**AfricaNUANCES**
**NU**trient **U**se in **A**nimal and **C**ropping systems - **E**fficiencies and **S**cales.

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Working paper 1
Version 2.0 - March 2005

# FARMSIM – The prototype analytical tool for AfricaNUANCES

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## 1. Introduction

While the level of complexity arising from the combination of the multiple scenarios to be considered within AfricaNUANCES is expected to be high (climate, soil types and degradation intensities, production activities, farm resource endowment, management decisions, etc.), the modelling approach for analysing livelihood strategies at farm scale should aim at simplicity. The dynamic model for exploration of strategic (i.e. long term) issues at farm scale – FARMSIM – will be based on the use of descriptive models/functions derived from experimental research, mechanistic modelling at lower hierarchical levels and experts knowledge. This approach resembles those adopted in previous models for long term analysis of different sustainability aspects of farming systems (e.g. Wolf et al., 1989; Janssen et al., 1987). Process knowledge, available response data and output of simulation models at component scale (crop/field, livestock production units) will be used to derive response surfaces. These form the basis for modelling at the farm/livelihood scale. The development of such an integrating dynamic model will be made possible through linking different ongoing research efforts, using a shell with different components as the basis for integration of outputs from the different thematic work packages within AfricaNUANCES.

This document presents the main ideas around the development of the analytical tool for AfricaNUANCES. The modelling approach to crop and soil processes was derived from the model SCAN (van Keulen, 1995), which was recently modified and used to analyse strategies for nutrient allocation in a simplified heterogeneous farm in Zimbabwe (Rowe *et al.*, 2005). Later developments from the original SCAN platform in the conceptualisation of the processes to be modelled are briefly discussed here. A model for livestock production and a model of nutrient dynamics through manure and organic resource handling and storage are also introduced. For the former, there is presently a running version whereas the latter is yet simply a conceptual model. The modelling approach described here is limited to the dynamic simulation tool. Potentially, multiple goal linear and non linear optimisation models would also be used for analysis at farm and region scale at specific points of knowledge integration.

We aim at developing an integrated bio-economic model, that lies in between the contrasting approaches described by Brown (2000): on one extreme, the biophysical models to which an economic balance has been addded, and on the other the economic optimisation models which include biophysical components as activities among the various choices for optimisation.

*A consistent definition of efficiencies and production situations*

Trenbath (1986) described two simple equations that identify the contributory components of resource use efficiency:

(1) Resource use efficiency = capture efficiency x conversion efficiency

Where:

(2) Capture efficiency = interception efficiency x absorption efficiency

These equations discriminate the components of efficiency in essentially the same way as the ‘three quadrant diagram’ for nutrient use efficiency developed by C.T. de Wit (see de Wit, 1992). Others have used the terms agronomic efficiency, uptake efficiency and physiological (or internal) efficiency for the three different aspects of resource use efficiency, capture efficiency and conversion efficiency, respectively. The separation of the various components of resource use efficiency allows exploration of the underlying mechanisms that contribute to (in-)efficiency in resource use (Giller et al., 2004). As different definitions of efficiency are dealt with throughout the description of the model, it will be made clear in each case whether such definition refers to resource use, to capture or to conversion efficiency.

Likewise, the concepts of potential, attainable and actual production situations for cropping and livestock systems are often referred to throughout the text. Figure 1 illustrates these concepts and shows the various yield defining, yield limiting and yield reducing factors affecting both crop and animal production.

