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Inputs and pathways of nutrients in a watershed in western Côte d'Ivoire. A comparison between forest and cocoa plantations

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Abstract

It is the aim of the Taï Region Project on Hydrology to identify nutrient pathways and matter fluxes as well as to determine agricultural influences on the water and nutrient cycle within a small tropical catchment. In comparing the results of different measuring sites (primary forest, two cocoa plantation 7 years and 25 years under cultivation), the respective nutrient inputs, pathways and exports will be surveyed, starting off with open field and throughfall precipitation, and then looking at the non saturated zone to ground water and the surface water export. Furthermore, an attempt is made to develop an innovative method based on physical and chemical parameters to assess water quality of tropical rivers.
Preliminary findings of major cation concentrations are presented describing the chemical profiles of the major cations potassium, calcium, magnesium and sodium. These profiles can provide good indications concerning possible sources and sinks and help to detect general differences between the three investigation plots. Calcium, magnesium and especially potassium are assumed to be the major leaching nutrients within the canopy layer and are additionally provided through litter input. Concerning their courses in the non-saturated zone the cations show differing tendencies due to vegetation characteristics, specific soil properties, nutrient uptake, mineral weathering and interactions between the nutrients.

Introduction

The Taï National Park in Western Côte d'Ivoire is one of the last great areas of undisturbed evergreen rain forest in West Africa which has been declared to World Heritage Site in 1972. The main effort of all integrated organizations and administrators is to protect and maintain the frontier between the National Park and the surrounding zone. This transition area is dominated by plantations of small farm holders and most notably stressed by an increasing human pressure.
In contrast to outspreading of plantations or poaching activities, the inland waters are not to be delimitated by a human-drawn border. The watersheds of the two main rivers of the Taï National Park (Hana and Meno) and lots of smaller creeks go beyond the borders of the Park. Within groundwater and surface waters both, nutrients and pollutants, are entering the ecosystem. For that reason, the subject of substance input is of utmost importance and is the main object of the investigation introduced subsequently in the following:

The investigation mainly aims at characterizing the nutrient pathways encompassing open field precipitation, throughfall precipitation, soil water, ground water and surface water export. Further aims are the comparison between nutrient pathways of forest and cacao plots in order to determine the influence of agriculture within the ecosystem and the theoretical approach to develop an innovative method to assess water quality of tropical receiving streams based on physical and chemical parameters (FISCHER & GEROLD 2001).

Investigation Site

The investigation site is located in western Côte d'Ivoire at the border of Taï National Park where the receiving stream (Hana) enters the forest (5°50' N/6°50' W). The total watershed of the Hana comprises a total area of approximately 5000 km² and is mainly covered with deciduous primary rain forest, whereas the part of the watershed focused on in this study has an area of about 55 km² and is dominated by agriculture (figure 1).

