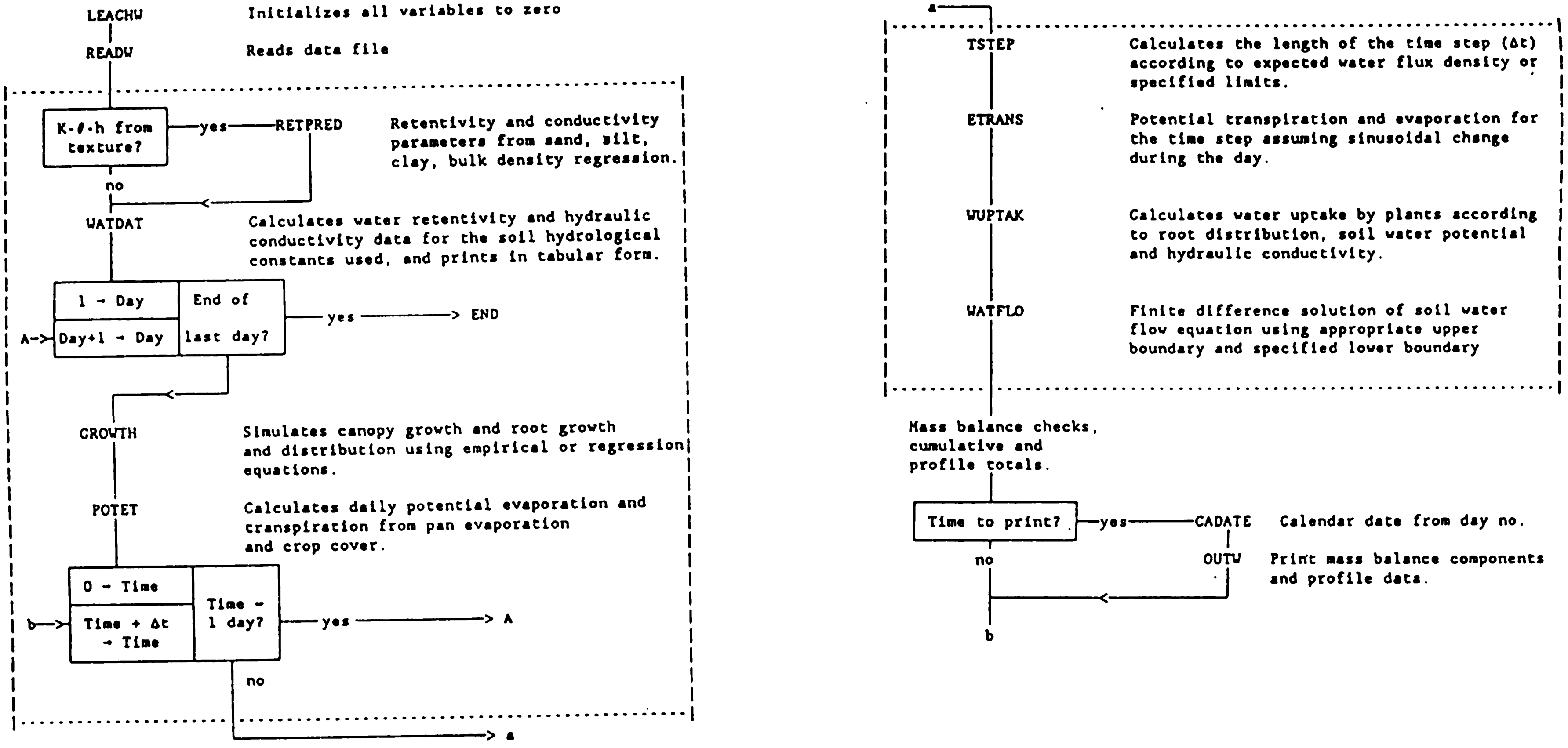
BRIGGS, L.J. and McCALL, A.G., 1904. An artificial root for inducing capillary movement of soil moisture. Science 137: 239-244.

GROSSMAN, J. and P. UDLUFT, 1991. The extraction of soil water by the suction cup method a review. J. Soil Sc. 42: 83-93.

Ir. Frits Meijboom and Dr. Meine van Noordwijk, DLO-Institute for Soil Fertility Research, P.O.Box 30003, 9750 RA Haren, the Netherlands.

The Rhizon SSS can be obtained from Eijkelkamp Agrisearch Equipment, P.O.Box 4, 6987 ZG Giesbeek, The Netherlands.

Annex 4.1 a: LEACHW flow chart



ANNEX 4.2 SPECIFIC NUMERICAL SOLUTIONS TO THE RICHARDS EQUATION

The Richard's equation

Richard's equation, the soil water flow equation for transient vertical flow derived from Darcy's law and the equation of continuity, is:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H}{\partial z}\right] - U\ (z,t) \qquad (2.23)$$

where θ is volumetric water content (m^3/m^3). H is hydraulic head (mm). K is hydraulic conductivity (mm/d). t is time (d). z is depth (mm). positive downwards and U is a sink term representing water lost per unit time by transpiration (d^{-1}).

Defining the differential water capacity, $C(\theta)$, as

$$C(\theta) = \partial\theta/\partial h \qquad (2.24)$$

where h is soil water pressure head, enables (2.24) to be transformed into an equation in which pressure potential is the only dependent variable:

$$\frac{\partial h}{\partial t}\ C(\theta) = \frac{\partial}{\partial z}\left[K(\theta)\ .\ \frac{\partial H}{\partial z}\right] - U\ (z,t). \qquad (2.25)$$

Differencing and solution procedure

To simulate flow and redistribution of water in soil by finite differencing techniques, the profile is divided into a number of horizontal segments and the total time period is divided into short time intervals. The time periods are not necessarily of equal length, as explained below. In this model the top node (i = 1) and the lowest node (i = k) are outside the soil profile and are used for maintaining the desired boundary conditions.

The first-order partial on the left-hand side of (2.25) may be approximated as:

$$\frac{\partial h}{\partial t} = \frac{h_i^j - h}{\Delta t} \qquad (2.26)$$

The second-order partial on the right-hand side of (2.25) may be approximated as:

$$\frac{\partial}{\partial z}\left[K(\theta)\,\frac{\partial h}{\partial z}\right] = \frac{\partial}{\partial z}\left[K(\theta)\,\frac{(\partial h + \partial z)}{\partial z}\right]$$

$$= \frac{1}{\Delta z_3}\left[\frac{K_{i-\frac{1}{2}}^{j-\frac{1}{2}}}{\Delta z_1}\left(h_{i-1}^{j-1} + h_{i-1}^{j} - h_i^{j-1} - h_i^{j} + 2\Delta z_1\right) - \frac{K_{i+\frac{1}{2}}^{j-\frac{1}{2}}}{\Delta z_2}\left(h_i^{j-1} + h_i^{j} - h_{i+1}^{j-1} - h_{i+1}^{j} + 2\Delta z_2\right)\right] \qquad (2.27)$$

where $\Delta z_1 = z_i - z_{i-1}$,

$\Delta z_2 = z_{i+1} - z_i$,

$\Delta z_3 = z_{i+1} - z_{i-1}$,

and $K_{i+\frac{1}{2}}^{j-\frac{1}{2}}$ and $K_{i-\frac{1}{2}}^{j-\frac{1}{2}}$ are hydraulic conductivities representative of the time step j-1 to j, of duration Δt. If Δz_1 and Δz_2 are equal, as currently assumed in LEACHM, then $\Delta z_1 = \Delta z_2 = 0.5\Delta z_3$.

Substituting (2.26) and (2.27) into (2.25), and slightly rearra gives:

$$C(\theta)_i^{j-\frac{1}{2}}\,\frac{h_j^{j} - h_{j-1}^{j}}{\Delta t}$$

$$= \frac{1}{\Delta z_3}\left[K_{i-\frac{1}{2}}^{j-\frac{1}{2}}\left(\left(h_{i-1}^{j-1} + h_{i-1}^{j}\right) + 2\Delta z_1 - h_i^{j-1} - h_i^{j}\right)/\Delta z_1 - K_{i+\frac{1}{2}}^{j-\frac{1}{2}}\left(\left(h_i^{j-1} + h_i^{j}\right) + 2\Delta z_2 - h_{i+1}^{j-1} - h_{i+1}^{j}\right)/\Delta z_2\right] - U_i^{j-\frac{1}{2}}$$

Equation (2.28) describes the change in water content at node i during time interval j-1 to j.

An equation similar to (2.28) may be written for all nodes. For there are thus k equations. Soil water pressure heads at the start of interval (h^{j-1} values) are known, and the set of equations is then solve the unknown pressure heads at the end of the time period (h^j values).

The Crank-Nicolson (1947) implicit method used in this model give weight to the h^{j-1} and h^j terms to approximate the second order term. If all the unknown h^j terms are gathered on the left hand side and all t known h^{j-1} terms on the right hand side, (2.28) becomes:

$$-h_{i-1}^{j}\left(K_{i-\frac{1}{2}}^{j-\frac{1}{2}}/\Delta z_1\right) + h_i^{j}\quad C_i^{j-\frac{1}{2}}\,\frac{\Delta z_3}{\Delta t} + K_{i-\frac{1}{2}}^{j-\frac{1}{2}}/\Delta z_1$$

$$+ K_{i+\frac{1}{2}}^{j-\frac{1}{2}}/\Delta z_2 \quad - \quad h_{i+1}^{j}\left(K_{i+\frac{1}{2}}^{j-\frac{1}{2}}/\Delta z_2\right) \quad =$$

$$h_{i-1}^{j-1}\left(K_{i-\frac{1}{2}}^{j-\frac{1}{2}}/\Delta z_1\right) + h_{i+1}^{j-1}\,K_{i+\frac{1}{2}}^{j-\frac{1}{2}}/\Delta z_2 + h_i^{j-1}\left[C_i^{j-\frac{1}{2}}\Delta z_3/\Delta t\right.$$

$$\left. - K_{i-\frac{1}{2}}^{j-\frac{1}{2}}/\Delta z_1 - K_{i+\frac{1}{2}}^{j-\frac{1}{2}}/\Delta z_2\right] + 2\left(\Delta z_1\,K_{i-\frac{1}{2}}^{j-\frac{1}{2}} - \Delta z_2\,K_{i+\frac{1}{2}}^{j-\frac{1}{2}}\right) - U_i^{j} \qquad (2$$

4v2,2.