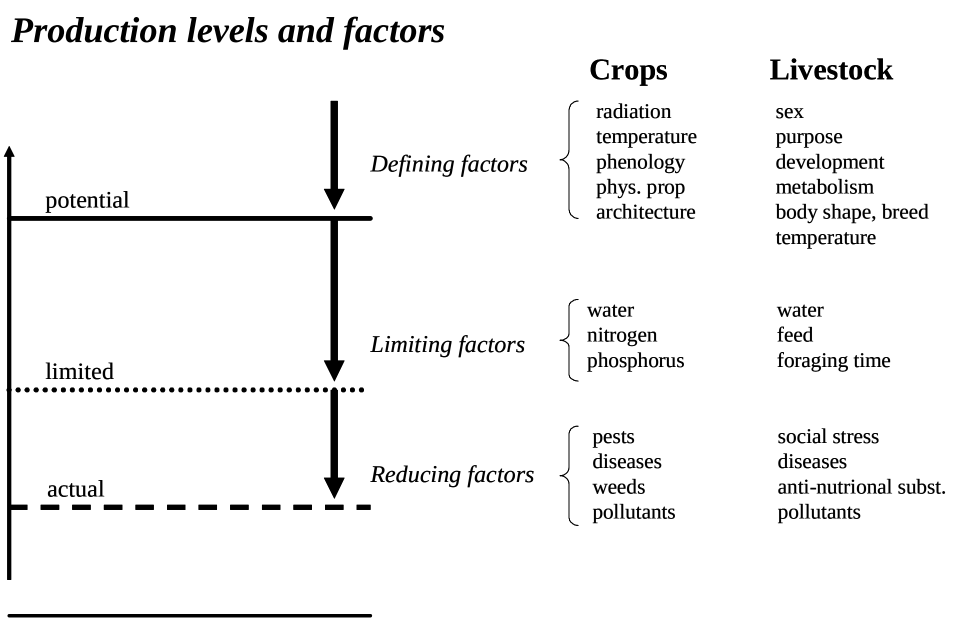


Figure 1: Concepts in production ecology for analysis and design of animal and plant-animal production system (van de Ven et al., 2003)

## 2. Model description

### 2.1 Overview

FARMSIM (FArm-scale Resource Management SIMulator) is the prototype, still largely conceptual model to be used as guideline for the development of the integrating analytical tool of Africa NUANCES (Figure 2). FARMSIM is a model shell that is developed in MATLAB 7.0 and allows for simulation of decisions on resource and labour allocation at farm scale, by considering a number of different fields within the farm. Such farm-scale decisions affect crop and soil processes taking place in each field, animal production by different units or 'herds' (e.g. cattle and shoats) and flows of materials through the composting heap, externalities to the environment such as soil erosion, and nutrient, labour and cash flows to, within and from the farm household.

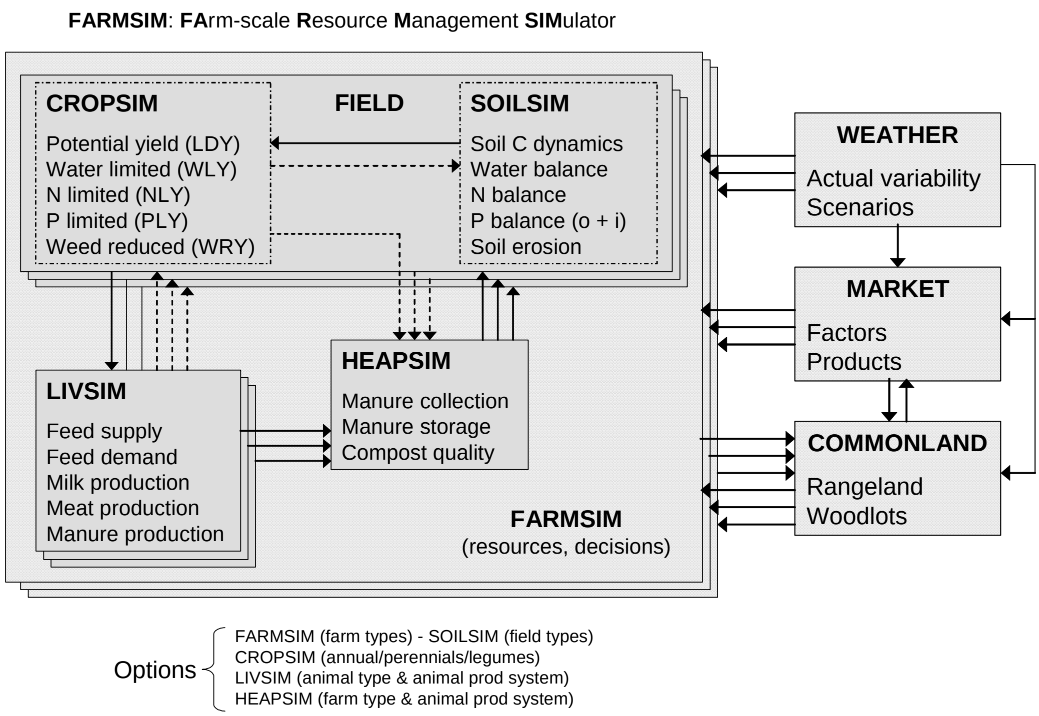


Figure 2: Overview of the integrating modelling shell FARMSIM. The economic balances and the household model are not explicitly considered in this initial prototype, but only through resource endowment, production orientation and household goals defined for each farm type (options).