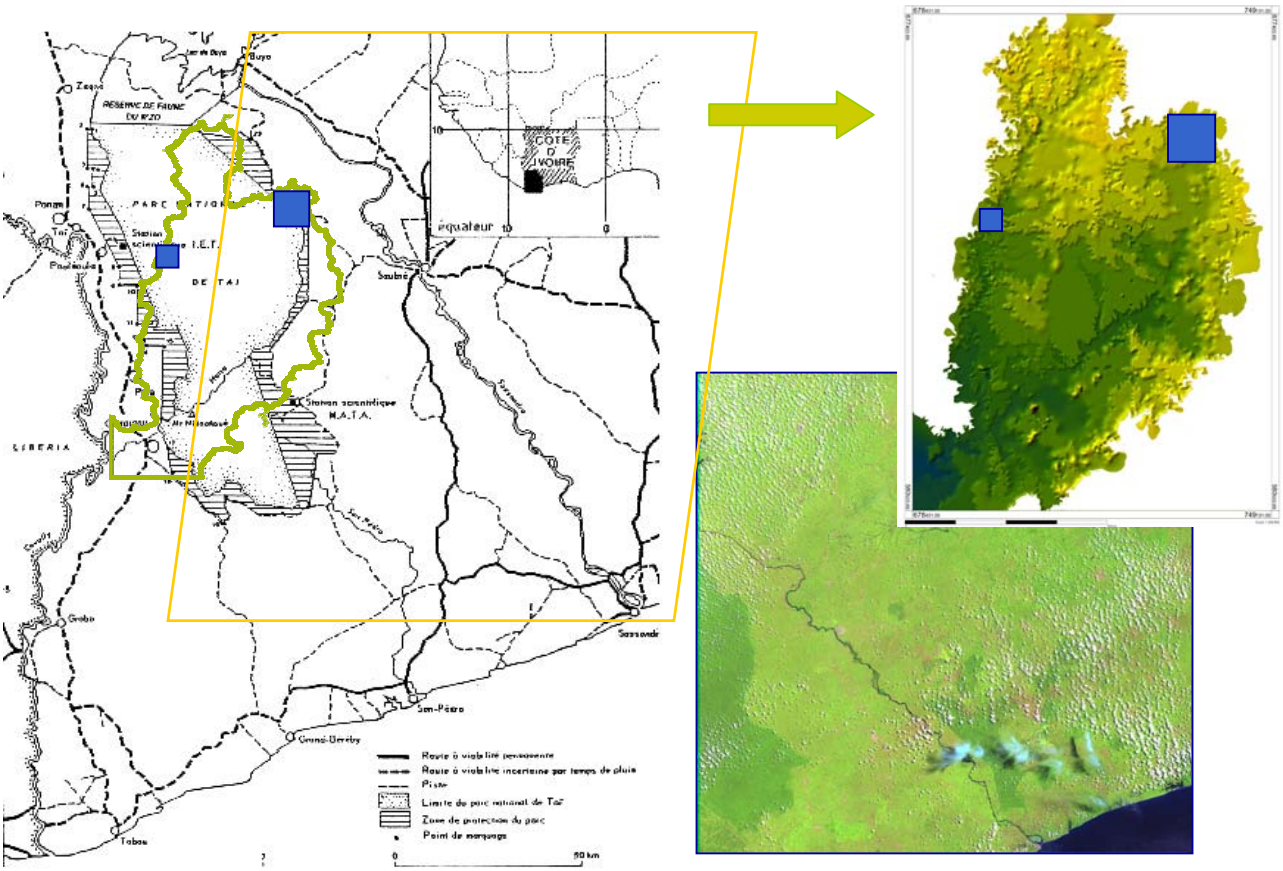

Figure 1: Location of the investigation site (modified according to Riezebos et al. 1994)
Digital elevation model of the Hana watershed (dist. 50 m) and satellite view.

The subequatorial climate is characterized by an annual precipitation amount of 1590 mm (Soubré region, A.N.A.M. 1987) and an annual precipitation of 1750 mm in 2002 at the investigation site, respectively.

The topography is a peneplain partly interrupted by inselbergs declining from 225 to 50 m asl from the north to the south of the National Park.

The geology is marked by chlorinated micaceous schists partially associated with granodioritic intrusions and mineralizations of gold and tungsten (PAPON 1973; AHIMON 1990). Soil differentiation depends on topography (plain-valley-catena) between Ferralsols, Acrisols, Cambisols and Gleysols (FAO classification) (STOORVOGEL 1993, RIEZEBOS ET AL. 1994, MUND & SZÖCS 2001). Within the main site, soils have been classified depending on base saturation as dystric or eutric Cambisols.

