Soil Degradation by different Land Use Impacts in Tropical Rainforests and Consequences for Land Rehabilitation

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Introduction

Despite the existence of international resource protection programs since the UNCED conference 1992 in Rio de Janeiro (AGENDA 21), rainforest conversion by non sustainable forestry as well as colonization accompanied by clearcutting continues. Following FAO (2001), the annual rate of rainforest disappearance in SE-Asia (Indonesia), Africa (Congo Basin), and Latin America (Amazonia) is 0.4 to 1.2%. Different types of disturbance as well as conversion sequences have specific consequences on matter turnover depending on climate, vegetation and soil.

According to Jordan (1985) and Brouwer&Riezebos (1998), the consequences of logging, slash&burn, annual crops and perennial tree crops on natural tropical forests are:

Decrease of biomass bound nutrient stocks due to nutrient uptake by crops, export with yields and burning; disturbance of the internal nutrient cycle with loss of organic litter layer, root mat and therefore higher nutrient leaching, decrease of soil organic matter and decrease in cation exchange capacity and plant available soil nutrients (e.g. Gerold 2001), soil erosion and degradation of the humus horizon and decrease of evapotranspiration. To avoid these, sustainable multi cropping systems or agro forestry systems are appropriate, but knowledge on water- and nutrient cycling in comparison with rain forest systems is still scarce. Based on project studies in Ecuador/Bolivia (Amazon basin), West Africa (Ivory Coast rainforest), and Indonesia (lowland rainforest in Sulawesi), consequences of clearcutting and agro-forestry (cocoa) on soil, water and nutrient cycling have been investigated.

The objective of this study was to compare changes of water- and nutrient cycling with conversion of rainforest to agro-ecosystems, especially referring to the supposedly sustainable cocoa plantations on sites in Ecuador and the Ivory Coast with low to medium soil fertility..

Methods and experimental research sites

Project region characteristics

The studies were carried out in the moist evergreen rain forests of Ecuador (1996-2000) and Ivory Coast (West Africa, 2001-2004) and moist semideciduous rain forest of Ivory Coast (1995-1998). These areas are part of the humid inner tropics (Af a. Köppen) with monthly air temperature between 24-28^{o}C and relative humidity between 75-81%. Because of different latitude (table 1) the moisture regime changes from the equatorial tropics in Ecuador with high rainfall per year (3050 mm) and >150mm/month to the seasonal inner tropics with bimodal rainfall distribution in Ivory Coast (1862 a. 1320 mm) with dry season (Harmattan) from December to January (Tai) or December to February (Bossématié). According to the climate situation of Ivory Coast with decreasing rainfall from SW (coastal zone) to NE on the moist evergreen forest follows the moist semideciduous forests, which was most important for timber production. Moderate rainfall with a longer drier season results in less soil nutrient depletion, which has been studied for the climatic and degradation gradient (due to timber exploitation) of state forests in Ivory Coast (moist evergreen to moist semideciduous forests, Gerold 1997). On the shallow dissected peneplains, typical soil catenas with Plinthosols, Ferralsols, Cambisols, Acrisols and Arenosols (FAO) occurr in all rain forest types from top to valley bottom. Therefore, within each climate-vegetation unit soil fertility depends on the soil units. Acrisols, Arenosols and Gleysols are the poorest soils, but the area of soil units with higher fertility and also the soil nutrient level decreases with the increasing rainfall or with increase of forest degradation (Gerold 1997). Overexploited forest soils show a significant decrease of humus content and therefore available nutrient decrease (CEC). Analysis of nutrient development on plinthic Ferralsols in the agricultural buffer zone of Bossématié state forest (shifting cultivation with maize/maniok/banana) after 30-40 years of traditional rotation shows N,P, Ca and K deficiencies in the topsoil (Gerold 1997).

In the Oriente of Ecuador (western part of Amazonian lowlands) soil differentiation and soil quality (chemical soil properties) is mainly influenced by the equatorial humid climate (table 1) and relief differentiation (age sequence) with tertiary hills, two peneplains and alluvial plain. Main soil types (USDA) in this relief sequence are oxic Dystropepts, andic Dystropepts and Eutropepts, Tropaquepts and Udivitrands. Under the consideration of the physical and chemical soil parameters as well as the usable soil depth, the soil utilisation potential can be ranked with following sequence (Gerold&Schawe 1999):
Andic Eutropepts>>Andic Dystropepts>Tropaquepts>>Typic Udivitrands>Oxic Dystropepts
Soil nutrient analysis and plant nutrient analysis (cocoa, coffee, banana, yucca, palma africana) shows mainly P & Mg deficiency with high P-fixation correlating with andic properties.