Equation (2.29) may be simplified by combining constants and writing in the general form

$$\alpha_i h^j_{i-1} + \beta_i h^j_i + \gamma_i h^j_{i+1} = \delta_i \qquad (2.30)$$

All the terms included in the constants α_i, β_i, γ_i and δ_i have known or estimated values. The k equations form a symmetric tridiagonal matrix which may be solved by means of a rapid Gaussian elimination method (Thomas Algorithm). A recursive formula by which the h^j_i terms may be calculated, is:

$$h^j_i = g_i + m_i h^j_{i+1} \qquad (2.31)$$

in which $g_i = (\delta_i + \alpha_i g_{i-1})/(\beta_i - \alpha_i m_{i-1})$ (2.32)

and $m_i = -\gamma_i/(\beta_i - \alpha_i m_{i-1})$ (2.33)

In the first stage of the solution g and m values are calculated for nodes 2 to k. Initial values of g_i and m_i are chosen to fulfill the desired surface boundary conditions. In the second stage h^j values are calculated, starting at the bottom of the profiles by substituting the boundary value h^j into (2.31) and working towards the surface. The h^j values then become starting h^{j-1} values for the following time period.

The flux of water (mm) moving between nodes during a time interval is calculated from:

$$W^{j-\frac{1}{2}}_{i+\frac{1}{2}} = [K^{j-\frac{1}{2}}_{i+\frac{1}{2}} - K^{j-\frac{1}{2}}_{i+\frac{1}{2}}(h^j_{i+1} + h^{j-1}_{i+1} - h^j_i - h^{j-1}_i)/2\Delta z_2]\Delta t \qquad (2.34)$$

q(z) - K(z)([illegible])

Positive values of W indicate downward movement and negative values, upward movement. Flux density q is defined as:

$$q^{j-\frac{1}{2}}_{i+\frac{1}{2}} = W^{j-\frac{1}{2}}_{i+\frac{1}{2}}/\Delta t \qquad (2.35)$$

The upper boundary flux of water

The upper boundary condition can be changed with time by adjusting h^j_1 to simulate ponded of non-ponded infiltration, evaporation or zero flux

During ponded infiltration, the pressure potential of the first node is set to zero.

A flux controlled surface boundary exists during periods of evaporation, non-ponded infiltration and zero flux. Writing (2.34) for surface flux density,

$$q^{j-\frac{1}{2}}_{1+\frac{1}{2}} = K^{j-\frac{1}{2}}_{1+\frac{1}{2}} - K^{j-\frac{1}{2}}_{1+\frac{1}{2}}(h^j_2 + h^{j-1}_2 - h^j_1 - h^{j-1}_1)/2\Delta z_1 \qquad (2.36)$$

where q is water flux density (mm day^{-1}). Assuming $m^j_1 = 1$, (2.31) becomes $g_1 = h^j_1 - h^j_2$.

Substituting g_1 for the unknown value of $h^j_1 - h^j_2$ in (2.36) and rearranging,

$$g_1 = 2\Delta z_1 [(q^{j-\frac{1}{2}}_1 - K^{j-\frac{1}{2}}_{1+\frac{1}{2}})/K^{j-\frac{1}{2}}_{1+\frac{1}{2}}] + h^{j-1}_2 - h^{j-1}_1 . \qquad (2.37)$$

This procedure enables a value of h^j_1 to be calculated which satisfies the surface flux condition.

Lower boundary condition

The lower boundary condition is maintained by adjusting the potential of e bottom node in order to represent a fixed depth water table, a free-raining profile, zero flux or a lysimeter tank.

- A permanent water table is simulated by setting the pressure potential of the lowest node k to a fixed value

$$h_k^j = \text{Profile depth} - \text{water table depth} + \Delta z/2. \qquad (2.38)$$

Under certain circumstances a constant negative pressure potential is assigned to the lowest node, for example, during suction drainage when the drainage system has negligible impedance, or when a water table is slightly deeper than the simulated profile depth.

- In a freely draining profile the hydraulic potential gradient is approximately unity,

$$(h_k^j + h_k^{j-1} - h_{k-1}^j - h_{k-1}^{j-1} + 2\Delta z)/2\Delta z \simeq 1 \qquad (2.39)$$

Since $h_{k-1}^j = g_{k-1} + m_{k-1} h_k^j$

42.4.

$$h_k^j = (g_{k-1} - h_k^{j-1} + h_{k-1}^{j-1})/(1 - m_{k-1}) \qquad (2.40)$$

Because g_{k-1} and m_{k-1} are calculated before a value for h_k^j is required and h_k^{j-1} and h_{k-1}^{j-1} are known, h_k^j may be calculated to satisfy the unit hydraulic potential gradient condition.

The soil hydrological properties may be such that a perched water table is simulated. In most circumstances LEACHM will correctly simulate the development of positive pressure potentials in part of the profile. Reducing the saturated hydraulic conductivity of the lower segments can be used as a means of simulating a fluctuating water table.

- For zero flux the hydraulic potential gradient is zero and following a similar procedure as above,

$$h_k^j = (2\Delta z - h_k^{j-1} + h_{k-1}^{j-1} + g_{k-1})/(1 - m_{k-1}) \qquad (2.41)$$

- A lysimeter may be simulated using a combination of the constant potential and zero flux conditions. Water can drain from the lysimeter when the bottom layer is saturated or has a pressure potential greater than that of a suction drainage system. No water can move into the lysimeter when h_k^j is less than the drainage system potential, and a zero flux condition is maintained at the bottom boundary.

Annex 4.3 a: Specified standard input file

Data are self explanatory in most cases. If this is not so, they are explained beneath each section.

```
Test data set LMS-B1
SIMULATION PERIODS (Data must be present for each item, even if it not used)
------------------
Date type (US:1 UK:2)                    2
starting date                       010393 Ending (date or day no.)      180693
Read theta(1) or pot'l(2)                2
No. of water applications               63
Cycles through data                      1 No. of crops                       1
K-Th-h from PSD:yes(1)no(0)              0 Trace 1(on) 0(off)                 0
-----------------------------------------------------------------------------
```

The theta or pot'l option defines whether the initial moisture content that will be read is expressed as volumetric water content (theta <1) or as pressure head. The number of water applications refers to the number of rain events during the simulaton period. K-Th-h from Pore Size Distribution refers to a different algorithm that can be used for calculating K-Th-h relations. In this simulation Van genuchten parameters are used.

```
PROFILE DETAILS
---------------
Profile depth     (mm)       .2000E+04 Bottom boundary condition          1
Segment thickness (mm)       .0500E+03 :1 or 5,water table depth  01.00E+03
-----------------------------------------------------------------------------
```

In this section of the input file the mesh is defined. Bottom boundary condition 1 means that a profile with a fixed watertable is simulated. The water table depth is set at 1 meter because this was the observed mean depth at the site during the measuring period

```
FOR UNIFORM PROFILE: (Any non-zero value here will override those in the
table of hydrological characteristics below unless K-Th-h calc. from PSD).
Soil bulk density Mg/cu.m   .0000E+00 Air -entry value' kPa     -.0000E+04
Exponent in Campbell's eq   .0000E+02 Sat'd K values (mm/day)    .0000E+04
----------------------------------------------------------------------------
```

In this section soil hydrological characteristics are defined. Since the Van Genuchten bypass subroutine was applied, this section is not used

```
CROP DATA
---------
Plants present: 1 yes, 0 no          1 Wilting point (soil) kPa  -.1500E+04
Max(actual tran/potl tran)  .1000E+01 Min.root water pot'l (kpa)-.3000E+04
Roots: Const(1);growing(2)           1 Max.root water pot'l (kpa) .0000E+04
If 1: root length (m)      1.5000E+04 Root flow resistance term  .1050E+01
----------------------------------------------------------------------------
```

These Data were mostly taken from literature

```
NUMBER OF OUTPUT FILES               3
  -- .OUT file --------                 ----- .SUM file ----------
                                       Summary print interval (d)        1
Node print frequency                 1 Three depth segments for the summary
Print options: 1, 2 or 3             3  file  (0's default to thirds of the
 1: Time intervals/print             1  profile)  (mm) :
 2: days/print                     1.0    Surface to [depth 1?]       0300
 3: No. of prints (even)             4    Depth 1 to [depth 2?]       0600
Tables printed: 1,2 or 3             3    Depth 2 to [depth 3?]       0800
****************************************************************************
****************************************************************************
          TIMES AT WHICH *.OUT FILE IS DESIRED (if print option = 3)
                 ------------------------------------
         Date or    Time of day       Date or    Time of day
         Day no.  (to nearest tenth)  Day no.  (to nearest tenth)
         -------- .----------------.----------.----------------
          010393        0.5           010493        0.5
          010593        0.5           010693        0.5
*************************************************************************
```

The .OUT file gives very detailed information and remained therefore largely unused. It was used as a checkup, giving mass balances at four times during the simulation. The upper two depths of the .SUM file are the depths at which measurements were made in the field.

```
*******************************************************************
Soil      Particle size distribution      Conductivity matching factor
Layer      Clay     Silt    Rho   Organic     Hydr. cond.    Matric pot'l
 no.                                carbon
             %        %    kg/dm3    %           mm/d               kPa
-----------------------------------   ---------------------------
        1       0       0       0       0       0       0
        2       0       0       0       0       0       0
        3       0       0       0       0       0       0
        .       .       .       .       .       .       .
        .       .       .       .       .       .       .
        .       .       .       .       .       .       .
        .       .       .       .       .       .       .
       38       0       0       0       0       0       0
       39       0       0       0       0       0       0
       40       0       0       0       0       0       0
---------------------------------------------------------------------
Particle density kg/dm3:  Clay    Sand  Organic matter
                          0.00    0.00     0.00
*********************************************************************
```

This section was not used, due to the use of the Van Genuchten subroutine

```
*********************************************************************
 Soil  |Starting values | Hydrological Characteristics|   Root
layer  |--------------- | ----------------------------|  fraction
 no.   | Pot'l or Theta |   AEV     BCAM     KS       |  (for const
       |  kPa           |   kPa              mm/d     |  root distr)
-----  |  ------ ------ |  -------  -----    -----    |   ------
    1     -1.7    0.572     -2.7       6.4    1000        0.05
    2     -1.7    0.572     -2.7       6.4    1000        0.05
    3     -1.7    0.572     -2.7       6.4    1000        0.14
    .       .       .        .          .       .           .
    .       .       .        .          .       .           .
    .       .       .        .          .       .           .
   38     -1.7    0.572     -2.7       6.4    1000        0.0025
   39     -1.7    0.572     -2.7       6.4    1000        0.0025
   40     -1.7    0.572     -2.7       6.4    1000        0.0025
*******************************************************************
```

Only the Pot'l (potential) and root fraction are read form this section. Root fraction distribution is given in figure 5.1.

```
                         CROP DATA
                         ---------
 Crop Planting Emergence  Maturity    Harvest  Rel.  Crop  Plants  Pan
  no                     Root  Plant           root  cover per     factor
     ...........Date or Day no ............    depth frac  sq. m
-------------------------------------------------------------------
   1 010393    010393 010393 010393  180693   1.00   1.00 001.5  1.00
*******************************************************************
```