Cocoa plantations with an average cultivation area of 6.5 ha/planter and an average age of the plantations of 19 years dominate the agriculture. To guarantee sufficient yield profits despite the old age of most cocoa plantations the intensified application of fertilizers and pesticides is obligatory (FISCHER ET AL. 2002). Other cash crops are coffee, hevea and oil palms and annual crops are rice, maize, yams, bananas, manioc, tarot, tomatoes, haricots etc. A vegetation and land use classification based on Landsat-7 ETM+ (2001) has been carried out covering an area of 3250 km² (SÜLTMANN 200). The classification showed with an overall accuracy of 97 % matching the test plots in the supervised classification that 49 % of soils are occupied either with cocoa and coffee, followed by hevea (11 %) and oil palms (2 %). An additional change detection analysis comparing the conditions of 2001 with those of 1986 (Landsat 5 ETM – overall accuracy of the supervised classification 92 %) recorded an increase of cocoa/coffee areas of more than 9 % mainly deriving from former forest areas (8.9 %) (SÜLTMANN et al. in preparation).
These results concerning dominating cocoa and coffee crops could be confirmed by SACHAU (2003) by interviewing the people of two villages within the main investigation site (Azoumanakro and Soubré 3). In the past, coffee dominated the cash crops within this region but has been constantly replaced by cocoa due to better economic value and lower labour-intensity. Currently, all farmers are planting cocoa, 18 % of them have additional coffee plantations. The cocoa plantations partly reach an age of 30 years and should be replanted, even though the yield profits are not assumed to improve significantly because of low soil fertility.

Within the main site three investigation plots have been installed (figure 2). As they represent the dominating cultures within the catchment area two cocoa plantations (7 and 25 years under cultivaton respectively) as well as one forest site within the National Park have been selected. Each of the plots is equipped with sampling units on throughfall precipitation, soil water and the top layer of groundwater. At each site a characteristic soil profile has been recorded. Two further plots have been selected for the sampling of open field precipitation and the daily quantification of rainfall amounts. At the gauging station the receiving stream has a mean runoff of 190 l/s. An automatic sampler gains regular and event-based samples and a multiparametric sonde registers water level, water temperature, pH, electric conductivity and dissolved oxygen.

