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TROPENBOS: NUTRIENT AND MOISTURE CYCLING - report* of the working group

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1. Introduction

Any management strategy for sustained land use of former or present tropical forest areas must be based on an understanding of the interactions between climate, vegetation and soil.

The traditional practice of shifting cultivation was within the limits of the carrying capacity of the ecosystem. Present land use has a higher impact on the ecosystem, due to a higher intensity and frequency of human activity. In designing strategies for sustained land use, the potential of an area may be over- or underestimated when the interactions climate-vegetation-soil are not fully understood.

Vital knowledge is:

- to understand the mechanisms and magnitudes of flows of water and nutrients between different compartments of relevant ecosystems;
- to understand the possible effects of changes in physical, chemical, and biotic parameters on nutrient and moisture cycling.

To obtain this vital knowledge field measurements are required.

To effectively determine what measurements should be done to facilitate data handling, and to be able to compare the results of nutrient cycling studies at various sites under natural and disturbed vegetations as well as under agriculture, a simulation model should be assembled or designed.

Due to the complexity of a soil-water-vegetation system, not every element in the natural system can be included and simplifications will be made where necessary. Simplifications do not need to weaken the model, but in fact, they may emphasize major processes operating in the system, rather than losing these processes in complexity.

The model will simulate growth as a function of nutrient and water availability, since these - and not light - usually are the most limiting factors for plant growth in tropical regions.

* This report is a joint effort of universities and institutes in Amsterdam (UvA, KIT), Groningen (RUG, IB), Wageningen (LU), and field workers of the Tropenbos Programme

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The model should contain a relatively small number of easily measurable parameters and have output data that:
- are fairly sensitive to variations in nutrient and water cycling;
- can be tested rather easily in the field.

After running and adapting the model using published and guesstimated data, a first, practical version of the model will be used to set up a list of sample types, analyses, and measurements that will be proposed for use in the nutrient and moisture cycling studies (a preliminary list is given in the appendix).

For financial reasons, it will probably be impossible to have detailed water and nutrient cycling monitoring programmes at all Tropenbos locations. Therefore, it may be useful to carry out detailed water and nutrient cycling studies at two or three locations, to test and validate the model intensively, and use the model, or a simplified version of it, for reconnaissance studies with fewer measured parameters and less data for validation at the other locations.

2. The model

2.1 Model considerations

The model should be based on equations that describe the physical, chemical and biological processes that affect the mechanisms and magnitudes of water and nutrient flows between different compartments in tropical ecosystems around the globe. A suitable model can be derived following a variety of approaches. However, two ingredients are always needed:
- knowledge of the theoretical behaviour of the system to imply the correct scientific principles;
- experimental or field data to calibrate and validate the model. Models vary according to the degree to which theoretical and/or empirical information is included, and the extent to which data are used to derive or estimate model parameters (Fig. 1).

A conventional approach is to use physical, chemical and biological theories to derive partial differential equations. It is clear that these models are likely to be non-linear, and therefore require finite difference and finite element approximations. A more popular approach which avoids solution problems is to linearize the equations, or to develop ordinary differential equation models. This has been applied in existing water and nutrient transport models on ecosystem scale, such as those by Goldstein (1983), Christophersen et al. (1982), and Cosby et al. (1984). In order to use these approaches, assumptions must be made to lump system characteristics or parameters. The advantage of this approach is that the model equations can be solved relatively easily and that model parameters can be determined by calibration against field data. The disadvantage is that errors may be introduced by the lumping of system characteristics. However, with sufficient care, the simplified modelling approach is often very satisfying and productive.

Summarizing, the model should meet the following requirements:
- model must run using easily obtainable data;
- mathematical equations must be based on physical, biological and chemical processes;
- model equations should be limited to commonly measured parameters;
- uniform model output for all locations.