Only one crop is modelled. Planting and harvest dates are the model default settings for perrenial crops. The four remaining parameters can be set to model the different crop types. The parameters defined above were used for forest. Since exact values were not known, parameters were adjusted to give the best possible fit.

```
RAIN/IRRIGATION AND WATER COMPOSITION
-------------------------------------
     START        AMOUNT      RATE
 Date or  Time of   mm       mm/day
 Day no.    Day
  ---------(10th) ------    ------
    .         .        .       .
    .         .        .       .
    .         .        .       .
 210593      0.5     24.9     150
```

7.3.a 2

```
                    220593      0.5         2       150
                    240593      0.5        58       150
                    250593      0.5      16.3       150
                    260593      0.5     144.8       350
                    270593      0.5       3.6       150
                    280593      0.5       8.9       150
                    290593      0.5        10       150
                    300593      0.5       0.9       150
                       .         .         .         .
                       .         .         .         .
                       .         .         .         .
*************************************************************************
```

In this section water application events were defined. Where total rain exceeded or aproximated the mean rain rate, rates were adjusted. This gives a very low resolution and descrete input, but no detailed data were available.

```
*************************************************************************
     POTENTIAL ET (WEEKLY TOTALS, mm) AND DEPTH TO WATER TABLE (mm)
-------------------------------------------------------------------------
-------------------------------------------------------------------------
      WEEK NO.    ET   WATER TABLE
      -----------------------------
      01         27.2      1000.0
      02         27.2      1000.0
       .           .          .
       .           .          .
       .           .          .
      23         27.2      1000.0
      24         27.2      1000.0
      25         27.2      1000.0
```

Mean ET values of 3.6 mm /day = 27.2 mm/ week were used

```
SIMULATION PERIODS (Data must be present for each item, even if it not used)
------------------
Date type (US:1 UK:2)                 1
Starting date                    010393 Ending (date or day no.)      031593
Read theta(1) or pot'l(2)             1
No. of water applications            37
Cycles through data                   1 No. of crops                       1
K-Th-h from PSD:yes(1)no(0)           0 Trace 1(on) 0(off)                 0
-----------------------------------------------------------------------------
PROFILE DETAILS
---------------
Profile depth     (mm)       .2000E+04 Bottom boundary condition          1
Segment thickness (mm)       .0500E+03 :1 or 5,water table depth  07.00E+03
-----------------------------------------------------------------------------
FOR UNIFORM PROFILE: (Any non-zero value here will override those in the
table of hydrological characteristics below unless K-Th-h calc. from PSD).
Soil bulk density Mg/cu.m    .0000E+00 Air -entry value' kPa     -.0000E+04
Exponent in Campbell's eq    .0000E+02 Sat'd K values (mm/day)    .0000E+04
-----------------------------------------------------------------------------
CROP DATA
---------
Plants present: 1 yes, 0 no           1 Wilting point (soil) kPa  -.1500E+04
Max(actual tran/potl tran)   .1000E+01 Min.root water pot'l (kpa)-.3000E+04
Roots: Const(1);growing(2)            1 Max.root water pot'l (kpa) .0000E+04
If 1: root length (m)       1.5000E+03 Root flow resistance term  .1050E+01
-----------------------------------------------------------------------------
NUMBER OF OUTPUT FILES                3
   -- .OUT file --------                 ----- .SUM file ----------
                                        Summary print interval (d)         1
Node print frequency                  1 Three depth segments for the summary
Print options: 1, 2 or 3              3  file  (0's default to thirds of the
 1: Time intervals/print              1  profile) (mm) :
 2: days/print                      1.0    Surface to [depth 1?]         300
 3: No. of prints (even)              4    Depth 1 to [depth 2?]         600
Tables printed: 1,2 or 3              3    Depth 2 to [depth 3?]        1000
*****************************************************************************
*****************************************************************************
          TIMES AT WHICH *.OUT FILE IS DESIRED (if print option = 3)
                -------------------------------------
        Date or    Time of day       Date or    Time of day
        Day no.  (to nearest tenth) Day no.  (to nearest tenth)
        -------- ----------------- ---------- ----------------
        042093         .5            040593          .5
        041093         .5            042093          .5
**************************************************************************
**************************************************************************
Soil        Particle size distribution       Conductivity matching factor
Layer      Clay    Silt    Rho    Organic      Hydr. cond.     Matric pot'l
 no.                              carbon
            %        %    kg/dm3    %             mm/d              kPa
-----------------------------------------------    ------------------------------
          1        0        0        0        0        0        0
          2        0        0        0        0        0        0
          3        0        0        0        0        0        0
          4        0        0        0        0        0        0
          5        0        0        0        0        0        0
          6        0        0        0        0        0        0
          7        0        0        0        0        0        0
          8        0        0        0        0        0        0
          9        0        0        0        0        0        0
```

```
     3       -2     0.535      -2.7        6.4      1000    0.1592
     4       -2     0.535      -2.7        6.4      1000    0.1101
     5       -2     0.572      -2.7        6.4      1000    0.0932

    35       -2     0.572      -2.7        6.4      1000    0.0006
    36       -2     0.572      -2.7        6.4      1000    0.0005
    37       -2     0.572      -2.7        6.4      1000    0.0004
    38       -2     0.572      -2.7        6.4      1000    0.0003
    39       -2     0.572      -2.7        6.4      1000    0.0002
    40       -2     0.572      -2.7        6.4      1000         0
*********************************************************************
                        CROP DATA
                        ---------
Crop Planting Emergence  Maturity   Harvest  Rel.  Crop  Plants  Pan
 no                  Root  Plant             root  cover per     factor
    ...........Date or Day no ............   depth frac  sq. m
---------------------------------------------------------------------
 1   10393    10393   10393   10393  31593   1.00   0.9   1000    0.6
*********************************************************************
                 RAIN/IRRIGATION AND WATER COMPOSITION
                 ------------------------------------

                   START      AMOUNT     RATE
                Date or  Time of  mm     mm/day
                Day no.    Day
                ---------(10th) ------    ------
                   10593      0.5      1.2       3.6
                   10693      0.5      1.9       5.7

                   30793      0.5      2.5       7.5
                   31293      0.5      6.6      19.8
**********************************************************************
**********************************************************************
    POTENTIAL ET (WEEKLY TOTALS, mm) AND DEPTH TO WATER TABLE (mm)
----------------------------------------------------------------------
----------------------------------------------------------------------
     WEEK NO.     ET   WATER TABLE
     ----------------------------
     01      27.2   7000.0
     02      27.2   7000.0

     15      27.2   7000.0
     16      27.2   7000.0
```

```
data set LLA plantation
IMULATION PERIODS (Data must be present for each item, even if it not used)
-----------------
Date type (US:1 UK:2)                 1
tarting date                     010393 Ending (date or day no.)      031593
ead theta(1) or pot'l(2)              1
No. of water applications            37
Cycles through data                   1 No. of crops                       1
-Th-h from PSD:yes(1)no(0)            0 Trace 1(on) 0(off)                 0
------------------------------------------------------------------------------
PROFILE DETAILS
--------------
rofile depth      (mm)       .2000E+04 Bottom boundary condition          1
Segment thickness (mm)       .0500E+03 :1 or 5,water table depth  07.00E+03
------------------------------------------------------------------------------
OR UNIFORM PROFILE: (Any non-zero value here will override those in the
table of hydrological characteristics below unless K-Th-h calc. from PSD).
Soil bulk density Mg/cu.m    .0000E+00 Air -entry value' kPa     -.0000E+04
```

ANX 4.3.6

gamma	depth	Ksat (cm/day)	R^2	nr.	name
4.0249	0-20	326.6	0.9867	1	los diamantes
0.1139	0-20	326.6	0.9895	2	
14.189	0-20	326.6	0.9939	3	
9.29	0-20	326.6	0.993	4	
1.4316	20-65	214.1	0.99	1	los diamantes
1.0882	20-65	214.1	0.994	2	
6.3268	20-65	214.1	0.9937	3	
0.5591	20-65	214.1	0.9882	4	
0.0001	65-105	214.1	0.962	1	los diamantes
0.0008	65-105	214.1	0.9641	2	
0.0001	65-105	214.1	0.9413	3	
0.0001	65-105	214.1	0.956	4	
0.0001	65-105	214.1	0.9536	5	
0.0001	0-40	328.1	0.9905	1	ligia
0.0008	0-40	328.1	0.9954	2	
0.0001	0-40	328.1	0.9952	3	
0.0001	0-40	328.1	0.9985	4	
0.0001	0-40	328.1	0.9992	5	
0.031	40-70	207.7	0.9911	1	ligia
0.0001	40-70	207.7	0.9899	2	
0.0219	40-70	207.7	0.9933	3	
21.3869	40-70	207.7	0.9624	4	
0.0564	40-70	207.7	0.99	5	
0.013	70-90	207.7	0.9896	1	ligia
0.1008	70-90	207.7	0.995	2	
0.0117	70-90	207.7	0.9952	3	
4.0338	0-25	336.8	0.9936	1	montelimar
0.0097	0-25	336.8	0.9918	2	
0.0001	0-25	336.8	0.9911	3	
0.7009	0-25	336.8	0.995	4	
17.4147	0-25	336.8	0.9958	5	
14.8487	25-55	285.7	0.9893	1	montelimar
12.3302	25-55	285.7	0.9881	2	
16.1861	25-55	285.7	0.9928	3	
15.5521	25-55	285.7	0.9895	4	
0.0236	55-80	285.7	0.9262	1	montelimar
0.0032	55-80	285.7	0.9215	2	
0.8494	55-80	285.7	0.9118	3	
1.1637	55-80	285.7	0.8949	4	

all soils are planted with banana

los diamantes: loamy topsoil on coarse sand

ligia : clayey topsoil on moderately coarse sand

montelimar : loamy topsoil on fine sand

4.3.e.2

Annex 4.5

hydrological observations of LLA and LMS sites

During high rainfall in the LLA palmito plantation (not at the sampling site, but on the slope) some surface runoff was observed, although this was small. Also, on mud tracks and hillslopes around the plantation surface runoff was observed, finding its source mainly in the plantation owners' living area (gutters etc.). During the measuring period rainfall exceeded infiltration capacity only during a few severe showers. The small LLA plantation surface runoff was due to two reasons: Firstly, excess water was absorbed by a layer of dead palmheart leaves covering the plantation soil. Secondy, rainfall interception and evaporation greatly deminished the amount of rain reaching the soil. Bruynzeel (1990) states that tropical plantations of limited area, surrounded by shorter vegetation, tend to show very high evapotranspiration of intercepted rainwater, the wet canopy acting as an air heat sink, giving rise to large interception losses during heavy rain storms.

At the forest no surface runoff was observed. Water was never observed to leave the forest by any other pathway than the well draining the area. Some runoff water may have come from the grassland, but this was difficult to verify since the plantation owner's house lies on the same sumit.