A crop and a soil model (CROPSIM and SOILSIM, respectively) are combined at field/plot scale, parameterised for varying crop and soil types; different instances of FIELD (i.e. different combinations of crops and soils) can be run to simulate the interactions occurring within the farm for different field types (options: e.g. infields and outfields, annual and perennial crops, etc.). LIVSIM is a prototype model to simulate animal production (milk, growth) and maintenance requirements, in which each model instance represents one livestock production type, characterised by production objectives (dairy, meat, manure, traction), animal species and breeds; this model needs to be complemented with a sub-farm model shell to regulate stocks and flows of livestock heads due to reproduction and mortality rates and market decisions (STOCKSIM). The dynamics of nutrients via manure collection, storage and use as well as changes in quality due to management will be simulated by the prototype model HEAPSIM, considering transfer efficiencies for the different processes (options: livestock production systems, type of storage and handling facilities, etc.). This sub-model will be complementary to the calculations of stocks and flows of other organic materials at farm scale. Finally, the variability of the weather and market conditions, as well as the dynamics of resource availability from common lands constitute inputs to FARMSIM that need to be kept track of and modify for scenario simulation. However, these will not be explicitly modelled.

Appendices I to III present diagrams summarising the conceptualisation of the different sub-models to be developed (CROPSIM, SOILSIM–CN, SOILSIM–P, SOLSIM–water, SOILSIM–erosion, LIVSIM and HEAPSIM) and integrated within FARMSIM. These sub-models will be discussed in the following sections. The economic balances and the household model are not explicitly considered in this initial prototype, but only through resource endowment, production orientation and household goals defined for each farm type (FARMSIM options: family size, age and composition, production activities, etc.). This modelling approach is consistent with the typologies for fields and farms developed earlier for the categorisation and description of farm heterogeneity at different scales (Tittonell et al., 2005 a and b). Similar approaches for stratification of these sources of variability are being used in ongoing PhD research projects within AfricaNUANCES (e.g. Ojiem, J. – '*Niche-based approach to soil fertility and farm productivity improvement by legumes in Western Kenya smallholder systems*'), which will contribute case studies to operate the model for scenario analysis.

## 2.2 CROPSIM: simulation of crop production

The basic structure for CROPSIM was derived from the model for long-term sustainability assessment SCAN (van Keulen, 1995). The approach to modelling crop growth in SCAN is based on defining potential growth rates for the crop under ideal (theoretical) growth conditions and using reduction factors due to water, N and P limitations on these growth rates. Availability of the former resources in the soil during the growing season are contrasted with crop requirements for potential yield, calculated from characteristic crop transpiration constants and minimum N and P contents in the plant. The ratio between the available and required water, N and P are used to reduce crop yields proportionally (i.e. water-, N- and P-limited yields). The final crop yield is then calculated (chosen) following von Liebig's Law: the most limiting factor determines crop yield.

In CROPSIM, the simulation of crop production uses resource (light, water, nitrogen and phosphorus) use efficiencies derived from process-models and experiments, instead of potential growth rates and minimum nutrient contents as in SCAN. Additionally, the influence of multiple factors on the overall resource use efficiency is taken account of by following Liebscher's instead of von Liebig's approach, by which sub-optimal ranges of resource use efficiencies through interaction between resources are simulated. A key tool to introduce the effect of interacting resources is the model QUEFTS (QUantitative Evaluation of the Fertility of Tropical Soils) (Janssen et al., 1990). The QUEFTS approach of varying nutrient use efficiencies in face of other limiting resources, based on empirical relationships developed for eastern Africa (FURP, 1994), can be readily introduced in CROPSIM. Additional differences from SCAN will be (i) the calculation of resource balances on a monthly time step instead of yearly, allowing for simulation of two cropping seasons a year, for periods without crops and for delay in planting dates, (ii) the consideration of perennial crops and crop rotations, and (iii) the inclusion of crop yield reduction factors due to weed competition.