2.2 Model elements

The TROPNUT model presented here includes the following elements:
- water balance (Fig. 2);

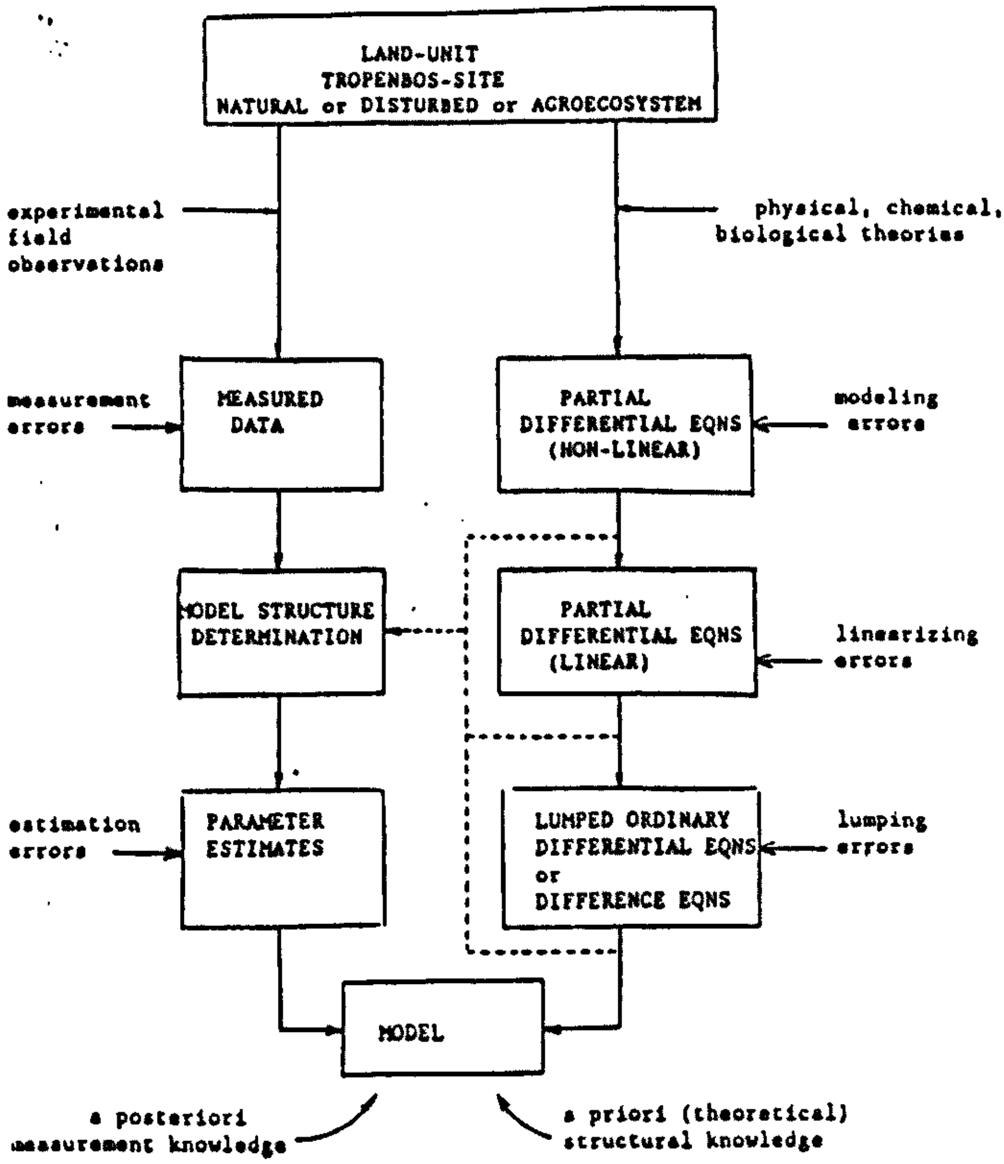

Figure 1 Combining theoretical knowledge and field measurements in the modeling procedure (Whitehead et al., 1984, adapted from Beck, 1984).

- atmospheric deposition (including dust);
- primary productivity + litterfall;
- uptake of plant nutrients + organic matter decay;
- nutrient transport.

The different compartments of the ecosystem are obtained through vertical and horizontal segmentation of the model (Fig. 3):
- atmosphere;
- above ground vegetation, organic and underlying mineral layers;
- soil layers (based on textural, chemical, and biological differentiation);
- mineral soil, soil solution, and drainage water;
- labile, stable and inert fractions (separate for organic and mineral layers).