Table 1. Site characteristic and human impact

Region	**Vegetation a. human impact**	**Climate**	**Soil unit** a. USDA/FAO	**Soil fertility***
Oriente Ecuador-Coca 0°25´S, 76°55´W	Moist evergreen rain forest, slash&burn a. tree plantation	Afh; tropical humid without arid month	Andic Dystropept/ Dystric Cambisol	Low-medium
Ivory Coast-Tai 5°50´N, 6°50´W	Moist evergreen rain forest; slash&burn a. cocoa plantation	Af; tropical humid with 2 arid month	Plinthudult/ Ferric plinthic Acrisol	Low-medium
Ivory Coast-Bossématié 6°29´N, 3°27´W	Moist semi-deciduous rain forest; selective logging, cocoa plantation	Af; tropical subhumid with 3 arid month	Plinthic Eutrudox/ Plinthic Ferralsol	Medium

* Evaluated after soil nutrient supply for maize and cocoa (ACRI 2004, Landon 1984, Sys et al. 1993)
a. project results from Coca (LANFER 2003), Tai (FISCHER 2004), Bossematié (HETZEL 1999)

In both countries, the lowland rainforests are influenced since 1960-70 by timber extraction and spontaneous colonisation with small farmers, due to continuous migration of day-labourers and small farmers from the Andes (Sierra&Costa) in Ecuador and from the savanna regions in Ivory Coast with high population increase (3-4%/year). In the project region of Coca (Ecuador), land use systems are dominated by cattle ranching and cocoa and coffee plantations, whereas in the Ivory Coast forest, conversion was mainly done for cocoa plantations (export crop). Due to the expansion of agricultural areas, rain forests show a rapid reduction and destruction with conversion rates between 0,6-4,9%/y, according to satellite image analysis (table 2). Therefore, rainforest conversion often takes place on soils with low fertility, resulting in unsustainable production and income. Outside the national parks and state forests virgin forest soils in both regions will disappear within the next decade, so development of sustainable production with permanent crops (cocoa, coffee, fruit trees) for small farmers with agro-forestry systems is essential even on nutrient impoverished or light degraded soils.

Table 2. Rain forest conversion for crop cultivation in the project regions of Ecuador, Bolivia and Ivory Coast

Region – year (total area in ha)	**Rain forest**	**Tree plantation a. cocoa**	**Annual crops a. pasture**	**Total conversion** (ha / %)*	**Forest conversion** (%/year)
	Reference year (ha) and change detection in %				
Ecuador-Coca 22.299 ha area 1986 – 1999 (%)	8.362 -58,2	-	-	4.874 -21,9	-4,9
Bolivia – Santa Cruz 5.819.700 1984 – 2001 (%)	5.347.400 -6,2	77.900 +8,1	323.500 +332	1.596.224 -27,4	-1,7
Ivory Coast Tai 315.300 ha 1986-2001 (%)	86.771 -8,9	165.848 +9,3	58.015 -1,3	7.723 -2,5	-0,6

*reference total area
data a. Hahn 1997, Krüger 2003, Gerold a. Lanfer 2001, Sültmann 2003

Methods for water and nutrient fluxes on experimental field sites

Within the project regions the dominant relief-soil units (peneplain&soil type) for different land use types were selected to compare main components of the vertical hydrological cycle excluding differences in inclination (lateral flows). Also, overland flow with nutrient loss did not occurr. Coupled with nutrient concentration measurements for the main input-/output fluxes and soil nutrient analyses, a complex investigation and calculation of the nutrient balance was possible. On the basis of previous regional field studies on soil differentiation, soil quality and land use differentiation (Gerold 1997, Gerold&Schawe 1999, Fischer 2004) the research plots for the agro-meteorological data logger stations were selected and instrumented. The measured parameters are listed in table 3. Litter input was collected monthly with $1m^2$ boxes in 1m height. Details on instrumentation, parameter discussion, measuring intervals, water- and soil analysis and accompanied field analysis of frame parameters (e.g. HEMIVIEW pictures for LAI) are described in Fischer (2004-Tai, Ivory Coast), Hetzel (1999-Bossématié, Ivory Coast) and Lanfer (2003-Ecuador). Site instrumentation for the comparison of water and nutrient fluxes on different vegetation/land use types within the same relief-soil unit is shown in table 3. For the calculation of water- and nutrient uptake by plants and plant available soil nutrient stock the root depth was restricted due to pedophysical (plinthic horizon) and pedochemical (very low $CEC_{eff.}$) restrictions in the B-horizon until 40cm (Ecuador) and 40(Tai)-50cm (Bossématié-Ivory Coast), so that nutrient leaching was calculated with 75-90cm and 105-120cm lysimeter nutrient concentrations. TDR-soil moisture measurements enables the calculation of aET parallel to the PENMAN-aET with the soil water difference method and the approximate calculation of nutrient uptake by the plants. For the agro-ecosystems, yield estimation (cf. table 4) and nutrient analysis of yield products leads to an estimation of yearly nutrient export.