During LLA rainfall events no immediate response flow from the well at the foot of the forest hills was observed. Also, no evidence of deep macropores was found. Thus preferential flow can be assumed to be unsignificant (Bruynzeel, 1990). It can be safely concluded that most of the precipitation water infiltrates the hill summits vertically, with a prevailing hydrological pattern of direct troughflow in the unsaturated zone, ending in groundwater flow to the well. Most precipitation water was observed to enter the soil as moisture fronts. Boring with an Edelman device, a day after rainshowers that succeeded several dry days, showed pronounced moisture fronts at app. 30 - 40 cm depth.

The groundwater table was, due to the steep topography, at least 7 meters below the hill summits.

During rainshowers exceeding infiltration capacity at LMS, exces water was observed to leave the plantation area immediately by draining channels as surface runoff. The forest stored most of the excess water in in the standing biomass and its O-horizon, and almost no surface runoff was observed. In the grassland, exces water often ponded the surface and infiltrated later.

For sandy LMS sites, the assumption of no preferential flow seems valid, since the soils are very permeable. Some preferential flow may have occured in loamy soils. Sampling pits were checked on macropores after sampling was finished. No evidence of big macropores was found,though some small ones were observed. The contribution of this small effect to moisture yields is unknown.

The groundwater table at all LMS sites was high, it fluctuated between 100 cm below the surface and probably not lower than 150 cm below the surface during the whole measuring period, with a maximum of 80 cm below the surface in the forest and the plantation.

Complete analysis list LLA and LMS

BENG	AUW lab - wageningen, the Netherlands
CATIE(CAT)	CATIE lab - Turrialba, Costa Rica
MAG	MAG lab - San Jose, Costa Rica

LLA	
R1	rainwater
a	forest subsoil
b	grassland topsoil
c	grassland subsoil
d	plantation topsoil
e	plantation subsoil
x	well draining forest

LMS	
R2	rainwater
1	forest topsoil
2	forest subsoil
3	grassland topsoil
4	grassland subsoil
5	plantation.Loamy topsoil
6	plantation.Loamy subsoil
7	plantation.Sandy topsoil
8	plantation.Sandy subsoil
9	grassland, waterlogged
AD	demineralized water

* $\Sigma+$ $\Sigma-$ CALCULATIONS WERE NOT POSSIBLE FOR MOST OF THE SAMPLES, SINCE MOST ANALYSES WERE PARTIAL.

TIC - TOTAL INORGANIC CARBON

nr.	code	DATE	LAB	pH	Ec	K	Na	Ca	Mg	NH4	NO3
0	AD	323	BENG	5.41	2	1	2	10	5		0
1	AD	425	BENG	5.47	2	2	3	12	2		0
2	R1	108	BENG	5.9		49	382	56	16	75	
3	R1	108	BENG	5.4		30	142	54	18	28	
4	R1	114	BENG/CAT	6.0		60	155	291	198		
5	R1	118	BENG/CAT	5.7		31	122	244	120		
6	R1	121	BENG	5.15	17	56	22	30	19		39
7	R1	126	BENG	5.51	10	20	7	11	6		0
8	R2	210	BENG/CAT	5.8	24						
9	R2	312	BENG	5.36	33	7	105	59	93		180
11	R2	509	BENG			29	189	69	51		
12	R2	514	BENG	4.21	23.1	8	31	6	5		17.81
13	R2	603	BENG	4.74	7.65	3	16	5	3		0
14	a	111	MAG			40	602	77	45	148	
15	a	114	BENG	6.0		37	430	221	85		
16	a	118	MAG	5.4		32	163	197	153		
17	a	120	MAG	6.9		20	58	57	31		
18	a	126	MAG/CAT	5.4		22	172	24	7		
19	a	127	MAG/CAT	5.2		18	103	14	6		
20	a	128	MAG/CAT	5.4		20	133	19	5		
21	a	129	MAG/CAT	5.7		24	140	148	12		
22	a	201	MAG/CAT	5	13.4	14	79	21	13		
23	a	208	CATIE	4.7	19.3	10	73	13	13		
24	a	210	BENG/CAT	4.7	16.9	8	81	13	11		
25	a	218	CATIE	4.5	16.5	6	81	6	9	1.73	0.62
26	a	226	BENG	4.8	26	11	99	18	37		49
27	a	312	BENG	5.6	20	6	84	29	22		31
28	b	111	MAG	4.7		21	80	107	22		
29	b	114	BENG	5.6		28	284	548	159		
30	b	120	MAG	5.3		26	58	408	120		
31	b	126	MAG/CAT	4.7		22	104	32	14		
32	b	127	MAG/CAT	4.5		20	28	27	11		
33	b	128	MAG/CAT	5.0		20	51	29	14		
34	b	129	MAG/CAT	4.9		20	46	38	11		
35	b	201	MAG/CAT	4.3	26	19	50	32	12		
36	b	208	CATIE	4.5	21.2	15	40	34	12		
37	b	210	CATIE	4.7	22.4	16	50	36	15		
38	b	226	BENG	4.6	26	11	57	60	19		0
39	c	111	MAG	5.4		18	80	78	18	3	
40	c	114	BENG	5.2		19	9	186	54		
41	c	120	MAG	7.0		18	9	291	74		
42	c	127	MAG/CAT	5.1		20	61	19	10		
43	c	128	MAG/CAT	5.4		18	35	25	8		
44	c	129	MAG/CAT	5.2		19	32	25	7		
45	c	201	MAG/CAT	4.6	13	6	26	23	9	0.1	
46	c	208	CATIE	4.7	8.3	4	24	18	7	0.3	
47	c	210	CATIE	4.8	10.6	5	23	25	10		
48	c	218	CATIE	4.9	10.6	8	22	28	7	0.37	
49	c	226	BENG	5.1	12	4	34	24	10		0
50	c	312	BENG	5.5	12	1	32	41	10		0
59	e	120	MAG	4.5		59	9	244	93		
60	e	126	MAG/CAT	5.1		52	32	33	12		
61	e	128	MAG/CAT	6.0		52	43	34	13		
62	e	201	MAG/CAT	4.6	66.1	128	53	117	40	0.74	5.19
63	e	208	CATIE	5.1	55.5	76	117	71	23		
64	x	126	MAG/CAT	5.3		46	135	27	36		
65	x	127	MAG/CAT	5.2		20	121	29	39		
66	x	128	MAG/CAT	5.1		20	135	32	39		
67	x	129	MAG/CAT	5.1		20	135	25	39		

nr.	code	DATE	LAB	pH	Ec	K	Na	Ca	Mg	NH4	NO3
68	1	219	BENG/CAT	6.1	77	49	213	310	63		364
69	1	222	BENG/CAT	5.88	56.1	6	78	366	69		400.4
70	1	317	BENG	6.73	210						
71	1	322	BENG	4.86	153	78	174	798	192		1849
72	1	323	BENG	6.88	120						
73	1	329	BENG	6.04	119	37	132	635	151		671
74	1	330	BENG	6.10	87						
75	1	401	BENG	6.12	69						341
76	1	408	BENG	6.14	54						236
77	1	413	BENG	6.52	86						
78	1	415	BENG	6.33	117						
79	1	420	BENG	6.20	74						
80	1	426	BENG	4.31	98.2	31	151	460	107		661.8
81	1	427	BENG	5.58	71	72	106	291	71		421.1
82	1	428	BENG	5.76	62	99	95	218	53		310.5
83	1	505	BENG	5.62	70.5	65	110	296	69		442.1
84	1	506	BENG			109	92	234	57		416.6
85	1	507	BENG			110	106	260	65		438.4
86	1	510	BENG	5.79	74.1	126	116	262	63		460.8
87	1	531	BENG	5.7	79.8	62	118	336	78		530.2
88	1	601	BENG		48	78	58	179	46		245.3
89	1	603	BENG			71	73	225	53		
90	1	604	BENG	5.74	48.3	87	56	178	44		276.2
91	2	219	BENG/CAT	6.63	92						
92	2	222	BENG	5.92	47.1	10	87	222	53		263.4
93	2	316	BENG	6.20	45	9	77	233	47		198
94	2	317	BENG	6.64	85						195
95	2	318	BENG	4.79	20						54
96	2	322	BENG	6.11	36	9	86	153	43		159
97	2	330	BENG	6.11	41	10	74	199	44		180
98	2	401	BENG	6.03	41	9	78	200	44		249
99	2	408	BENG	6.14	39	8	76	192	40		213
100	2	413	BENG	6.01	38						188
101	2	415	BENG	6.65	62						
102	2	420	BENG	6.28	41						194
103	2	426	BENG	5.83	39.1	9	85	162	39		182.7
104	2	427	BENG			8	76	153	37		
105	2	428	BENG			15	93	160	38		165.2
106	2	505	BENG	6.23	36.8	9	80	155	37		179.7
107	2	507	BENG			11	85	167	37		89.9
108	2	510	BENG			11	79	151	36		165.9
109	2	531	BENG	5.97	46.3	15	142	155	46		188.8
110	2	601	BENG			9	78	171	41		
111	2	603	BENG		38.7	10	78	173	41		213.7
112	3	323	BENG	6.94	124	11	205	509	414		17
113	3	330	BENG	6.86	110	6	177	500	397		0
114	3	408	BENG	6.77	97	2	171	410	320		0
115	3	426	BENG	6.41	57.4	9	107	196	166		0
116	3	428	BENG			9	119	178	165		
117	3	505	BENG		52.3	6	112	180	160		0
118	4	323	BENG	6.80	53	104	138	160	47		23
119	4	330	BENG	6.91	46	108	94	174	49		25
120	4	408	BENG	6.83	70	150	117	249	72		47
121	1	415	BENG	6.99	65	142	92	265	73		0
122	1	426	BENG		50.3	325	202	257	54		0
123	1	128	BENG			148	69	117	51		