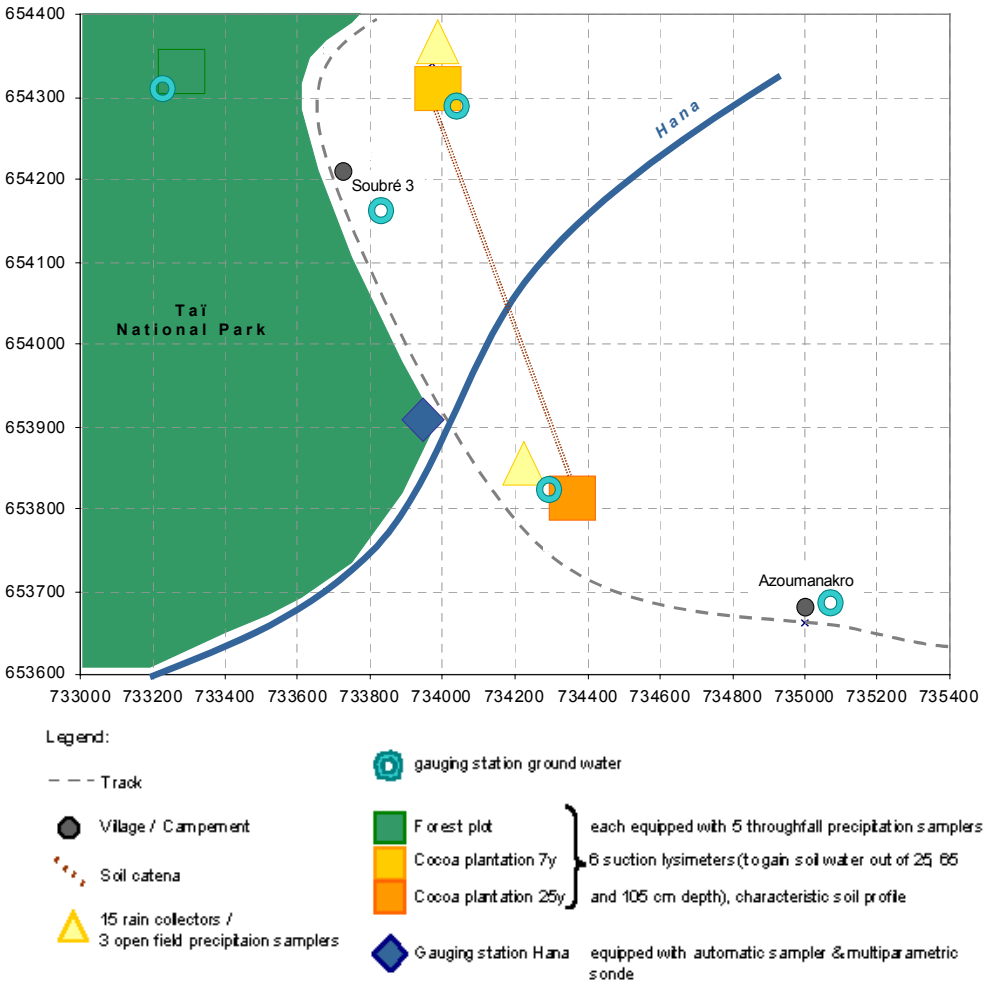

Figure 2: Location and instrumentation of the investigation plots

Material and Methods

Basic data concerning land occupation, soils and households are acquired by means of a land use classification based on satellite images and the application of agrochemicals by interviewing the local farmers.

The sampling routine of the different measuring plots are developed in order to compare the nutrient inputs and pathways within the different plots:
Besides the daily quantification of precipitation rates, weekly samples of open field and throughfall precipitation, soil water and groundwater are taken. The soil water stations consist of suction cups installed at depths of 25, 65 and 105 cm respectively as well as one central collecting unit. The depths of the cups reflect the different horizons of the soil profiles, assuming that beyond a depth of 105 cm most of the water is drained to the groundwater. An automatic sampler gains samples of the receiving stream 3 to 5 times a week and event-based samples at rising or declining water level.
All samples are analyzed concerning various parameters as water temperature, electric conductivity and pH (*in situ* / on the spot), phosphate, ammonium, nitrate, sulfate und chloride – (Project laboratory unit Soubré), elemental analysis (including aluminum, calcium, iron, potassium, copper, magnesium, manganese, sodium, total phosphorous, sulfur, silica and zinc) (Laboratory Göttingen via ICP-OES, Inductively Coupled Plasma Related Optical Spectroscopy), Total Organic Carbon (TOC), Dissolved Organic Carbon (DOC) and Total Nitrogen bound (TNb)

(Laboratory Göttingen, TOC Analyzer). Concerning the receiving stream these parameters are complemented by discharge, suspended load, content of dissolved oxygen and oxygen saturation.

Results and Conclusions

In the following, preliminary findings of major cation concentrations are presented referring to the sampling period between December 2001 and April 2003. The results describe the chemical profiles of the vertical nutrient fluxes with the major cations potassium, calcium, magnesium and sodium encompassing:

P	Open field precipitation
TF	Throughfall precipitation
SW 25	Soil Water, 25 cm depth
SW 65	Soil Water, 65 cm depth
SW 105	Soil Water 105 cm
GW	Groundwater
RS	Receiving Stream (Hana)

Potassium

The nutrient profile of potassium at the forest plot shows a significant increase from open field precipitation (0.4 ppm) to throughfall precipitation (4.4 ppm) due to leaching effects within the canopy layer. Within the non-saturated zone, a decrease of potassium concentration because of nutrient uptake is notable (1.9 to 0.2 ppm) which is followed in a slight increase of values from soil water to groundwater (0.7 ppm) and the receiving stream (1.6 ppm) attributed to mineral weathering and direct input of organic material by dense river bank vegetation.
In comparing the forest plot with the 7 year old and the 25 year old cocoa plantation respectively, first of all higher leaching rates within the canopy layer can be detected reaching up to a maximum mean value of 6.9 ppm at the younger cocoa plantation as well as lesser inputs of potassium via litter and/or a more rapid decrease of concentration within the non-saturated zone.
Concerning the differences between the two cocoa plantations tree densities as well as rainfall distribution have to be taken into account. The varying tendencies of potassium paths within the soil water are due to the different soil conditions and the proportions of potassium and calcium/magnesium competing for ion exchange sites especially in case of K-fixation in the presence of illites and vermiculites.
Additionally, the differences of K inputs in litter have to be considered. As shown by GEROLD & HETZEL (1998) and HETZEL (1999) in comparing a cocoa plantation with a semideciduous rain forest in eastern Côte d'Ivoire, forest litter provided about 96 kg K/ha/a and the cocoa litter 73 kg K/ha/a. Concerning the K root uptake, the differences are even more obvious: forest root uptake has been up to 5 times higher than cocoa root uptake.
Taking into account soil properties, higher leaching rates at the cocoa plots are expressed in lower cation exchange capacities ($CEC_{eff.}$) in the subsoil (forest 18.0 / cocoa 7y 15.3 / cocoa 25y 11.5 $cmol_c/kg$). The analysis of the three characteristic profiles led to available potassium contents of 1.9 $cmol_c/kg$ at the forest plot, 1.3 and 1.1 $cmol_c/kg$ at the younger and older cocoa plot respectively. These values directly reflect the differences between the soil water concentrations.