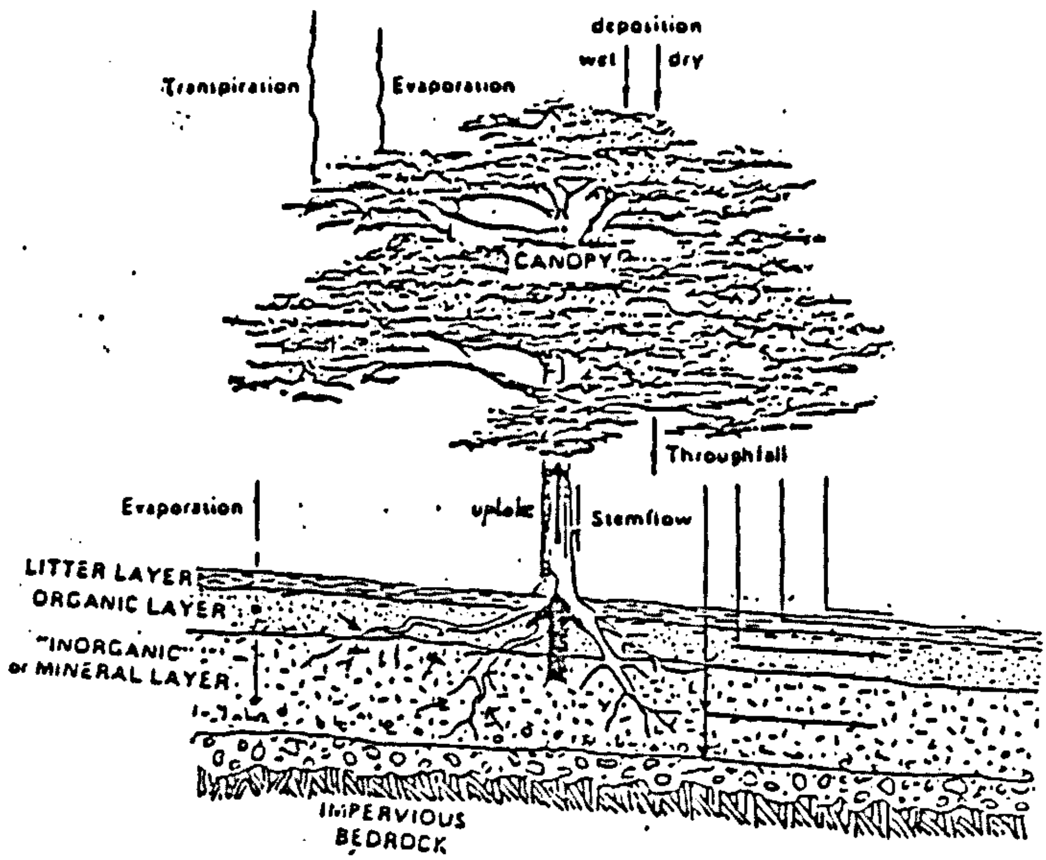

Figure 2 Water balance and processes in a forest ecosystem (source: Goldstein, 1983)