nr.	code	DATE	LAB	pH	Ec	K	Na	Ca	Mg	NH4	NO3
132	5	318	BENG	6.23	95.3	6	150	434	165		518.6
134	5	322	BENG	6.18	77.4	5	126	383	146		390.5
136	5	323	BENG	6.43	84.4	3	128	432	151		461.5
138	5	329	BENG	6.26	78.3	3	131	413	150		416
140	5	330	BENG	5.96	64.3	4	158	308	113		331.2
141	5	401	BENG	6.58	73.5	16	161	310	128		373.2
142	5	401	BENG		69.6	3	68	371	120		207.7
143	5	408	BENG			41	134	289	95		337.5
144	5	408	BENG		37.3	2	56	182	53		58.38
145	5	426	BENG/CAT	5.91	85.9	14	125	402	144		358.9
147	5	427	CATIE	5.87	36.1						187.3
148	5	531	BENG	5.85	105	7	92	544	158		446.1
150	5	603	BENG	5.94	29.3	2	44	154	41		40.78
151	5	603	BENG	6.01	35.1	2	104	147	54		20.19
153	5	604	BENG		29.9	2	45	171	42		
154	6	219	BENG/CAT	7.24	88	17	258	351	287		83
155	6	219	BENG/CAT	6.55	83	15	277	287	243		99
156	6	222	BENG/CAT	7.19	61	3	164	313	202		141.6
157	6	222	BENG/CAT	6.98	112.5	20	196	393	330		376.5
159	6	316	BENG	7.14	91.7	8	228	344	292		452.7
163	6	318	BENG	6.25	72.9	15	205	247	220		208.1
164	6	318	BENG	6.76	80						
165	6	322	BENG	6.73	74.2	4	193	253	230		254.4
166	6	322	BENG	6.68	87.4	5	170	326	279		255.2
167	6	323	BENG	6.91	66.6	7	199	241	212		213
168	6	323	BENG	6.03	82.5	6	177	298	266		258
171	6	330	BENG	6.92	77.2	7	208	281	244		216.6
172	6	401	BENG	6.08	71.7	5	169	272	234		144.5
173	6	401	BENG	5.84	81.9	7	225	335	274		264
174	6	408	BENG	6.93	61.1	4	188	229	201		141.2
175	6	408	BENG	6.87	62.6	3	163	225	205		96.46
176	6	413	BENG	6.79	48.5	2	140	173	148		29.26
177	6	413	BENG	6.68	38.7	1	140	134	119		27.95
178	6	415	BENG	6.86	44.9	2	167	334	138		81.83
179	6	420	BENG			5	141	102	99		0
180	6	420	BENG	6.58	34.5	2	153	335	115		16.96
181	6	426	CATIE	6.71	50.3	2	134	163	149		128
182	6	427	CATIE		72.7	4	167	253	213		160.2
183	6	428	CATIE			5	154	93	104		
184	6	531	BENG	6.43	44.4	4	127	293	11		54.75
185	6	531	BENG	6.39	59.5	5	164	208	176		153.7
187	6	603	BENG		33.9	4	119	108	76		0
188	6	604	BENG			8	200	256	219		
203	8	322	BENG			87	176	583	86		208.1
204	8	401	BENG			57	164	386	163		332.4
205	8	408	BENG			37	159	311	115		242.4
206	8	420	BENG			41	169	465	144		
207	8	420	BENG			99	115	232	49		0
210	8	603	BENG	6.3	81.9	47	161	336	115		
211	8	604	BENG			83	135	489	124		54.07
212	8	604	BENG			28	163	360	116		

nr.	code	DATE	LAB	pH	Ec	K	Na	Ca	Mg	NH4	NO3
213	9	323	BENG	6.83	87	164	204	228	131		0
214	9	408	BENG	7.16	98	234	117	313	199		0
215	9	415	BENG	7.11	89						39
216	9	426	BENG			35	306	2982	254		14.66
217	9	428	BENG			236	488	154	86		0
218	9	428	BENG	6.73	104.9	37	256	444	278		0
219	9	505	BENG			167	93	117	73		0
220	9	505	BENG	7.06	125.4	37	283	568	364		0
221	9	603	BENG	6.76	48.8	24	238	466	256		0
222	9	603	BENG			33	185	217	125		0

'CONTAMINATED' SAMPLES:

nr.	code	DATE	LAB	pH	Ec	K	Na	Ca	Mg	NH4	NO3
10	R2	425	BENG	7.67	1964	14	9999	6	6		0
51	d	111	MAG			617	132	551	136	74	
52	d	111	MAG	5.6		94	0	268	75	3	
53	d	128	MAG	6.2		700	732	445	79		
54	d	201	MAG/CAT	4.7	125	354	127	237	120		6.6
55	d	208	CATIE	4.9	188.8	284	111	437	0		1.48
56	d	226	BENG	4.4	272	286	132	1399	299		1378
57	e	111	MAG	5.2		57	36	84	20		
58	e	114	BENG	5.7		60	244	384	91	16	
124	5	219	BENG/CAT	6.68	167	41	144	894	268		842
125	5	219	BENG	6.56	660	326	347	3371	1203		3180
126	5	222	BENG/CAT	6.35	213	120	22	1250	354		1140
127	5	222	BENG/CAT	6.43	643	290	172	3472	584		3049
128	5	316	BENG	6.20	148.6	6	217	714	247		727.2
129	5	316	BENG		148.8	4	118	816	277		1040
130	5	317	BENG	5.87	302	139	15	1782	2484		1955
133	5	318	BENG	5.53	352	151	14	2187	968		2272
135	5	322	BENG	5.28	312	166	9	1905	1920		1412
137	5	323	BENG	5.53	309	154	9	2287	586		2088
139	5	330	BENG	4.52	164.1	3	113	940	307		957
146	5	426	BENG/CAT	5.56	254	13	151	1541	440		1034
149	5	531	BENG	5.36	162.3	53	157	766	262		726.3
152	5	604	BENG		82.5	21	267	739	90		103.5
158	6	316	BENG	7.06	78.5	5	228	2423	231		153.1
160	6	317	BENG			16	173	3724	209		212.5
161	6	317	BENG	6.90	91.2	10	229	3340	266		306.8
162	6	318	BENG	7.10	80.8	10	196	1309	232		204.1
169	6	329	BENG	6.69	71.5	7	208	2322	226		235.5
170	6	330	BENG	6.98	75.7	5	188	1131	231		126.3
186	6	603	BENG	6.85	71.8	7	199	1639	230		
190	7	316	BENG			316	1110	3870	1720		1025
192	7	318	BENG	6.54	421	519	139	2012	628		1027
193	7	322	BENG	5.46	220	167	41	1161	436		1247
194	7	322	BENG	5.66	1084	375	2790	3984	624		5164
195	7	323	BENG	4.64	706	1680	206	2592	1248		3829
196	7	329	BENG	4.64	522	1260	158	1981	1200		3371
197	7	329	BENG	5.70	93.9	35	97	3200	173		579
198	7	401	BENG		108.4	35	107	2556	212		711.4
199	7	401	BENG			655	135	1371	664		2147
200	7	420	BENG			699	1620	1164	612		
201	7	420	BENG			37	761	328	128		
202	8	219	BENG/CAT		671	160	624	4052	1020		
208	8	426	BENG/CAT		145	45	250	2968	226		0
209	8	531	BENG	6.29	162.9	42	254	764	264		898.8
191	7	317	BENG	5.38	3750	1300	8950	12220	1780		12284

CONTINUED LIST

nr.	code	dte	LAB	T/C	Si	Cl	SO4	Al	PO4	Mn
0	AD	323	BENG	78		12	2			
1	AD	425	BENG	117		14	0			
2	R1	108	BENG	340	0	229	89	1	4.56	
3	R1	108	BENG	150	0	111	68	1	16.12	
4	R1	114	BENG/CAT							
5	R1	118	BENG/CAT							
6	R1	121	BENG	67		90	28			
7	R1	126	BENG	72		34	12			
8	R2	210	BENG/CAT				97			
9	R2	312	BENG	144	45	72	0	0		
11	R2	509	BENG		9.05				0.03	
12	R2	514	BENG	50.37	3.79	59.12	67.35		0.11	
13	R2	603	BENG	63.31	31.82	26.73	8.41		0.18	
14	a	111	MAG		68			41	10.72	
15	a	114	BENG							
16	a	118	MAG							
17	a	120	MAG							
18	a	126	MAG/CAT							
19	a	127	MAG/CAT							
20	a	128	MAG/CAT							
21	a	129	MAG/CAT							
22	a	201	MAG/CAT							
23	a	208	CATIE							
24	a	210	BENG/CAT							
25	a	218	CATIE							
26	a	226	BENG	117	33	124	9	0		
27	a	312	BENG	106	13	107	1	0	0.01	
28	b	111	MAG							
29	b	114	BENG							
30	b	120	MAG							
31	b	126	MAG/CAT							
32	b	127	MAG/CAT							
33	b	128	MAG/CAT							
34	b	129	MAG/CAT							
35	b	201	MAG/CAT							
36	b	208	CATIE							
37	b	210	CATIE							
38	b	226	BENG		83	118	47	8		
39	c	111	MAG	64	99	40	49	1	0.3	
40	c	114	BENG							
41	c	120	MAG							
42	c	127	MAG/CAT							
43	c	128	MAG/CAT							
44	c	129	MAG/CAT							
45	c	201	MAG/CAT							
46	c	208	CATIE							
47	c	210	CATIE							
48	c	218	CATIE							
49	c	226	BENG	83	20	33	39	0	0.01	
50	c	312	BENG	89	79	41	38	0	0.01	
59	e	120	MAG							
60	e	126	MAG/CAT							
61	e	128	MAG/CAT							
62	e	201	MAG/CAT							
63	e	208	CATIE							
64	x	126	MAG/CAT							

CONTINUED LIST

nr.	code	dte	LAB	TIC	Si	Cl	SO4	Al	PO4	Mn
68	1	219	BENG/CAT	95	35	155	106	0	0.03	
69	1	222	BENG/CAT	63.31	36.27	52.74	4.56	0.4		
70	1	317	BENG	286						
71	1	322	BENG	117	37	636	20	0	0.01	
72	1	323	BENG							
73	1	329	BENG	117	40	214	29	0	0.04	
74	1	330	BENG							
75	1	401	BENG			140	53			
76	1	408	BENG			125	39			
77	1	413	BENG							
78	1	415	BENG							
79	1	420	BENG							
80	1	426	BENG	56.84	50.87	125.7	11.62	0		
81	1	427	BENG	69.79	49.93	66.58	63.67	0	0.1	
82	1	428	BENG	71.41	50.12	81.15	61.69	7.21	0.02	
83	1	505	BENG	77.89	53.51	71	39.87	0		
84	1	506	BENG		50.12	59.7	44.03	0	0.17	
85	1	507	BENG		49.93	80	29.19	1.79		
86	1	510	BENG	69.79	55.4	80.1	33.95	2.2		
87	1	531	BENG	79.51	72.15	69.01	15.37	0	0.01	
88	1	601	BENG		51.06	51.83	46.77	0	0.01	
89	1	603	BENG		62.79			23.19	0.05	
90	1	604	BENG	56.84	55.02	59.46	41.98	0	0.03	
91	2	219	BENG/CAT							
92	2	222	BENG	79.51	202.4	76.84	10.44	0	0.14	
93	2	316	BENG	139	178	70	5	0	0.01	
94	2	317	BENG	199		132	161			
95	2	318	BENG	100		88	20			
96	2	322	BENG	150	153	62	2	0	0.09	
97	2	330	BENG	100	183	66	8	0	0.05	
98	2	401	BENG	78	185	63	3	0		
99	2	408	BENG	94	185	62	3	0		
100	2	413	BENG	139		60	39			
101	2	415	BENG							
102	2	420	BENG	172		88	48			
103	2	426	BENG	105.5	205.5	0	6.87			
104	2	427	BENG							
105	2	428	BENG		211.1	82.79	5.46	55.69	0.02	
106	2	505	BENG	88.26	210.7	0	6.87	0		
107	2	507	BENG		212.2	40	524.6	4.64	0.09	
108	2	510	BENG		212.8	69.55	0	5.26	0.01	
109	2	531	BENG	129.8	200.3	85.86	48.9	2.42	0.02	
110	2	601	BENG		220.7			3.87	0.04	
111	2	603	BENG		226	71.86	0	86.69	0.04	
112	3	323	BENG	776	127	464	64	0	0.36	
113	3	330	BENG	807	132	459	44	0		
114	3	408	BENG	637	121	377	33	0		
115	3	426	BENG	242.2		243.3	49.18	0	0.02	
116	3	428	BENG		128.9			34.52	0.04	
117	3	505	BENG		112.7	197.1	36.56	1.12	0.01	
118	4	323	BENG	383	119	95	75	0	0.02	
119	4	330	BENG	367	125	112	33	0		
120	4	408	BENG	345	129	281	50	0		
121	4	415	BENG	480	139	171	46	0		
122	4	426	BENG		161	77.76	66.57	142.2	0.07	
123	4	428	BENG		148.8			102.7	0.08	