Results and discussion

From the perhumid Ecuadorian site to the humid and subhumid sites in Ivory Coast a clear decrease of rainfall exists. Between the same vegetation units, interception loss is in the same magnitude (table 4) and comparable with rainforest data from literature (Bruijnzeel 1990). For agro-forestry systems data are scarce. Throughfall increases with the rainfall gradient, which leads to high soil moisture contents in Ecuador through the year.

Table 3. Field methods – parameter and configuration of data-logger stations

Parameter	Sensor/calculation	Height	Accuracy
Air temperature	RTD Pt100	2m above canopy surface	+- 0,1 K
Air humidity	Rotronic-hygrometer C80 (with ventilation)	"	+- 1,5%
Anemometer	A100R (start at 0,25m/s)	"	+- 0,1m/s
Photosynthetic active radiation	PAR type QS	"	+- 3% (240-650nm)
Global radiation a. Albedo	Pyranometer type 8101	"	+-5%(0,3-3,0 µm)
Net radiation	Pyrradiometer type 8111	"	<30 W/m2 (0,3-100 µm)
Rainfall	Aerodynamic raingauge ARG100 with 500cm2, Throughfall additionally 40 bulk sampler	1,2 m	Water collection for nutrient analysis every morning and/or 2x/week
Soil temperature	Fernwall-Thermistor TH2	3,10,30,50,70,120 cm depth	+- 0,1 K
Soil heat flux	Heat flux plate	3 a. 10 cm depth	
Soil moisture	Sensor Trime-MUX6	20,40,60,90,120 cm depth	+- 2% (0-70 Vol.%)
Soil solution	Soil lysimeter (3 per depth)	20,40,70,120 cm depth	Sampling suction 0,6 bar; water collecting weekly
pET	after PENMAN, modified by DOORENBOS a, PRUIT		
aET	Modified PENMAN-pET with $r_a + r_c$		In Ivory Coast additionally with soil water difference method

Table 4. Water fluxes in rainforest and agro-ecosystems in Ecuador and Ivory Coast (in mm/year)

Region/land use	Rainfall	Throughfall	AET (%I)*	Drainage Water
Ecuador (1997-98)- rain forest	3050	2596	1803 (15)	1247
Ecuador - cocoa	3050	2750	1746 (10)	1304
Ecuador – coffee	3050	2691	1507 (12)	1543
Ecuador - pasture	3050	-	637	2413
Ivory Coast (2002)– rain forest - Tai	1862	1620	1527 (13)	335
I. C. – cocoa-Tai	1862	1657	1322 (9)	540
I.C. (1996)– seasonal rain forest Bossématié	1320	1108	1077 (16)	243
I.C. – cocoa - Bossématié	1320	1206	962 (9)	358

* AET a. modified Penman-Monteith, I = Interception
data from own projects with Hetzel 1999, Lanfer 2003, Fischer 2004

After soil suction measurements only 40 days at rainforest site and 14 days at pasture crosses the level of 100hPa with restricted infiltration loss (Lanfer 2003). Contrarily, deep drainage water in the semideciduous rain forest occurs only during the main rainy season from April to June, at the cocoa site from April to August (Hetzel 1999). With the change from rainforest to tree plantation and pasture interception and transpiration loss decreases and drainage water within the same soil units increases. Absolute values depends to the climatic region (table 4). Not only due to the increase of nutrient concentration in drainage water after forest conversion (which happens mostly in first two years; Uhl&Jordan, 1984), but in longer run due to the higher leaching amount soil nutrient depletion occurs. As an example, the Ca&Mg concentration in drainage water at the cocoa site in Bossématié is half of the forest site, but nutrient loss by leaching is in the same order of magnitude (table 7).