Balances for different resources for crop growth (light, water, N and P) are calculated on a monthly base and integrated for the season, with adjustments for early or late planting dates. From these seasonal resource balances, resource availabilities for crop growth are calculated (Appendix I). There is a ‘ceiling’ yield for the aboveground biomass (AB) that is determined by the amount of light captured by the crop and converted into dry matter under (presumably) optimal growth conditions (light determined yield). Use efficiencies (capture + conversion) for water, N and P are then used to calculate seasonal crop production (resource limited yield), considering thereafter yield reduction by weed competition (actual AB yield). As depicted in the diagram of Appendix I, there are three important *noda* that need careful attention and support from process knowledge in CROPSIM: (i) the fraction of incident radiation intercepted by the crop seasonally, (ii) the integrated reduction factor due to resource availability, and (iii) the reduction factor due to weed competition. These three key points are critical for simulation of management decisions, since they will be certainly affected by different resource and labour allocation strategies.

*The seasonal fraction of radiation intercepted (FRINT)*

From the total amount of photosynthetically active radiation (PAR) potentially available for crop growth during a season, in a given location, crops can only intercept a fraction: FRINT, calculated as the total amount of PAR intercepted by the crop from emergence to harvest over the total amount of PAR reaching the surface of the earth in a particular location during the growing season (Figure 3). The value of FRINT varies primarily for different crop types (i.e. crop species, perennials vs. annuals) and cultivars (duration of crop growth, temperature sum, distribution of leaves in the canopy and their morphology, etc.). Management may affect the value of FRINT through two main effects: (i) by modifying the architecture of the crop canopy or (ii) by asserting in matching the environmental supply and the crop demand through a proper timing of crop development within the season.

Figure 3 also shows the amount of radiation intercepted by a maize crop grown at low plant population densities, according to simulations performed with a ‘biological-process’ based model, which serves to illustrate the dependence of FRINT on this management factor. As observed in smallholder systems of sub-Saharan Africa, farmers often adjust plant densities to the perceived fertility of their soils. Additionally, the presence of intercrops will also affect the value of FRINT. Using the same model, simulations were run for different planting dates for maize. The results indicate that the value of FRINT changes during the development of the crop (the final value integrates the seasonal fraction), and that delaying the planting date of maize in this case (Mexico) reduced the total fraction of the incident radiation intercepted by the crop for the entire season (Figure 4 A). Field appraisals also showed that farmers delay the planting (and weeding) of the more remote fields within their farms. Thus, the value of FRINT can be described as a function of the delay in the planting date from an optimum, early date (Figure 4 B). However, the effect of the panting date might not be the same for different cultivars of a certain crop, as shown for maize also in Fig. 4 B.

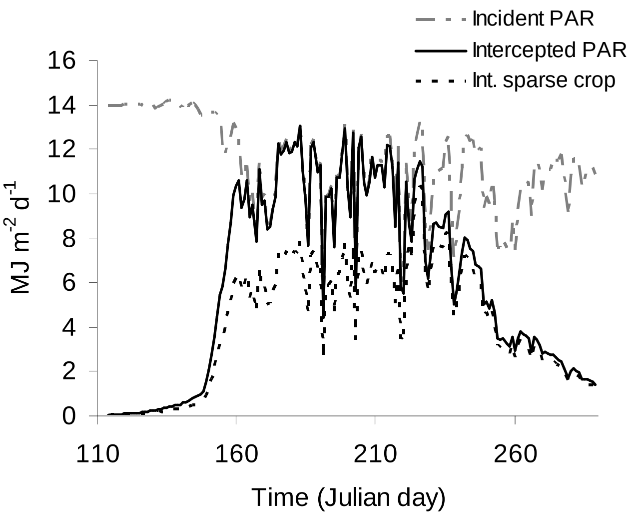


Figure 3: A modelling exercise to illustrate the fraction of seasonal incident PAR that can be intercepted by a maize crop grown at different plant population densities