CONTINUED LIST

nr.	code	dte	LAB	TIC	Si	Cl	SO4	Al	PO4	Mn
132	5	318	BENG			158.6	46.17		0.02	
134	5	322	BENG		221.6	99.99	85.03	0		
136	5	323	BENG		193.8	110.7	63.19	0	0.02	
138	5	329	BENG		217.4	96.47	78.47	0		
140	5	330	BENG		187.4	60.36	64.26	3.63		
141	5	401	BENG		197.1	78.89	71.97	0.5		
142	5	401	BENG		159.8	222.3	115	0		
143	5	408	BENG			72.96	54.03			
144	5	408	BENG			128.6	113.4		0.4	
145	5	426	BENG/CAT		157.7	242.3	67.56	0	0.03	
147	5	427	CATIE	82.75		68.43	8.42		0.42	
148	5	531	BENG		143.5	325.7	77.69	0		
150	5	603	BENG		126.1	17.77	163.4	0	0.29	
151	5	603	BENG			6.05	52.33			
153	5	604	BENG							
154	6	219	BENG/CAT	965	398	44	29	0	0.28	
155	6	219	BENG/CAT	863	373	81	56	0	0.16	
156	6	222	BENG/CAT			59.77	8.68			
157	6	222	BENG/CAT		258.9	285.8	40.69	0		
159	6	316	BENG		408.6	189.3	116.8	1.8		
163	6	318	BENG		424	87.17	10.51	0.06		
164	6	318	BENG							
165	6	322	BENG		423.2	88.62	18.02	1.58		
166	6	322	BENG		394.2	242.9	14.13	0		
167	6	323	BENG			70.81	16.96			
168	6	323	BENG		388.7	228.8	13.07	0		
171	6	330	BENG		436.4	59.77	11.01	0		
172	6	401	BENG		430.4	204.6	11.29	0	0.01	
173	6	401	BENG		443.7	59.06	12.79	0		
174	6	408	BENG		451.3	40.29	8.4	0		
175	6	408	BENG		429.3	175.5	9.96	0		
176	6	413	BENG		424	113.8	12.84	0		
177	6	413	BENG			23.69	4.91			
178	6	415	BENG			28.23	5.34			
179	6	420	BENG			79.6	14.8		1.83	
180	6	420	BENG			19.23	4.79			
181	6	426	CATIE		395.5	83.27	16.63	0		
182	6	427	CATIE			0	18.18			
183	6	428	CATIE							
184	6	531	BENG		378.5	89.13	29.79	44.69	0.06	
185	6	531	BENG		421.6	54.48	21.56	3.56		
187	6	603	BENG		278.3	0	45.56	0.27	0.02	
188	6	604	BENG						0.05	
203	8	322	BENG		183.6	307	60.83	0	0.95	
204	8	401	BENG		145.4	368	2.18	0.6	0.01	
205	8	408	BENG		143.9	288.9	1.69	6.15		
206	8	420	BENG						0.28	
207	8	420	BENG			130.9	17.08		0.4	
210	8	603	BENG						0.03	
211	8	604	BENG			23.85	54.07		0.45	
212	8	604	BENG						0.49	

CONTINUED LIST

nr.	code	dte	LAB	TIC	Si	Cl	SO4	Al	PO4	Mn
213	9	323	BENG	579	183	177	133	0		
214	9	408	BENG	884	192	183	47	0	0.01	
215	9	415	BENG	725		151	39			
216	9	426	BENG		506.4	102.4	11.5	4.67	2.09	
217	9	428	BENG		196.6	257.4	343.8	0	0.76	
218	9	428	BENG		459.8	167.7	34.81	2.3	0.07	
219	9	505	BENG		155.6	105.9	47.91	1.81	0.02	
220	9	505	BENG		464.4	158.4	20.9	0.42	0.01	
221	9	603	BENG		561.7	156.1	24.94	0	0.08	
222	9	603	BENG		494.6	118.2	27.64	4.92	1.18	

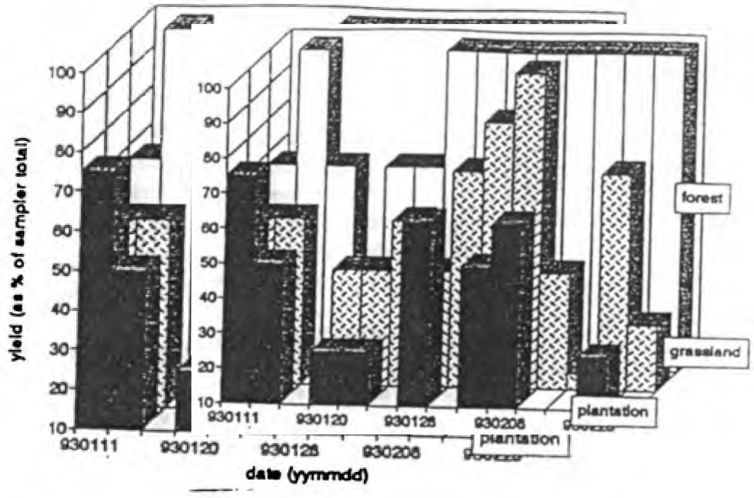
CONTINUED LIST, 'CONTAMINATED' SAMPLES

nr.	code	dte	LAB	TIC	Si	Cl	SO4	Al	PO4	Mn
10	R2	425	BENG			12773	0		0.03	
51	d	111	MAG		178			8	8.56	7
52	d	111	MAG	72	93	104	47	51	0.38	2
53	d	128	MAG							
54	d	201	MAG/CAT							
55	d	208	CATIE							
56	d	226	BENG	172	130	543	218	41		
57	e	111	MAG							
58	e	114	BENG	54	60	29	40	2	1.4	2
124	5	219	BENG/CAT	177	245	362	89	1		
125	5	219	BENG	410	176	2140	29	0		
126	5	222	BENG/CAT		281.5	561.8	109.1	0	0.04	
127	5	222	BENG/CAT		241.3	2250	106.2	0		
128	5	316	BENG		119.5	416.3	35.48	1.37	0.01	
130	5	317	BENG		232.6	547.1	58.78	0		
131	5	317	BENG			167.2	54.81		0.1	
133	5	318	BENG		232.6	645.8	62.85	0		
135	5	322	BENG		257.8	225.3	259.9	0		
137	5	323	BENG		240.9	574.6	71.39	0		
139	5	330	BENG		241.1	204.9	66.9	0.56		
146	5	426	BENG/CAT		163.7	964.7	44.25	0		
149	5	531	BENG		220	427.6	111.9	0		
152	5	604	BENG			20.27	103.5			
158	6	316	BENG		393.9	77.78	23.48	2.08		
160	6	317	BENG			94.05	21.92		1.45	
161	6	317	BENG			113.3	18.24		0.85	
162	6	318	BENG			147.2	27.11		0.1	
169	6	329	BENG		428.2	64.32	12.06	0		
170	6	330	BENG		393.7	179.9	15.18	0.44		
186	6	603	BENG						0.06	
189	7	219	BENG/CAT		204.2			9.11		
190	7	316	BENG			700.9	603.8		1.45	
192	7	318	BENG		191.5	20.57	121.6	0		
193	7	322	BENG		205.9	430.7	37.88	0		
194	7	322	BENG		255.3	2803	0	0		
195	7	323	BENG		231.9	1806	255.7	11.78		
196	7	329	BENG		219.6	1340	0	36.51		
197	7	329	BENG		194.9	154.3	36.77	0	0.04	
198	7	401	BENG			136.2	28.67		0.03	
199	7	401	BENG		204.6	825.5	11.79	3.16	0.03	
201	7	420	BENG						0.28	
202	8	219	BENG/CAT		118.7			7.3		
208	8	426	BENG/CAT			0	9.68			
209	8	531	BENG		152.1	363.1	8.62	0		
191	7	317	BENG		169.1	7226	1889	5.31		

Annex 5.2 Sampling drawbacks

Soil moisture sampling was often restricted by drought and malfunctioning apparatus. In order to obtain a soil moisture sample the suction of the sampling apparatus should exceed the pF of the soil. No problems were expected meeting this requirement, since vacuum bottles were always evacuated for at least 70%, and the soils under investigation are tropical, with theta values ranging up to 0.95 (!). Nevertheless, drought turned out to be a problem.

The LLA palmheart plantation was observed to be always drieer than the grassland, which was in turn drieer than the forest. This pattern recurs in the sampler yields. (see annex 5.1 and figure 5.1.1.)



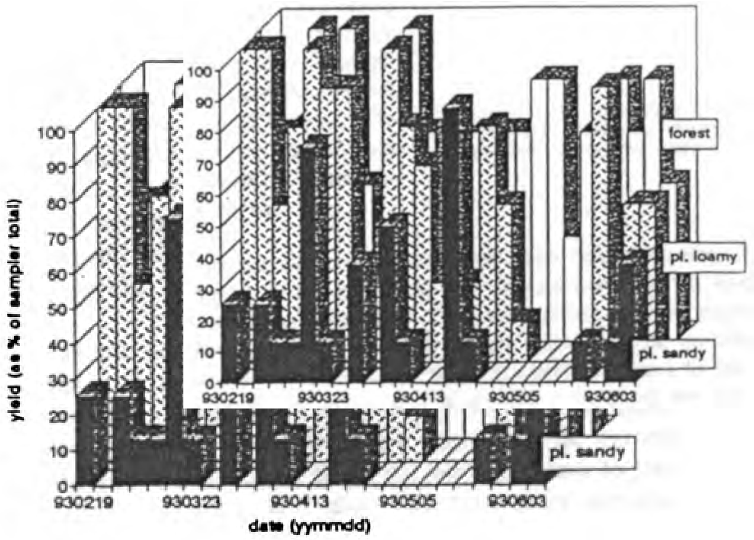


Figure 5.1.1 a. LLA sampler yield

Figure 5.1.1 b. LSS sampler yield

The dryness of the palmheart plantation seemed especially pronounced at the measuring site itself. A main reason for this was found in the rain interception characteristics of the site.