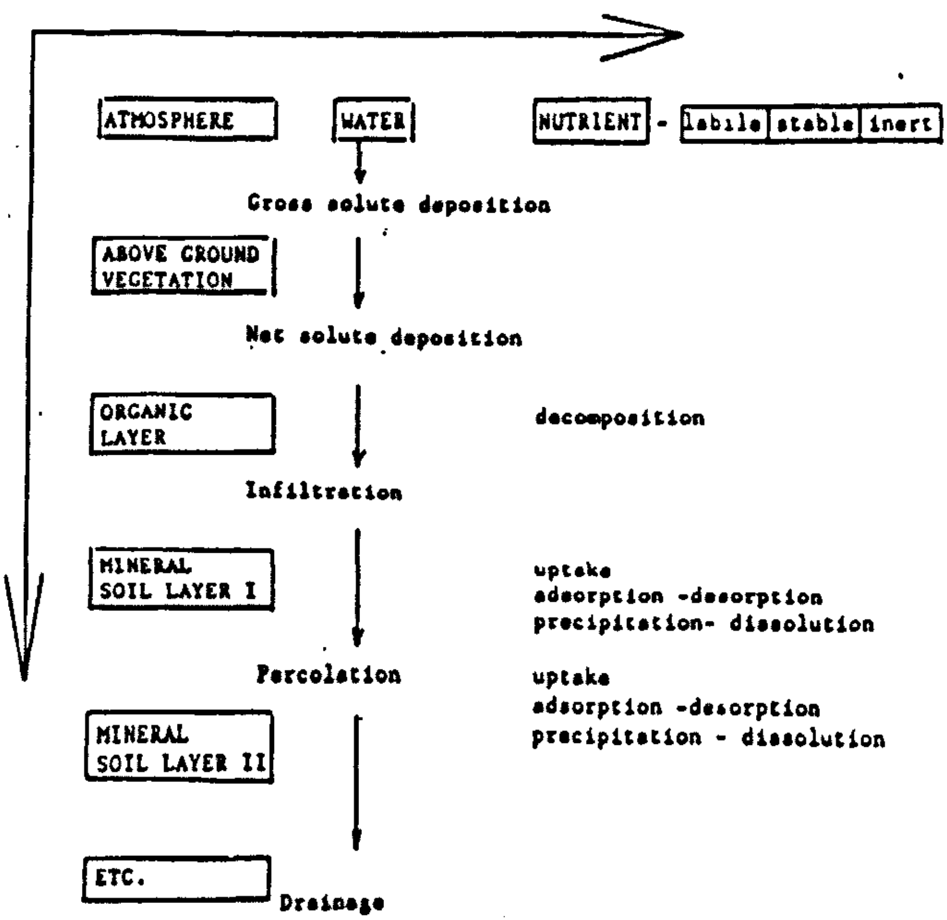

Figure 3 Vertical and horizontal segmentation in order to compartalize the system.

Key elements are the ecosystem variables (Vitousek and Sanford, 1986) (Fig. 4):
- climate;
- structural characteristics of vegetation and successional status;
- soil and land characteristics, including management practices.

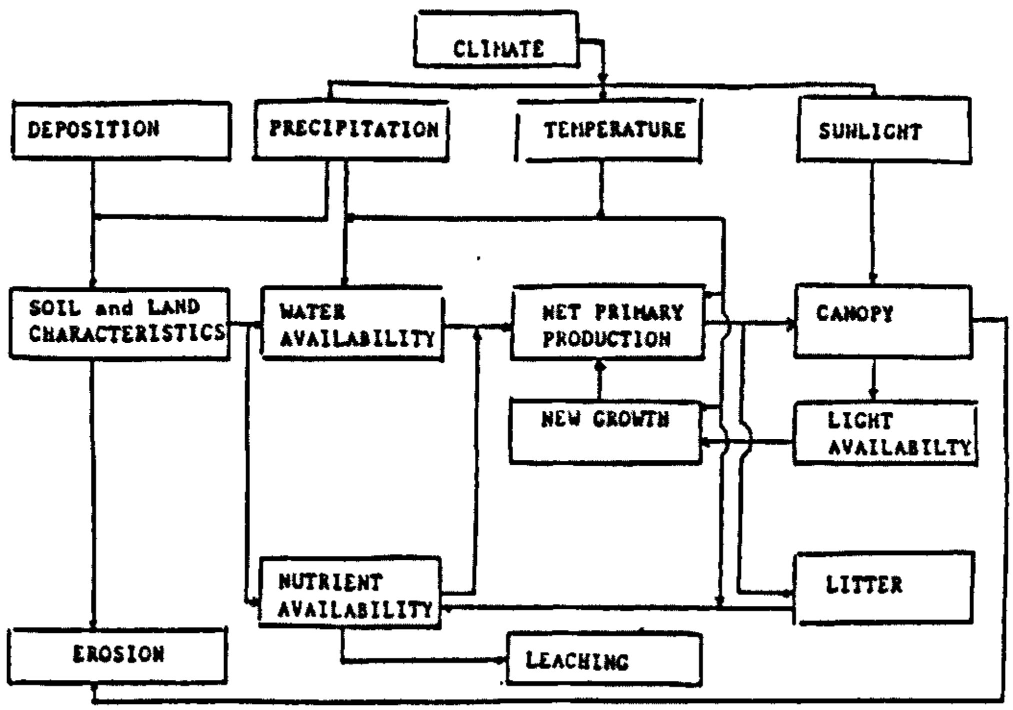

Figure 4 Physical, chemical and biological interactions and feed-back loops in tropical ecosystems.

For all locations the output should be uniform and consist of:
- water and nutrient flux density (amounts per unit time and unit of area) between different compa ments;
- primary production.

Since nutrient and moisture availability will be the driving force in the model, these factors are discuss below in more detail.