Table 5. Approximate nutrient budget (rainfall – leaching) for different rain forest sites in South America and West Africa (in kg/ha*y)

Region	Annual Rainfall*	Annual Drainage*	Ca	Mg	K	P	N
Ecuador-Coca[1]	3050	1247	-9,2	-4,6	16,2	2,0	13,9
Venezuela-San Carlos[2]	3565	1595	7,0	2,8	8,0	-5,5	-2,6
Brazilia-Jari[3]	2300	1225	-1,0	-4,8	-2,5	0,1	
Brazilia-Belém[4]	1956	455	9,0	14,0	5,0	2,8	18,0
Ivory Coast-Tai[5]	1862	335	6,8	1,3	5,7	5,8	19,7
Ivory Coast-Banco[6]	1810	630	-13,0	2,7	4,2	2,1	8,6
Ivory Coast-Bossématié[7]	1320	158	2,1	-2,5	8,3	6,4	13,1

Data from own projects (Hetzel 1999[7] Lanfer 2003[1], Fischer 2004[5] a. Bruijnzeel 1990[2,3,6], Hölscher 1995[4] ; * in mm/year

Including some results from other research sites for the evergreen rain forest in South America for the external nutrient budget (rainfall – leaching) we see, that for main nutrients often Ca and Mg are leached in a higher extent in relation to the rainfall input. The positive balance in eastern Amazonia (Belém) results from higher nutrient concentrations with the atlantic airmasses despite lower rainfall amount in relation to western and central amazonia. Also in West Africa maritime air mass (SW-monsoon) and the continental dust input with the Harmattan during the dry season contributes to similar or even higher rainfall nutrient inputs (s. Tab. 7). The incident rainfall nutrient flux at Coca for Ca, Mg and K is comparable to inner amazonian sites of San Carlos (Venezuela) and Jari (Brazilia) (Bruijnzeel 1990), whereas the eastern Amazon (Belém, Hölscher 1995) is influenced by the atlantic air mass with much more higher nutrient concentrations and input for Ca, Mg, Na-cations. Also, rainfall in West Africa is more influenced by the SW-monsoon (rainy season) and Harmattan (dry season) with enriched dust deposition, so that despite lower rainfall per year at Tai nutrient input has comparable level to Coca and in the seasonal rainforest the input for Ca, Mg, K is doubled. The dry deposition in the Bossématié for the cations (Ca, Mg, K, Na) has a portion of 15-20% (2-3 kg/ha*y,Walter 1998).

Comparing the different land use types in Ecuador, the doubling of drainage water from forest site to pasture causes for critical elements a 3-4x higher nutrient loss by leaching (table 6). After 20-30 years for great pasture areas in South America, soil degradation happened, due to burning and nutrient leaching (Barber 1995). Soil nutrient development, analysed with false time series on traditional shifting cultivation plots for the plinthic Ferralsols at Bossématié shows nutrient deficiency for Mg, K and P after 30 years (Gerold 1997). But the 25 years old cocoa plantation still have available nutrient stock for the macronutrients (table 7) above critical levels (Schroth&Pity 1992). In the Tai-region for cocoa only P-stock (290 kg/ha) is critical, due to higher leaching and P-fixation by high Fe-Al-oxides in the soil. Because of different water balance (throughfall and drainage water) rainforest and cocoa plantations in the Tai-region have less nutrient leaching (except P) than at the Ecuador-site. The same leaching level at Bossématié depends on the higher nutrient status of the soils with higher

Table 6. Nutrient fluxes in different agro-forestry systems and pasture in the Oriente of Ecuador (for critical elements in kg/ha*y)

Vegetation/land use	Rainfall			Throughfall			Leaching		
	Ca	Mg	P	Ca	Mg	P	Ca	Mg	P
Rain forest	8,1	2,2	2,1	53,4	16,8	13,7	17,3	6,8	0,1
Cocoa plantation	8,1	2,2	2,1	20,0	15,0	8,3	12,2	3,8	0,1
Coffee plantation	8,1	2,2	2,1	12,8	4,9	8,1	32,3	6,6	0,2
Pasture	8,1	2,2	2,1	-	-	-	63,3	38,0	0,4

Vegetation/land use	Rainfall - Leaching			Litter input			Soil nutrient stock* a. CEC (kg/ha)		
	Ca	Mg	P	Ca	Mg	P	Ca	Mg	P_{550}
Rain forest	*-9,2*	*-4,6*	2,0	508,6	53,3	25,2	3.060	712	42
Cocoa plantation	*-4,1*	*-1,6*	2,0	120,9	32,8	7,3	4.309	339	34
Coffee plantation	*-24,2*	*-4,4*	1,9	81,9	19,4	11,7	3.455	655	109
Pasture	*-55,2*	*-35,8*	1,7	12,2	10,4	3,8	3.560	324	38

*available nutrients a. $CEC_{eff.}$ (1M NH4Cl), P_{550} and main plant rooting until 0,5m soil depth
data from projects with Lanfer 2003, Gerold a. Lanfer 2001

macronutrient concentrations in the soil solution. The different water fluxes causes a significant higher leaching nutrient loss for annual and pasture systems than for agro-forestry systems (cocoa, coffee).