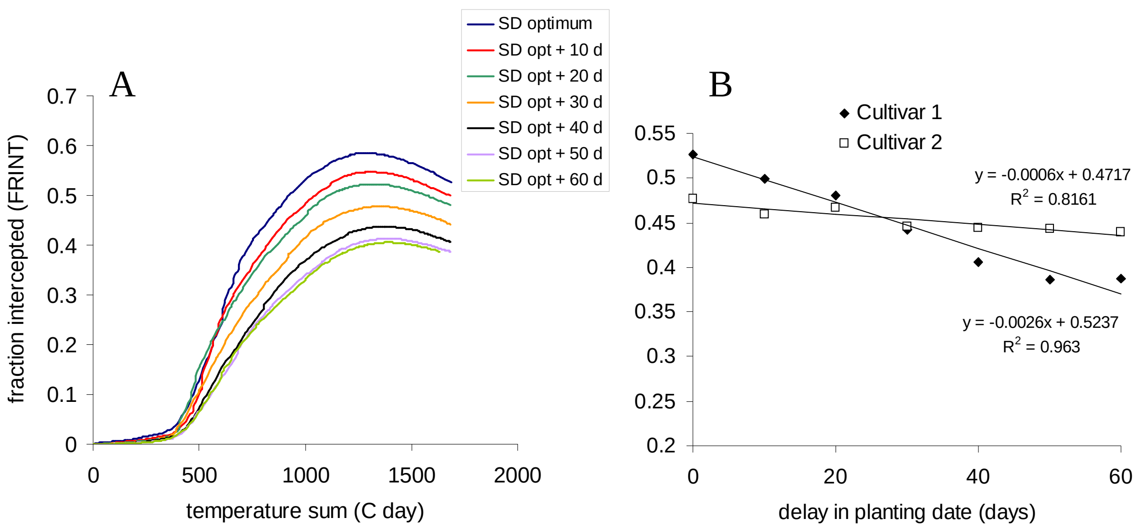


Figure 4: (**A**) Fraction of seasonal radiation (FRINT) intercepted by maize crops planted at different dates (model exercise for maize in Mexico); SD: sowing date. (**B**) Changes in the value of FRINT as a function of the days of delay in the planting date (from an optimum date) fro two maize cultivars (modelling exercise). Cultivar 1 was the same used in the simulations for Figs. 3 and 4 A.

The example above illustrates two main things: firstly, the advantage of this approach to calculate the ‘ceiling’ crop yields against the ‘potential’ yield approach; even when yield limiting resources such as N are available for crop growth, management decisions such as date of planting or the choice of cultivars may affect yields (and thereby N utilisation efficiency). This new 'ceiling' yield will in its turn affect crop demands for other resources, and therefore also the value of the yield reduction factors due to nutrient availability. Secondly, this exercise illustrates the potential for linking process-based models to generate parameters and variables that can be introduced as descriptive functions in a model for explorations at farm scale (FARMSIM).

*An integrated reduction factor for resource availability*

Using coefficients for the use efficiency (capture, conversion) of different resources (WUE, NUE, PUE) has the advantage that these values have been extensively reported for different crops and growing conditions worldwide, and may also help interacting the work of different working packages within this project. These coefficients give also the opportunity for studying interaction between resources for agricultural production – a central topic of AfricaNUANCES (Giller et al., 2004). Thus, the efficiency with which e.g. N is used by a certain crop will depend on water or on P availability for the crop, or on both at the same time (Figure 5). Therefore, N use efficiency (conversion, in this case) will vary between maximum and minimum values set by the characteristic range of N contents in the biomass of that particular crop. In the model, the reduction factors to affect the value of NUE can be calculated by contrasting e.g. available to required P levels, the latter derived from the range of N/P ratios for a certain crop, and calculating a fractional proportionality.

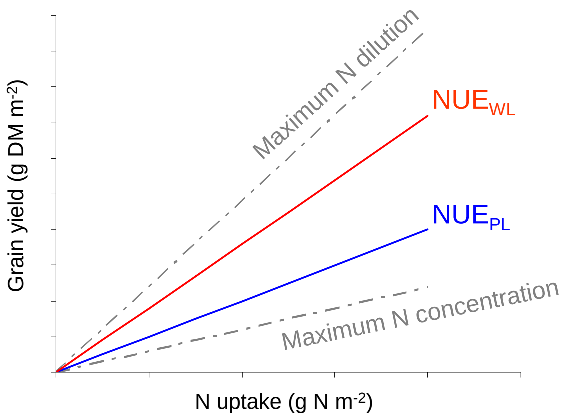


Figure 5: Theoretical relationship between N uptake and grain yield of a cereal crop. The slope of the line represents the N use efficiency (conversion) by the crop, or the inverse of the N content in the grains. Minimum and maximum NUE values are determined by characteristic ranges of N contents in the seeds of a certain crop. $NUE_{WL}$: NUE affected by water limitation; $NUE_{PL}$: NUE affected by P limitations.