2.2.1 Moisture

Standard data will be used as input for a water transport model. Soil and vegetation characteristics, lo term average weekly or fortnightly precipitation, and evapotranspiration should suffice, except for one two sites, where more detailed hydrological measurements will be made. At those sites temperature, ra fall, throughfall, stemflow and soil moisture will be monitored. It would be benificial to select small, we defined catchment areas for these sites in order to check the water balance on an annual basis throu streamflow monitoring.

Standard meteorological data from neighbouring stations and *in situ* rainfall and throughfall measur ments will be used to formulate and/or adapt literature interception models (Rutter, 1971; Jackson, 197 Gash, 1979). Actual interception calculated from the measured difference between gross rainfall an throughfall will be used to validate semi-empirical interception formulations (as a function of rainfall and vegetational cover).

Evapotranspiration consists of evaporation and interception and precipitation water, as well as transpiration of soil water. Instead of using Thornthwaite's and Mather's (1957) method to calculate potential evapotranspiration, which is based on latitude and air-temperature, more realistic results can be obtained applying a reference potential evapotranspiration calculated by Penman, or other methods which take into account a more complete range of meteorological observations applied to a reference crop (Er) or open water evaporation (Eo). The Penman-Monteith equation is most often used to assess bulk evaporation, which require meteorological data above the forest. Since these are probably not available at all sites, relations of these parameters should be formulated with standard meteorological data. Actual crop potential evapotranspiration can then be calculated from a crop coefficient (Kc) and the reference crop potential evapotranspiration (Er) (Doorenbos and Pruit, 1977; Doorenbos and Kassan, 1979). Van Grinsven et al. (1987) sucessfully applied Penman's (1948) open water evaporation (Eo) and crop factor (f1) to calculate potential evapotranspiration (PET). PET is the sum of potential transpiration (PT) and soil evaporation (PE) based on the fraction of soil surface covered by green vegetation (f2). Potential transpiration was reduced by a fraction of the actual interception (f3).

This resulted in the following set of equations:

$$PET = f1\ Eo$$

$$PE = (1-f2)\ PET$$

$$PT = f2\ PET - f3\ Iact.$$

The distribution of potential root water uptake with depth in each compartment was assumed to be proportional to the mass of roots. The programme will calculate moisture contents for each compartment and time-step, and if evapotranspiration exceeds precipitation, corrections will be made proportional to the potential water loss and water capacity (Pastor and Post, 1984). Transpiration calibration will be performed with moisture measurements at each site.

Vertical water transport modelling through the use of a *cascade* model will be calibrated with moisture measurements taken at one or two of these sites. Empirical functions will be formulated if lateral drainage and run-off occurs.

During monitoring data loggers will be used for meteorological data and continuous moisture recordings at different depths in the profile.

Field measurements:
- rainfall, throughfall and stemflow collectors;
- open pan evaporation;
- venturi flume (to check water balance and for erosion measurements);
- texture (sand, silt, clay);
- saturated hydraulic conductivity (Ksat);
- vegetational cover;
- root distribution.

Model input:
- temperature;
- rainfall;
- potential evaporation;
- interception;
- soil moisture retention.

2.2.2 Nutrients and primary production

In modelling the flow of nutrients two aspects are considered here:
- the - mainly chemical - behaviour of nutrients in the soil;
- the relation between nutrients and primary production.

The role of micro-organisms is implicitly included in the second part through a sub-model for organic matter decomposition.

As water moves from one compartment to another, it carries nutrients and other chemical constituents with it. The concentration of the constituents will change depending on the equilibration time with the mineral, organic and biotic phase. Resulting concentrations of all chemical species within each compartment will be calculated using the principles of mass conservation, and kinetic and equilibrium constraints. Due to the vertical segmentation every compartment will be characterized by the mass of each chemical species present in the biotic, solid and liquid phase. Calibration will be executed with moisture levels monitored at the different sites.

However, in order to assess the availability of nutrients for nutrient cycling, a distinct differentiation is needed between labile, stable and inert pools, as well as identification of its distribution in inorganic and organic phases. Differentiation is implemented since each phase is characterized by intrinsic kinetic mechanisms and rates. The soil chemical module will determine the nutrient concentrations associated with the soil solution. Due to the physical process of advection (percolation), chemical species are added to the soil solution through organic matter decay and weathering of mineral components. In addition, chemical species in solution rapidly equilibrate with those on the ion-exchange sites and possibly precipitate in deeper soil layers. Removal of nutrients occurs through precipitation, nutrient uptake, drainage or erosion.