Comparing the main nutrient input fluxes the great importance of the internal nutrient cycle with throughfall and litter input is obvious (table 6,7). In Ecuador the nutrient deficit for Ca, Mg and K (rainfall – leaching) is compensated in rain forest and cocoa system by throughfall enrichment. Litter input, very similar for cocoa in the three research sites plays the main role for soil nutrient supply. The total litter production of cocoa for Ecuador and Ivory Coast is quite similar (5.600 a. 5.500 kg/ha*y), whereas litter production in rainforest types greatly differs (19.900-Coca, 10300-Tai, 7500-Bossématié). In several plot studies on vertical nutrient fluxes the nutrient uptake by plants (above ground biomass) is more or less balanced by the litter input (Jordan 1985). Therefore the relationship between throughfall and leaching is an indicator for the establishment of long term sustainable agroforestry systems. For the cocoa-plantations in Ecuador (Coca) and Ivory Coast (Tai a. Bossématié) these balances are positive for the macronutrients, whereas coffee-plantation and pasture have negative values with the consequence that without external inputs (fertilization) the coffee- and also oil palm-plantations (s. Lanfer 2003) have decreasing yields and soil nutrient impoverishment. The pasture is adapted to low nutrient cycling , but the high leaching amount in relation to the nutrient input fluxes leads to further soil degradation (table 6).

Table 7. Nutrient fluxes in rain forest and cocoa plantation in Ivory Coast
(Tai-NP a. Bossématié for critical elements in kg/ha*y)

Vegetation/land use	Rainfall			Throughfall			Leaching		
	Ca	Mg	P	Ca	Mg	P	Ca	Mg	P
Rain forest - Tai	7,2	2,5	6,1	20,7	9,9	7,6	0,4	1,2	0,3
Cocoa (25a) -Tai	7,2	2,5	6,1	20,8	11,4	8,2	5,0	2,7	1,6
Seasonal rain forest-Bossématié	14,8	4,6	6,5	25,0	11,8	8,5	12,7	7,1	0,1
Cocoa-Bossématié (25a)	14,8	4,6	6,5	22,8	12,1	8,0	12,0	5,8	0,1

Vegetation/land use	Rainfall - Leaching			Litter input			Soil nutrient stock* a. CEC (kg/ha)		
	Ca	Mg	P	Ca	Mg	P	Ca	Mg	P_{550}
Rain forest - Tai	6,8	1,3	5,8	85,0	35,5	13,8	14.150	3.040	700
Cocoa (25a) - Tai	2,2	*-0,2*	4,5	95,4	33,2	3,8	7.030	750	290
Seasonal rain forest-Bossématié	2,1	*-2,5*	6,4	171,5	40,3	5,8	11.603	2.240	748
Cocoa-Bossématié (25a)	2,8	*-1,2*	6,4	92,0	33,8	1,9	6.057	971	805

*available nutrients a. $CEC_{eff.}$ (1M NH4Cl), P_{550} and main plant rooting until 0,5m soil depth
data from from projects with Fischer 2004, Hetzel 1999

Conclusions

For the same climate-vegetation types and relief-soil units different rainfall amounts and rainfall distribution causes different water fluxes with decreasing drainage water from perhumid amazonian rain forest to atlantic rain forest and semideciduous rain forest. Less nutrient leaching in general is the consequence. Oceanic rainforests (West Africa) possess similar nutrient deposition rates compared to Central Amazonia, due to higher concentrations in rainfall, influenced by SW-monsoon (Na, Cl, Ca, Mg, P) and NE-passat (Harmattan: Si, K, Ca, Mg,N). With rain forest conversion to annual crops or pasture nutrient leaching increase by the factor 3-5, whereas in cocoa plantations the increase is significant lower. The litter input possess an important function for the internal nutrient cycling. For the studied cocoa sites nutrient input with litterfall shows no great difference. Estimation of total input/output relation for the studied cocoa sites (2,1-2,5 for Ca,Mg,K), which includes nutrient uptake and yield export, indicates the possibility of sustainable cocoa agro-forestry systems even on soils with low-medium nutrient status in our research regions. To restore degraded soils, beside the soil nutrient status the knowledge on main nutrient fluxes is important. Agro-forestry systems with regional depending nutrient enriched throughfall and high litterfall can be used for the rehabilitation of degraded soils.

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