Young palmheart palms are usually planted in rows with an aproximate 2 m interrow distance. During showers rain falling on the plants was observed to reach the soil for the greater part as stem flow or as crown drip, due to the characteristic shape of the young plants. This caused part of the soil under the palms to remain dryer. Since fertilizer is normally aplied in this drier zone, the sampling site was located there (fig 5.1.2). Unfortunately, this was discovered too late in the course of the LLA work to change it.

For LMS soils drought was most limiting in the sandy soils planted with banana. Sandy soil under forest was affected least by drought, less than loamy soils planted with banana. LMS grassland sampling was not limited by drought.

Considering the evaporation characteristics of the investigated landuse types and their resulting soil moisture capacity the problems described above are not surprising. Tropical forest retains water far better than a grassland, and plantations are known to have very high values of evaporation.

Rhizon samplers were limited in supply. They were expected to last within the soil for at least two months. This turned out to be an overestimation of the robustness of the equipment. Many samplers were destroyed by tropical soil biota, sometimes within days. The biota were most active shortly after a period of intense rainfall. Newly placed samplers lasted for several days, giving good yields, and then stopped functioning completely because of leaks. This problem was most severe at the forest sites. Sometimes up to one fifth of the porous polymer coating was eaten away. At La Lucha, sampling of the forest A-horizon had to be stopped, samplers being destroyed so quickly, that no yields at all were obtained.

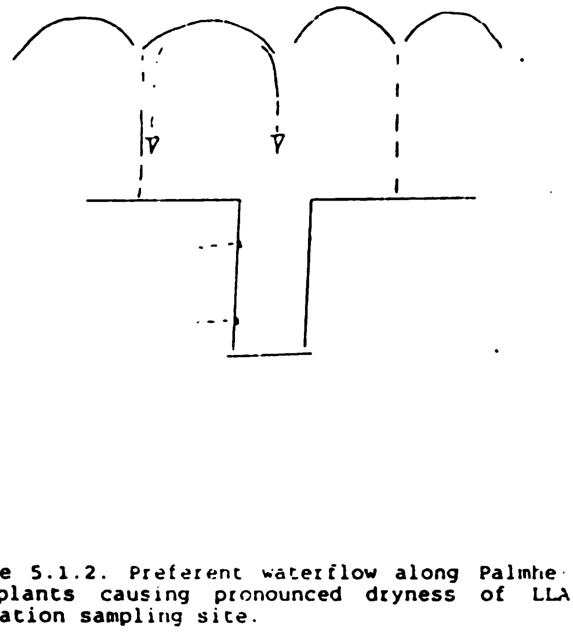


figure 5.1.2. Preferent waterflow along Palmheart plants causing pronounced dryness of LLA plantation sampling site.

Another source of soil moisture sampler trouble was bad manufacturing. The front of the tube, entering the soil (see Annex 3.1), is sealed by the manufacturer with a kind of resin. For sturdyness, samplers contain a stainless steel wire. This wire often already partly perforated the resin capping before the sampler had been used. Pressure applied while introducing the sampler into the soil, no matter how careful this was done, often caused samplers to be perforated. Perforated samplers lose vacuum slowly by air entry, and give very little yield. Air entry and vacuum loss in these samplers, still partly sealed by the wire, is so slow it can not, in contrast with large leaks induced by soil biota, be detected instantly. (Large leaks show on the vacuum pump manometer after bottles have been evacuated). According to manual instruction samplers should be allowed at least 24 hours to settle before they produce yield, so much time was lost with attempts to apply suction to leaking samplers.

Finally a simple and effective method, based on the old dutch tube repair method was conjured up to check samplers on suspected small perforation leaks. After introducing a sampling tube into the soil, the glass vacuumbottle attached to it was partly filled with distilled water, and subsequently evacuated. Turning over the bottle, possible entering air could immediatly be seen as small bubbles coming from the needle tip. Applying this little test, the above described leaking was found to occur far more often than suspected. About 40% of the samplers turned out to leak immediately after introduction, some of them even due to small airholes in the porous polymere material itself (bad manufacturing). Potentially leaking samplers had all been badly sealed with the resin. Several materials were tried to provisionally reseal these samplers, before use. The best material turned out to be the Canada Balm normally applied to prepare microscope samples. Samples obtained from thus treated samplers did not show anomalies in any of the elements analyzed on.

It is advisable for future researchers using the same sampling equipment under similar circumstances, to take some similar resin material with them. While repairing or preparing a sampler, the diameter of a provisionally applied cap should of course not exceed the tube diameter. This leads to problems when introducing the sampler into the soil(The hole prepared for the sampler should be as small as possible, to allow the best possible contact between soil moisture and the sampler). If possible, a method for preventing sampler consumption by soil biota should be thought of.

Future soil moisture research of the area should be carried out in the rainy season, when rainfall distribution in time is more homogeneous. Best period is probably july - november.

Further problems:

Septum stopper bottles were at times (accidentally or on purpose) destroyed by local inhabitants and cattle.

During rainfall fertiliser was observed to be dispersed to the non-fertilized sites as well. On loamey sites this was very clear, fertilizer could effectively be monitored there by algae on the moist soil, even after the greater part of it had been dissolved.

Annex 5.4: Used data and calculations to verify low Ca/Mg ratio of weathering, calculated weathering stoichiometry and dissapearance rates of Si, Mg, Ca, Na and K

To verify the assumption that Mg is released out of the parent material in larger quantities than Ca, thus resulting in a low Ca/Mg ratio flux of solutes, soil profile data from the Attantic zone (Nieuwenhuyse (1995) and B.v.Ooijen and N.walraven(unpublished)) were used. Table 5.4.1 shows the calculations performed to obtain the required data.

table 5.4.1: Used data and calculations to verify low Ca/Mg ratio of weathering

Content of minerals in a soil profile time series, adapted from data by A.Nieuwenhuyse (profile means) and expressed as fraction of the initial content. ((100 - (original data))/100).

apparent age (ka)	SiO_2	MgO	CaO	Na_2O	K_2O	P_2O_5	Al_2O_3	Fe_2O_3	PROFILE
'0'	1	1	1	1	1	1	1	1	-
2	0.92	0.84	0.76	0.86	0.99	0.90	0.97	0.94	AT4
2.5	0.97	0.86	0.76	0.89	0.94	0.86	1.02	1.00	AT5
3.5	0.89	0.86	0.75	0.73	0.77	0.47	1.00	1.07	AT7
2?	0.86	0.83	0.73	0.69	0.91	1.69	0.98	1.02	YB
18	0.51	0.51	0.29	0.24	0.28	0.69	1.04	1.00	RPA
125	0.40	0.35	0.12	0.09	0.36	0.67	1.01	0.98	RF1
125	0.43	0.07	0.00	0.00	0.04	0.42	1.08	0.85	RF2
450	0.12	0.00	0.00	0.00	0.00	0.08	0.98	1.08	RCR

Calculated profile content of minerals expressed as percentage of oxide in the parent material.
Percentages of reference ('0'= 'fresh material') were taken from B. v.Ooijen and N. Walraven (the youngest profile)

apparent age (ka)	SiO_2 %	MgO %	CaO %	Na_2O %	K_2O %	P_2O_5 %	Al_2O_3 %	Fe_2O_3 %	PROFILE
'0'	48.7	2.91	1.87	1.69	1.16	0.27	22.3	8.73	-
'2'	44.8	2.44	1.42	1.45	1.15	0.24	21.7	8.20	AT4
2.5	47.2	2.50	1.42	1.50	1.09	0.23	22.8	8.73	AT5
3.5	43.3	2.50	1.41	1.23	0.89	0.13	22.3	9.34	AT7
2?	41.8	2.41	1.37	1.17	1.06	0.46	21.9	8.90	YB
18	24.8	1.48	0.54	0.41	0.32	0.19	23.2	8.73	RPA
125	19.4	1.02	0.22	0.15	0.42	0.18	22.6	8.55	RF1
125	20.9	0.20	0.00	0.00	0.05	0.11	24.1	7.42	RF2
450	5.84	0.00	0.00	0.00	0.00	0.02	21.9	9.42	RCR

table 5.4.1: Continued

Calculated content of oxides expressed as moles per 10 kg parent material.
(percentage / 100) / molar weight * 1000 * 10.
Profile AT4 is left out because of trendbreak.

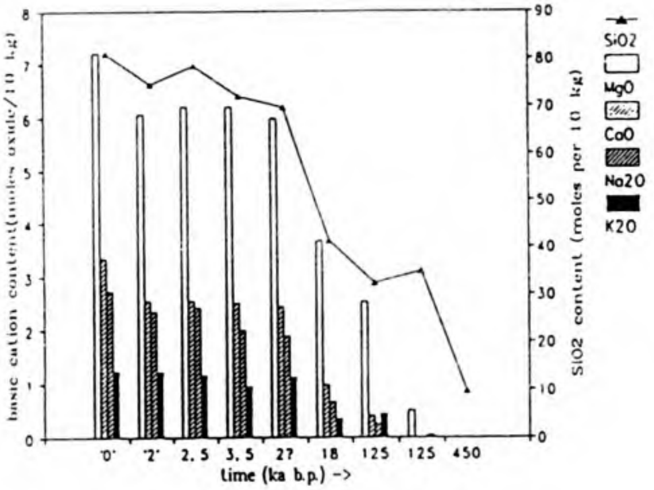
app. age (ka)	SiO_2	MgO	CaO	Na_2O	K_2O	P_2O_5	Al_2O_3	Fe_2O_3	PROFILE
'0'	81.0	7.2	3.3	2.7	1.2	0.2	21.9	5.5	-
2.5	78.5	6.2	2.5	2.4	1.2	0.2	22.3	5.5	AT5
3.5	72.1	6.2	2.5	2.0	0.9	0.1	21.9	5.9	AT7
2?	69.6	6.0	2.4	1.9	1.1	0.3	21.5	5.6	YB
18	41.3	3.7	1.0	0.7	0.3	0.1	22.8	5.5	RPA
125	32.4	2.5	0.4	0.2	0.4	0.1	22.1	5.4	RF1
125	34.8	0.5	0.0	0.0	0.0	0.1	23.7	4.6	RF2
450	9.7	0.0	0.0	0.0	0.0	0.0	21.5	5.9	RCR