*Yield reduction by weed competition (WRF)*

There are two aspects of main interest in the calculation of this reduction factor: (i) the effect of weed competition itself, which will depend on crop and weed type and agroecological conditions (i.e. competitive abilities), and (ii) the effect of management, or more generally of farmers' decisions on labour allocation to weeding and its interaction with timing of other farm activities. Yield reduction due to weed competition has been addressed by different approaches; from process-based modelling of competition mechanisms to more descriptive functions relating yield losses to weed density or relative weed leaf area or the length of the period that the crop remains free of weeds, etc. The latter seems promising as it relates quite straightforwardly to labour allocation to weeding during the season (determining also the opportunity of weeding during crop development). In search for an algorithm to relate the amount of labour invested in weeding to WRF, the farm-scale decisions shell FARMSIM uses an expert knowledge-derived function, considering periods of off-peak labour demands in the farm (Figure 6). This relationships and potentially others need further consideration, to count on a set of relevant WRF curves for different farming situations; such relationships need to be underpinned by studies using process based models and knowledge, and accounting for farmer' decision making.


Figure 6: Yield reduction factor due to weed competition as a function of the amount of labour invested in weeding.

### 2.3 SOILSIM: simulation of C and nutrient dynamics, water balances and soil erosion

SOILSIM is the 'soil sub-model' of the model FARMSIM, designed to explore long-term strategies and options for soil management. The general approach is to use simple models, with few parameters, but robust and sensitive enough to explore different scenarios across regions. In the case of C dynamics, some extra detail is considered due to the importance of the evolution of soil organic matter as an indicator of sustainability. SOILSIM calculates soil water, C, N and P balances and their availability for crop growth, and soil losses by erosion. SOILSIM was derived from the original SCAN model by simplifying the simulation of basic processes, to reduce the number of parameters to be estimated, thereby extending its flexibility of use for different situations. For example, the number of C pools in the soil was reduced and by that also the number of flows and paths to be considered in the model (thereby reducing the number of parameters describing decomposition/stabilisation processes). Such simplifications are made on the basis of the supportive process research simultaneously done in the different working packages of AfricaNUANCES (i.e. WP5 Soil quality, in this case).

### 2.3.2 C, N and P dynamics in SOILSIM

*Carbon*

Three C pools are considered in the model: C in crop residues and other soil amendments (e.g. manure), C in the active, decomposing organic matter pool (often referred to as microbial biomass), and C in the humified, soil organic matter (Appendix II – Fig. 1). For each pool, there is a constant maximum decomposition rate ($k_R$, $k_A$ and $k_S$) and a stabilisation fraction ($e_A$, $e_H$ and $e_S$) or partitioning coefficient (1 – $CO_2$ production). In this model, $e_A$ represents the growth efficiency of the microbes; $e_H$ is the humification coefficient (chemical stabilisation) and $e_S$ represents the physical stabilisation of C in the soil (the turnover rate $k_S$ will be affected by soil texture). A fraction of soil C is considered inert (initialisation), and a certain amount is seasonally lost by soil erosion.

In an initial step, $k_R$, $k_A$, $e_A$ and $e_H$ need to be calibrated from data on decomposition experiments. Once these parameters are known, the parameters for soil C turnover can be calibrated. The C/N ratios of the different pools are introduced as model parameters. Other quality aspects of the soil amendments such as lignin and polyphenol contents will be considered to calculate potential decomposition rates.

Without considering erosion losses, and assuming that the value of the fraction inert is zero, the amount of C in the soil C pool is calculated as:

$$C_S = C_S(i) + dC_S/dt * t$$

The rate of change of soil C is then:

$$dC_S/dt = - C_S * k_S + C_S * k_S * e_S$$

Or, expressed as $CO_2$ production:

$$dC_S/dt = - ( 1 - e_S) * k_S * C_S$$

Both $k_S$ and $e_S$ may be integrated in one single rate as:

$$dC_S/dt = - k'_S * C_S$$

Where $k'_S$ represents: $( 1 - e_S) * k_S$ , and this can be fitted to experimental data on SOM evolution.