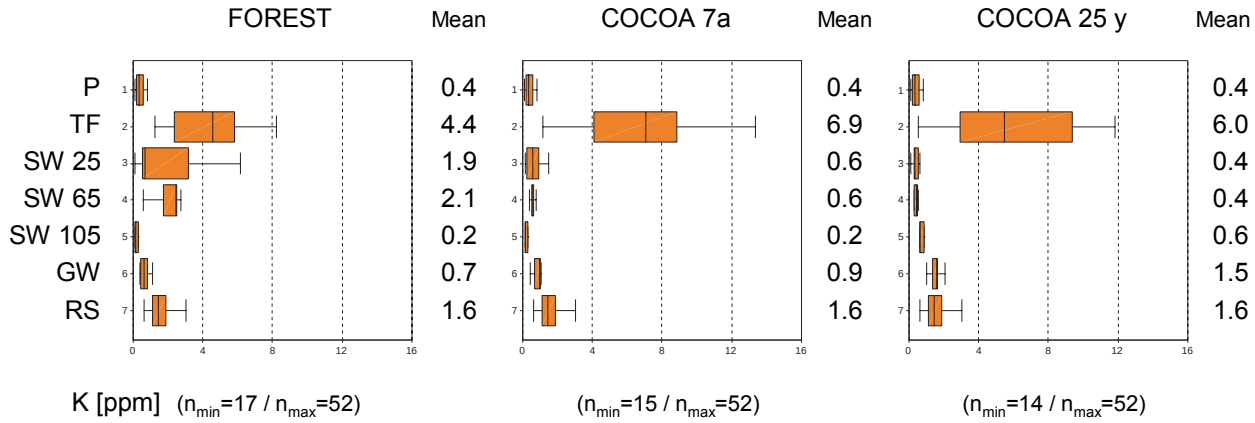

Figure 3: Potassium concentrations [ppm] at the three investigation plots (median, minimum/maximum, 25th and 75th percentiles and mean values)

Calcium

The calcium concentrations show a slight increase of concentration from open field precipitation (0.5 ppm) to throughfall precipitation again with maximum mean values at the younger cocoa plantation.

Following the chemical profile from soil water in 25 cm depth to 105 cm, differing tendencies are given. Whereas at the forest and the younger cocoa plot first a slight increase and then decrease can be noted, the highest mean value is detected in the 25 cm level of the 25 year old cocoa plantation (5.7 ppm) - continuously decreasing to 105 cm (1.1 ppm). To explain these tendencies, litter inputs, a selective nutrient uptake and the soil conditions within the specific horizons have to be considered. HETZEL (1999) calculated for a semideciduous forest an input of Ca with litter of 172 kg/ha/a whereas at the cocoa plantation litter input of Ca is only 92 kg/ha (with corresponding Ca root uptakes of 126 kg/ha/a concerning the forest stand and 43 kg/ha/a at the cocoa plantation).

Low values within groundwater reaching from 0.2 ppm at the forest plot to 1.6 ppm at the 7 year old cocoa plantation are taken over by a concentration of 3.9 ppm within the receiving stream. This value relatively elevated compared to the other compartments of the chemical profile is not only due to canopy leaching and litter input but as well due to mineral weathering in deeper soil layers and strata.