Calculated cumulative loss of oxides (moles/10 kg) from parent material with progression of time, relative to fresh material contents. For the sake of comprehensiveness, profile YB was given an age of 5 ka.

substituted age (ka)	SiO_2	MgO	CaO	Na_2O	K_2O	P_2O_5	Al_2O_3	Fe_2O_3	PROFILE
'0'	-	-	-	-	-	-	-	-	-
2.5	2.4	1.0	0.8	0.3	0.1	0.0	-0.4	0.0	AT5
3.5	8.9	1.0	0.8	0.7	0.3	0.1	0.0	-0.4	AT7
5	11.3	1.2	0.9	0.8	0.1	-0.1	0.4	-0.1	YB
18	39.7	3.5	2.4	2.1	0.9	0.1	-0.9	0.0	RPA
125	48.6	4.7	2.9	2.5	0.8	0.1	-0.2	0.1	RF1
150	46.1	6.7	3.3	2.7	1.2	0.1	-1.8	0.8	RF2
450	71.2	7.2	3.3	2.7	1.2	0.2	0.4	-0.4	RCR

				calculated weathering stoichiometry from calculated cumulative loss				
age (ka)	calculated release of CaO/MgO	subs. age (ka)	Si/Si	Mg/Si	Ca/Si	Na/Si	K/Si	PROFILE
2.5	0.79	2.5	1	0.42	0.33	0.12	0.03	AT5
3.5	0.83	3.5	1	0.11	0.09	0.08	0.03	AT7
5	0.74	'5'	1	0.11	0.08	0.07	0.01	YB
18	0.67	18	1	0.09	0.06	0.05	0.02	RPA
125	0.63	125	1	0.10	0.06	0.05	0.02	RF1
150	0.50	150	1	0.15	0.07	0.06	0.03	RF2
450	0.46	450	1	0.10	0.05	0.04	0.02	RCR
mean	0.66		100	15.3	10.6	6.9	2 .2	= mean x 100

As becomes clear from table 5.4.1, during Andisol formation and the subsequent degradation to oxisols, Atlantic Zone volcanic material looses large amounts of Si and basic cations. The apparent weathering stoichiometry of Si : Mg : Ca : Na : K is 100 : 15 : 11 : 7 : 2 on the average. For young soils, in the age range of the LMS soils, the stoichiometry of weathering Si : Mg : Ca : Na : K is higher, approximately 100 : 30 : 20 : 10 : 3. The Ca/Mg ratio of the released solutes is always lower than 1, as expected. Figure 5.4.1 a, b and c and table 5.4.2. show that the evolution of Si and basic cation content of the soil profiles vs. time can be expressed as first order reactions, indicating that the rate determining step is a first order reaction. Table 5.4.2 shows calculated reaction rates.



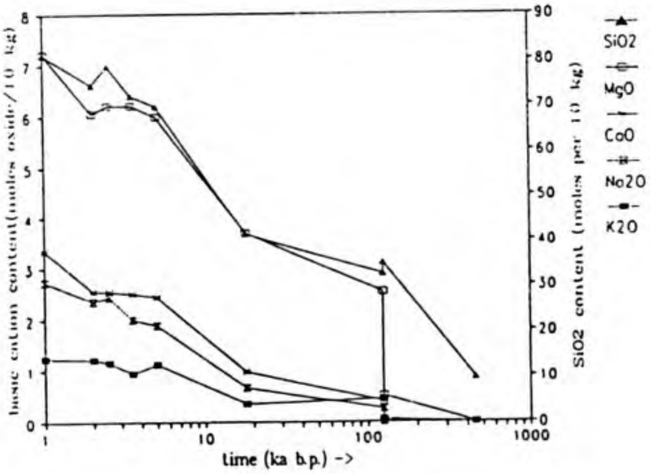


figure 5.4.1. a. Content of Si and basic cations of a number of Atlantic Zone soil profiles versus time.

figure 5.4.1. b. Content of Si and basic cations of a number of Atlantic Zone soil profiles versus the logarithm of time. Data appear to fall on a straight line, indication to the fact that the rate determining step is a first order reaction.

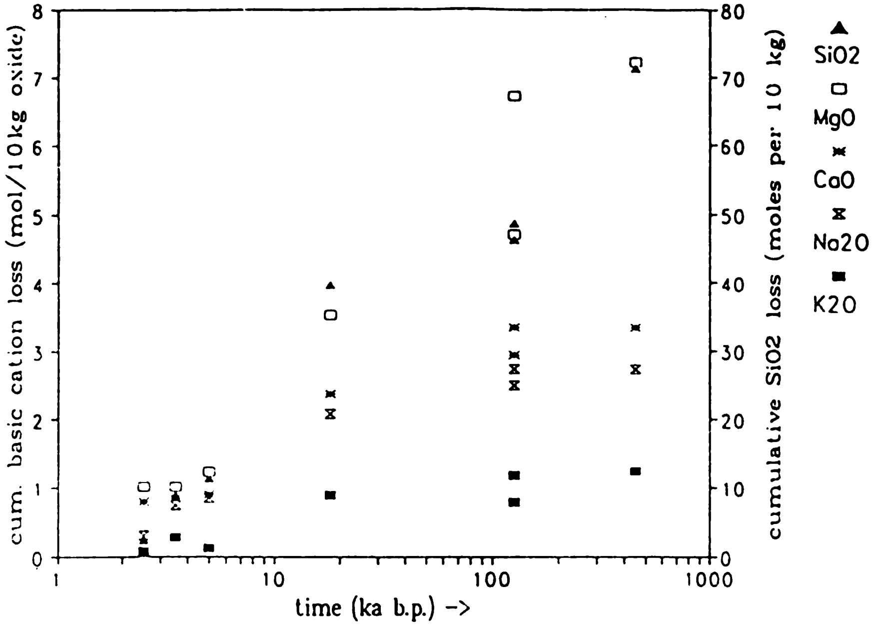


figure 5.4.1. c. Cumulative loss of Si and basic cations from a number of soil profiles versus the logarithm of time.

<u>table 5.4.2: Calculated regression equations and reaction rate constants.</u>

regression equation. y = a * x + b
y = Calculated cumulative loss of oxides (moles/10 kg), x = logarithm of time
regression parameters

	SiO_2	MgO	CaO	Na_2O	K_2O
b	0	0	0	0	0
a	23.158	2.664	1.550	1.292	0.486
R^2	0.907	0.904	0.947	0.942	0.790
S in a	1.888	0.218	0.079	0.073	0.063
S in b	6.353	0.732	0.265	0.247	0.211

loss of mineral oxide = k * ln (t). k = a / 2.303

k	10.06	1.16	0.67	0.56	0.21

the last datapoint (450 ka) was not included in the calculation, because oxide contents may have reached zero before this time

The rate constants found in table 5.4.2. confirm not only the weathering stoichiometry of table 5.4.1., they also suggest that the release rate of Mg is always higher than the rate of Ca release. This is consistent with the main mineral composition of volcanic ash. The main Mg phase is Augite, a highly weatherable Pyroxene. The main phase of Ca and Na are Anorthite and Albite, whereas the main K phase is believed to be Microcline. The found weathering rates are in agreement with the normal weatherability order of the above mentioned minerals, that is an expression of their connectivity degree: Augite > Anorthite > Albite > Microcline. Less carefull examination of weathering data has led to the suggestion that the apparent quicker dissapearance of Ca out of the mineral soil is due to the formation of iron oxide coatings on Augite minerals during weathering, that inhibit a fast weathering of this mineral. The found reaction rates suggest that there is no need for this explaining mechanism.

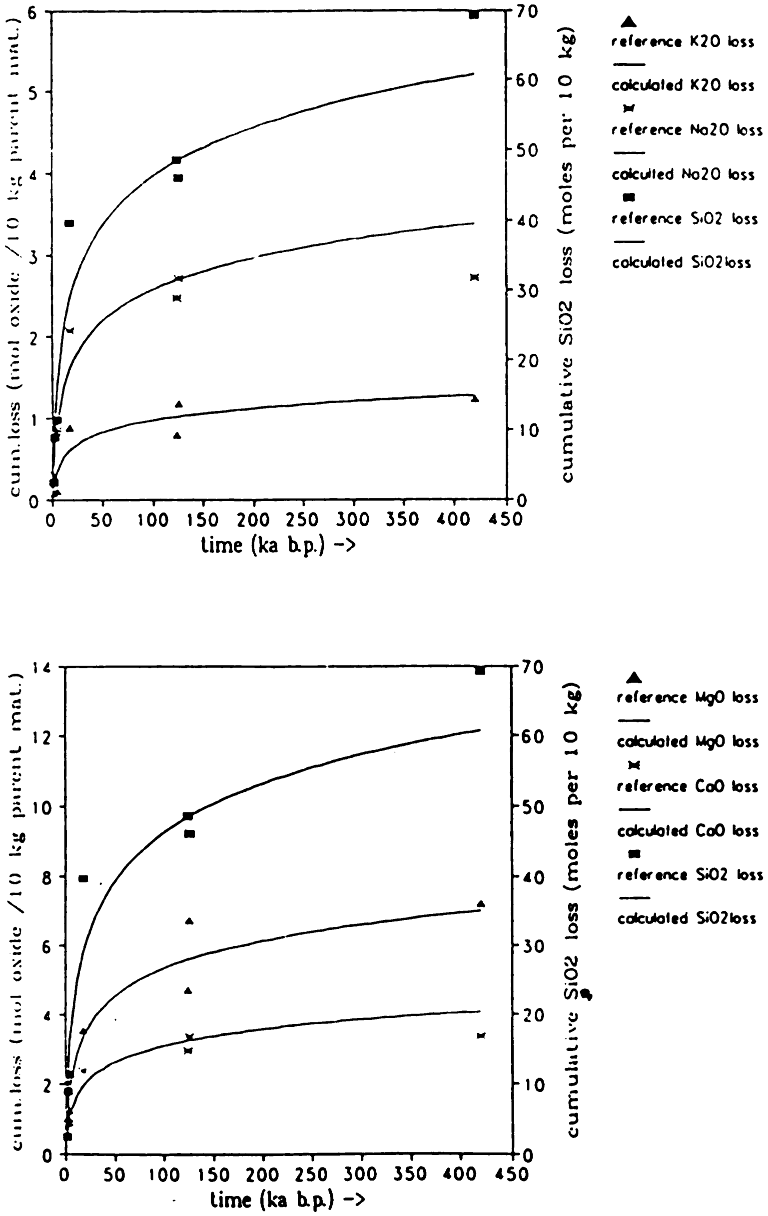


figure 5.4.2. Calculated disappearance of Si and basic cations with the found reaction rate constants.