Processes will be considered, by the chemical module, of:
- wet and dry (including dust) deposition, interception and evaporation in the canopy;
- accumulation, leaching and decomposition of the organic layer;
- evapotranspiration, decomposition, nutrient uptake, nitrification, root respiration, anionsorption, weathering, cation-exchange and chemical equilibrium in the organic and mineral layers.

This implies that the upper compartment (atmosphere) will be characterized by:
- precipitation, throughfall and stemflow quality;
- vegetation characteristics (biomass, LAI, nutrient content).

Underlying litter layer will be characterized by litter mass, fine litter mass fractions as well as by its chemical composition. Humus and soil compartments by its humus mass fraction, soluble organic acids, pH, alkalinity, major cat- and anions, CEC, base saturation, mineral composition, CO_2 and root distribution.

Based on work at the Tropenbos location Côte d'Ivoire, a preliminary model has already been written for the growth of vegetation in relation to the availability of nutrients. In this case P is the most limiting growth factor, and therefore used as the driving force in the model. The time step is one year.

The need for N is based on the dry matter production as controlled by P. P in the soil is divided into an organic and inorganic part, and each part into a labile and stable fraction. The P taken up from the soil solution is divided over wood and leaves. Leaf fall and wood fall are included in the model. Redistribution of P within the plant was estimated. With a maximum dilution of P in leaf and wood the need for N is calculated. The remainder of N in the soil is leached. In general this is a model for dry matter production controlled by one nutrient; the flows of other nutrients are obtained as a derivative.

In this preliminary model for Côte d'Ivoire soil processes are described in less detail than in the proposed model on nutrient behaviour, and the time step is much larger. It is planned to connect the two models once sensitivity analyses have been carried out.

It is expected that this combined model will best serve the purposes of:
- guiding the field research;
- predicting the consequences of changes in the ecosystem.

Field measurements:

1. characterization of Site: State Variables:
- textural analysis;
- pH;
- total elemental composition (fine earth + clay);
- mineralogical composition;
- total carbon, total N, org-N;
- total P, org-P, P-Olsen;
- total S;
- CEC + exchangeable cations;
- structural status and vegetational cover (inventarisation).

2. Monitoring (flux and rate determination):
- amount of phytomass;
- major elemental concentrations of live material (leaves, twigs, wood);
- amount of litter fall (leaves, twigs, wood);
- major elemental concentration of litter fractions (leaves, twigs, wood);
- weight loss determination of litter fractions (litterbag experiments) in litter and humus layer;
- deposition of dust, rainfall, throughfall (stemflow);
- soil moisture analysis for major cat- and anions including Al, Si, org-C, total-N and total-P;
- CEC + base saturation;
- pH-H_2O;
- P-Olsen.

Model input:
- soil characteristics;
- rainfall and air- and soil temperature;
- nutrient deposition (wet + dry);

- distribution fraction of nutrients - uptake distribution (successional status);
- successional composition of vegetation cover;
- total nutrient concentrations in (1) leaf, (2) twig, (3) stem and (4) litter as well as in solid mineral phase of each compartment;
- available nutrient pools: P-Olsen, NH_4 and NO_3 concentrations, exchangeable cation concentrations;
- litter fall and decomposition rate (leaves, twigs and wood).

Some points raised during the general discussion

* The working group does not know how much money is needed be cause some things in the list might be superfluous and others may be lacking. The group does know, however, what to do and by what methods.
* Three scientists-technicians are needed per site, plus material and equipment. However, models can be made from a couple of sites, monitoring in great detail.
* In Ivory Coast it took from April till October 1987 to develop the model just discussed. However, the data were collected before by other people.
* Conclusions on water and nutrient conditions at a certain site cannot be drawn without measurements. In soil science spatial variability models are being developed; watersheds can be monitored and this offers opportunities to calibrate the models. A lot of developments are expected in this area in the coming years.

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Appendix

Methods of recording, sampling and analysis; frequency and intensity (number of replicates) of measurements.

The TROPNUT model requires *input parameters* obtained from measurements. Which measurements have to be performed is given at the end of the subchapters: Moisture, and Nutrients and primary production. Financial constraints (manpower) make that the whole set of measurements can be done only at a limited number of sites (intensive data acquisition); at the other sites a much smaller set of data, with less replicates must do (extensive data acquisition). Extensive data collection will be at all sites for a period of four years; for a complete set of data from the intensive measurements a minimum of two years recording is needed.