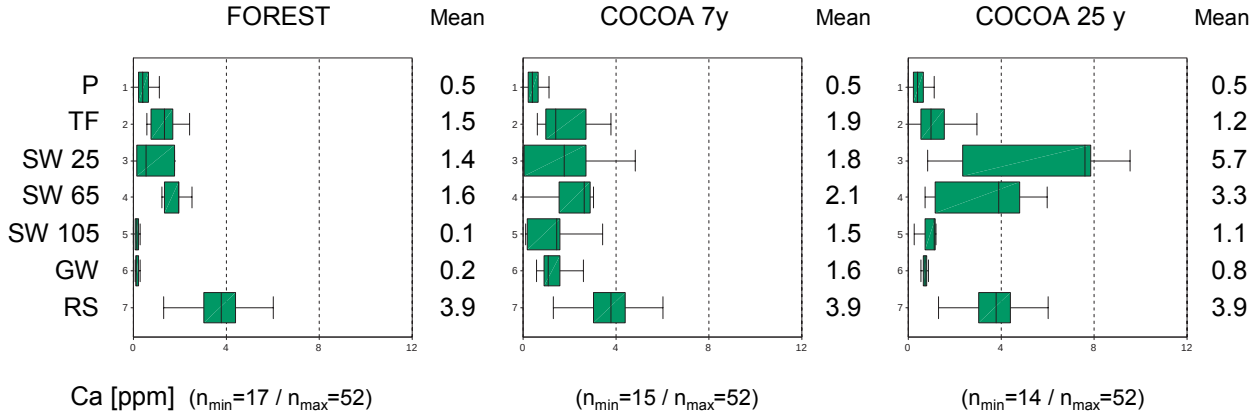

Figure 4: Calcium concentrations [ppm] at the three investigation plots (median, minimum/maximum, 25th and 75th percentiles and mean values)

Magnesium

Following the profile of Magnesium the courses are comparable to those of Calcium: leaching effects concentration increases, elevated concentrations within the receiving stream due to deep mineral weathering and similar tendencies within the non-saturated zone at the forest plot and the older cocoa plantation are similar, as well. In contrast to calcium the magnesium concentration show an inverse course at the younger cocoa plot with a slight decrease and then increase again, but noting that the differences between the 65 and the 105 cm level at the younger cocoa plot are not significant, so far.

The overall tendencies of Ca and Mg shows decreasing concentrations continuing to the 105 cm layer corresponding to rooting depths and the cation exchange capacity (as described for Potassium).

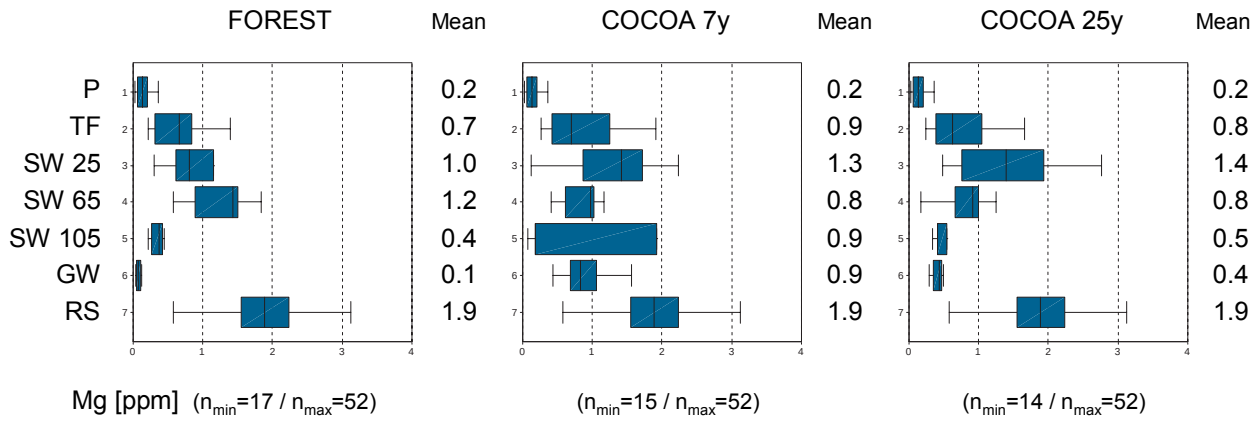

Figure 5: Magnesium concentrations [ppm] at the three investigation plots (median, minimum/maximum, 25th and 75th percentiles and mean values)

Sodium

Besides a slight increase from 1.5 ppm in open field precipitation to 2.3 ppm at all plots in throughfall precipitation the concentrations of sodium show very high values within soil water. Whereas at the forest plot highest mean values are obtained in the 25 cm layer (79 ppm) the maxima of mean values at the cocoa plots is reached in 105 cm depth (48 ppm and 103 ppm respectively).