*Nitrogen*

Nitrogen mineralisation follows C decomposition, considering the C/N ratios of the different C pools. The C/N ratio of the active OM ($C:N_{aom}$ ~ 8) determines the magnitude of the immobilisation flow from mineral soil N. The net rate of change of mineral nitrogen in the soil can be generically expressed as:

$$dN_{min}/dt = NetN_{min} + FertN – N_{upt} – N_{lost}$$

where,

$NetN_{min}$ = N mineralization – N immobilisation

$N_{lost}$ is calculated as the fraction of total soil mineral N lost by denitrification, volatilisation and leaching. This fraction needs to be calibrated for different agroecological conditions (soil types, rainfall) using experimental data on N release, N application and N uptake.
Thus, the amount of mineral N available in the soil is partitioned between crop uptake, N immobilisation by microbes and N losses by different processes. This partitioning needs further attention, as it determines the priority for N allocation to the different processes. In models for high-input farming situations, losses and immobilisation are first discounted, and then the remaining N is assumed to be taken up by the crop. Under low-input conditions, uptake or immobilisation may have priority over e.g. leaching.

*Phosphorus*
Four soil P pools are considered: two organic pools, one related to the active biomass ($ACTP_O$) and the other to the stable organic matter ($SOMP_O$), and two inorganic pools, a stable ($STABP_I$) and a labile ($LABP_I$) one (Appendix II – Fig. 2). Organic materials incorporated in the soil (plant residues, manure) have a characteristic fraction of P in the stable form ($F_{ops}$) and a certain C/P ratio. P release from the organic pools follows C decomposition, according to the C/P ratios of the different pools, so that there may be mineralization and immobilisation of P. Likewise, inorganic fertilisers have a characteristic fraction of P in the stable form ($F_{ips}$). The equilibrium between stable and labile inorganic P in the soil is represented by transfer rates between both pools ($TR_{LTS}$ and $TR_{STL}$). Such transfer rates are likely affected by soil properties such as texture and pH. Generically, the net rate of change of the labile P in the soil is calculated as:

$$dLABP_I/dt = STABP_I * TR_{STL} – LABP_I * TR_{LTS} + FertP_I * (1 – F_{ips}) + NetP_{min}$$

where,
$NetP_{min}$ = P mineralization – P immobilisation

The labile $P_I$ pool represents the amount of P potentially available for the crop. However, not all available P will be taken up by the crop but a fraction of it, which depends on factors such as the extent of soil exploration by roots, water availability, etc. This fraction needs calibration, and contributes to the P use efficiency of the crop (i.e. interception or uptake efficiency).

### 2.3.3 Water balance

The calculation of the water balance in the soil and water availability to the crop has not been modified from that of the original SCAN model, using monthly rainfall (PP) and potential evapotranspiration (PET) data (Appendix II – Fig. 3). The infiltration capacity of the soil is related to its sorptivity, which is a function of particle size distribution and affected by soil and crop management (Driessen, 1986). On the basis of this, the annual fraction runoff is calculated, taking into account the slope of the field. Soil water holding capacity (WHC) is calculated from soil depth and the specific WHC per unit soil depth, derived from the textural composition of the soil. The sum of the monthly difference between PP and the sum of PET and WHC is assumed to drain below the rooting zone. Seasonal evaporation is derived from the total amount of water stored in the root zone, taking into account the fraction of sand in the soil and soil cover, due to the crop and residues left on the soil. The difference between total infiltration and drainage plus soil evaporation is assumed to be available for transpiration by the crop. However, the fraction of total water available that the crop will effectively use will depend on timing of crop development within the season (similar to what happens with light interception, cf. FRINT).

A major problem here is that the distribution of rainfall within the month is not known, which affects both the distribution between infiltration and runoff, and the partitioning of infiltrated water among deep drainage, direct soil evaporation (both non productive in terms of crop growth) and crop transpiration. For sandy soils prone to high percolation rates, a drainage coefficient (or seasonal fraction drained) could be introduced and calibrated against experimental and modelling data and functions. Such coefficient may allow better simulations of the competing processes of drainage and crop uptake, particularly under conditions of uneven rainfall distribution.