Dataloggers will be needed for amount and intensity of rainfall, for soil moisture and for soil temperature. They will be linked to a personal computer (one per site).

parameter	method	frequency	number of replicates intensive	number of replicates extensive	remarks
MOISTURE:					
rainfall (mm)	continuous recording (+ data logger)	continuously (resolution 15 min.)	1	-	
"	cumulative	weekly	-	1	from existing meteo-station (non-project)
through fall (mm)	cumulative, gutters (PVC piping 0.1 X 2.0 m)	weekly	10	-	
stemflow	eye observation	n.a.	n.a.	-	
evaporation	pan	daily	1	-	
moisture content (volumetric) of organic layer	gravimetric	variable (= monthly)	10	-	
soil moisture	capacitive moisture probes at 4 depths (+ data logger)	daily	4	-	probes developed by TFDL; range not limited. N.B. no tensiometers
texture	pipette method (standard treatment, H_2O_2)	once	10	10	pF curves not needed for model; needed is relation between hydraulic conductivity (K) and soil water potential (ψ)
saturated hydraulic conductivity	column (cube method), at 4 depths	once	10	10	
soil temperature	thermo couple at 4 depths (+ data logger)	daily	1	-	
air temperature	standard		1	-	every location will have at 1 site (intensive measurem. a proper meteo-station
vegetational cover		seasonally	10	-	needed for interception model
root distribution					
- relative root mass per layer	root auger 4 depths	once	50	50	
- total root mass	literature?	once	n.a.	-	
	excavating?	once	≥1	-	
erosion	if catchment:				
	- discharge	continuously			
	- solutes and suspended solids	every 4 weeks			+ event sampling
overland flow		p.m.			
NUTRIENTS: characterization of site:					
total elemental composition	X-ray fluorescence seperately for clay and fine earth 4 depths		4	4	
CEC + exchangeable cations	$BaCl_2$, 0.01 M; ECEC; $BaCl_2$-TEA, pH 8.2; NH_4 OAc, pH 7.0; 4 depths + litter layer	once	10	10	
pH - H_2O - KCl - $CaCl_2$	standard 4 depths + litter layer	once	10	10	
mineral composition	rontgen diffraction of soil and clay, 4 depths	once	4	4	not in organic layer
organic C	Kurmies, Walkley-Black	once	10	10	

parameter	method	frequency	number of replicates intensive	extensive	remarks
total N (in soil)	spectrophotometric after digestion (H_2SO_4 - Se - salysilic acid + H_2O_2)	once	10	10	
total P (in soil)	spectrophotometric after digestion (H_2SO_4 - Se - Salitylic acid + H_2O_2)	once	10	10	
total S (in soil)	ICP (Inductively-coupled plasma atomic emission spectrometry)	once	10	10	
organic P (in soil)	Kurmies	once	10	-	
"	regression	n.a.	-	(1)	
available P	Olsen, Bray (I-IV)	2	10	10	
monitoring: phytomass t. site^{-1} (per species)	forestry	once	1	1	for forested sites
"	harvest	yearly	4	4	for agricultural sites
elemental concentration per species - leaves	digestion or X-ray fluorescence	2-4	50	-	
"	"	1	-	50	
- twigs/wood	"	once	20	20	
litterfall - mass (separated in leaves and twigs)	traps, 0.5 x 0.5 m	weekly	15	-	
- elemental concentration (separate for leaves and twigs)	digestion or X-ray fluorescence	2-4	15	-	
Wood litter (>5 cm ø; >30 cm ø)	inventarisation per site during 4 years	4	total site area	-	
"	"	once	-	area	
decomposition rate of leaves and twigs for 3 species	litter bags with varying mesh (3-4 sizes)	2 starts 4 samplings	5	-	
dust deposition mass + elemental composition (N,P)	Tainah?	seasonal	?	-	only during season
rainfall and throughfall elemental composition (NO_3, NH_4, N total, C total)		weekly (sampling) monthly (analysis)	1*		* pooled sample for whole site
soil moisture elemental composition (NO_3, NH_4, N total, C total)	cups* at 4 depths	every 4 weeks	2		* for forest floor tension plate, continuous suction of ca. 1m H_2O