Concerning the sodium concentrations within the non-saturated zone various factors have to be considered. Atmospheric sources of sodium can be excluded due to the distance to sea borders as well as due to low levels of sodium within open field precipitation. Sodium is adsorbed only to a minor extent within at mineral surfaces and sodium is not a major nutrient and is thus not taken up by plant to the same extent as e.g. calcium or potassium. Under humid conditions sodium stays in solution and is rapidly leached. For this reason, normal concentrations do not extent values of 70 ppm (DVWK 1996). The high values of the different plots and layers and especially the enrichment from 25 to 105 cm at the cocoa plantations might also be due to varying water movement within the soil resulting from dryer periods in combination with root water uptake and active nutrient exclusion.

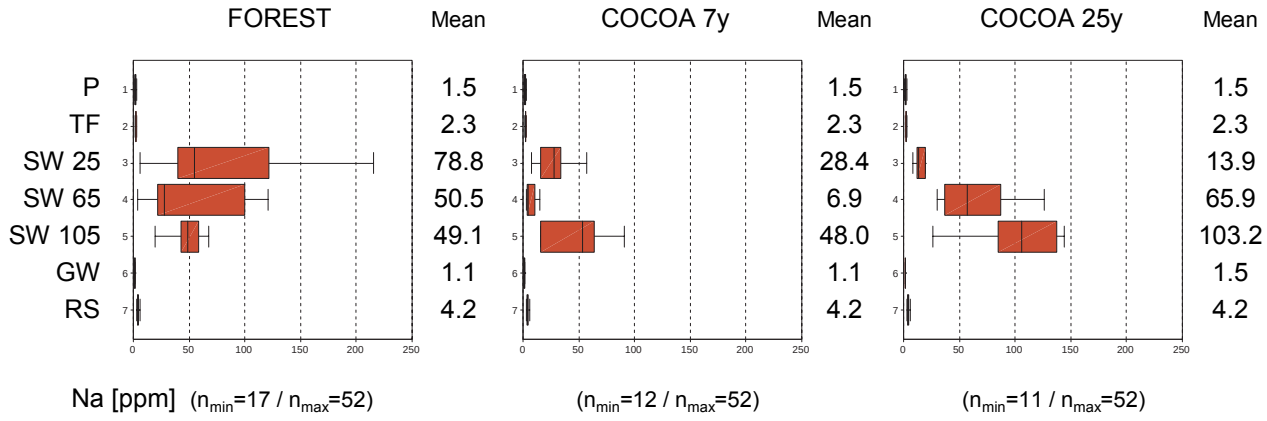

Figure 6: Sodium concentrations [ppm] at the three investigation plots (median, minimum/maximum, 25th and 75th percentiles and mean values)

For the solubility of nutrients and thus all cations described pH values are of major concern. Lowest values are found at each of the investigation plots in groundwater (mean pH 5.0 to 5.4) – highest value within soil water ranging from 7.4 to 8.0. Especially the elevated concentrations of sodium within the soil water layers are expressed in the values of electric conductivity (table 1). In comparing the results of mean sodium concentrations and mean conductivity for the example of the 25 year old cocoa plantation both values increase constantly: 25 cm – Na 13.9 ppm / eC 402 µS/cm, 65 cm – Na 65.9 ppm / eC 628 µS/cm and 105 cm – Na 103.2 ppm / eC 754 µS/cm.

	Forest				**Cocoa 7y**				**Cocoa 25 y**			
	ph		**eC [µS/cm]**		**pH**		**eC [µS/cm]**		**pH**		**eC [µS/cm**	
	mean	s.d.	Mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
P (n=35)	6.1	0.4	13	8	6.1	0.4	13	8	6.1	0.4	13	8
TF (n=35)	6.0	0.3	43	20	6.2	0.4	52	24	6.3	0.4	48	23
SW 25 (n=23)	7.7	0.6	396	211	7.6	0.3	143	69	7.4	0.6	402	223
SW 65 (n=24)	7.5	0.5	341	238	7.7	0.6	80	63	7.9	0.2	628	216
SW 105 (n=20)	7.6	0.4	322	115	7.8	0.4	263	146	8.0	0.3	754	229
GW (n=18)	5.0	0.3	18	4	5.4	0.3	41	7	5.0	0.3	40	5
RS (n=68)	6.9	0.2	63	14	6.9	0.2	63	14	6.9	0.2	63	14

Table 1: pH and electric conductivity at the investigation plots giving mean values and standard deviation (s.d.)

The overall tendencies of potassium, calcium and magnesium concentrations are comparable. A moderate to high input via canopy leaching and an enrichment of contents due to litter decomposition before entering the mineral soil horizon is followed up by decreasing values to the depth of 105 cm soil water and low levels in groundwater. The increase of concentrations in the receiving stream due to mineral weathering in deeper soil layers and strata and direct input of organic material by dense river bank vegetation.

Several factors do influence these general tendencies. Above all, the specific soil conditions, rooting depths, nutrient uptake and competing cation interactions have be taken into account. Additionally, tree density and thus litter production vary.
Sodium has to be regarded with special emphasize since the very high values within soil water extend "normal" values for humid climates which might also be caused by varying water movement within the soil resulting from dryer periods in combination with root water uptake and active nutrient exclusion.

The limiting cation is to be potassium. Very low levels could be found in soil solution and are reflected as well in contents of available potassium in the soil itself (FISCHER & GEROLD, in preparation). A very low nutrient flux of K with the soil water percolation has also been demonstrated by BERNHARD-REVERSAT (1975) with 1.2 kg/ha/a (Banco, Côte d'Ivoire). HETZEL (1999) calculated a K flux in soil water percolation of only 2 kg/ha/a (Bossématié, Côte d'Ivoire) but nevertheless is assuming a positive K balance of the Bossématié forest ecosystem indicating a better K recycling.

The chemical profiles of major cations can provide good indications concerning possible sources and sinks and help to detect general differences between the three investigation plots.
Calcium, magnesium and especially potassium are assumed to be the major leaching nutrients within the canopy layer and are additionally provided through litter input. Concerning their courses in the non-saturated zone the cations show differing tendencies due to vegetation characteristics, specific soil properties, nutrient uptake, mineral weathering and interactions between the nutrients, competing for ion exchange sites. For the calculation of matter fluxes and the amounts of nutrient inputs and exports these chemical profiles are to be correlated with daily rainfall amounts, interception, evapotranspiration, physical soil properties and stream discharge.

Perspectives
The main perspective of the project is the calculation of organic and inorganic matter fluxes. Besides ongoing sampling and analyses, nutrient concentrations are compared including detailed time series analyses and multi-parametric correlations in order to detect time-dependent interactions within the open system. Nutrient fluxes are then calculated from concentrations and related water quantities, soil properties and the watershed area.
To explain the different matter inputs and exports a detailed evaluation of soil data is necessary concerning the characteristic soil profiles as well as concerning two depth profiles reaching down to 15 m at the forest plot and 8 m at the younger cocoa plot respectively.
GIS-mapping is done including general site properties and the results concerning soils, agriculture, the application of agrochemicals etc.
Concerning the theoretical approach to develop a classification system for water quality of receiving streams in the inner tropics, a comparative sampling of other receiving streams within the region is planned, a data base with reference values will be created and evaluation criteria are developed.

Project structure The Taï Region Project on Hydrology is financed by the DFG/BMZ programme (Deutsche Forschungsgemeinschaft / Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung). It was initiated in 2001 and is an active cooperation between the University of Cocody-Abidjan (Centre Universitaire des Recherches et d'Application en Télédetection, CURAT – Côte d'Ivoire) and the Georg-August-University of Göttingen (Landscape Ecology - Germany). The interdisciplinary working group consists of Ivorian and German scientists, students and local collaborators.

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