### 2.3.4 Soil erosion

Modelling of soil losses by erosion processes is of interest from a double perspective: at farm scale, soil erosion contributes to soil C and nutrient depletion and impacts on the physical degradation of the soils. At village, watershed and regional scales, soil erosion constitutes an externality of agriculture to the environment, e.g. affecting the quality of drinking water, as often natural streams or ditches are used to obtain water for direct consumption by humans in Sub-Saharan Africa. However, the appropriate modelling approach for each of these scales of analysis may not be the same. At field scale, erosion losses have been largely described (and predicted) using the classical universal soil loss equation (USLE). The different terms of this equation have been studied and tabulated values given to simulate soil losses by water erosion under tropical conditions (e.g. Roose et al., 1975). This approach was used in the original SCAN model, and no modifications have been yet introduced (Appendix II – Fig. 4). For the simulation of the landscape dynamics the LAPSUS model (Schoorl et al., 2000) looks promising as a tool to monitor environmental externalities within the integrated analytical tool of AfricaNUANCES. LAPSUS (LandscApe ProcesS modeling at mUlti dimensions and scaleS) is a basic surface erosion/deposition model based on the continuity equation for sediment movement (Kirkby, 1986).

## 2.4 LIVSIM: Simulation of livestock production, herd dynamics and market decisions

Livestock production is simulated by LIVSIM (Appendix III – Fig. 1), currently a running model written in MATLAB 7.0, which is based on production ecological concepts for animal production systems (van de Ven et al., 2003). Different instances of LIVSIM within the farm represent different animal production units: e.g. confined dairy cows, oxen for traction, marauding zebu breeds for beef, sheep and goats, etc. Each production unit has a certain size that is expressed in tropical livestock units (TLU), e.g. a certain composition in terms of animal species and categories (i.e. a ‘herd unit’) may be integrated by all the animals that are taken to the communal grasslands every day, and may include zebus and shoats, and within those different age classes and status. All animals integrating a herd may be assigned a TLU value (often a fraction) and the total TULs are summed up to calculate the size of the herd. However, to calculate feed demands and rates of reproduction and mortality of the herd, it is necessary to keep track of its composition in terms of species, ages and gender.

Both supply and demand of feeds depend on the type of animal production system (dairy cows tethered in the home compound fields vs. free grazing cattle kept as a mid-term investment of the household). Feed supply depends on the availability of organic resources to be used as feeds (e.g. crop residues), on the availability of communal grasslands or common areas for collecting natural forages, and eventually on the access to feed resources offered in the local markets (e.g. Napier grass bundles). According to the intrinsic quality of these resources affecting their intake and digestibility by the type of animal to be fed, the amount of ingestible digestible dry matter is then calculated (feed availability).

Feed requirements for potential production (IDDM: ingested digestible dry matter) are derived from the energy needs ruminants, set as 36 g IDDM per $kg^{0.75}$ per day. From that, the following decision rule follows in the model, to select the conversion function to be used:

if $IDDM_{availble} > 36$ g $kg^{0.75\ -1}$ $d^{-1}$

(1) Weight gain (kg $d^{-1}$) = 49 x $10^5$ x (IDDM – 36) x Body $weight^{0.75}$

if $IDDM_{availble} < 36$ g $kg^{0.75\ -1}$ $d^{-1}$

(2) Weight loss (kg $d^{-1}$) = 58 x $10^5$ x (36 – IDDM) x Body $weight^{0.75}$

For lactating animals, potential feed requirements are calculated by multiplying potential IDDM times 1.2. When the available IDDM equals the potential requirements, the potential production level is achieved; this is described by equation (1) for body weight gain. When availability falls bellow potential IDDM requirements, there is weight loss according to equation (2). However, in the case of female animals in their reproductive phase, the first effect of suboptimal IDDM availability is a reduction of milk production, followed by reduced growth and eventually reproductive capacity and/or the age of first calving. Thus, animal production (growth, milk, calving) is calculated from the actual feed intake, in terms of IDDM, and from that also the production of manure, which together with feed refusals represent inputs for the sub-model HEAPSIM.

A sub-routine of FARMSIM accounts for the size and composition of the different herds belonging to the farm household (STOCKSIM). The net rate of change in the number of animals depends on the rates of reproduction and mortality (related also to nutritional status), and on market decisions in terms of purchasing or selling animals. The former are a function of herd composition and (nutritional, sanitary) status, affected by management decisions. Market decisions are derived from household strategies, goals and production orientation (thus related to farm typology).

## 2.5 HEAPSIM: Simulation of nutrient dynamics in the manure heap

HEAPSIM is a conceptual model to simulate the dynamics of nutrients throughout the processes of manure collection, handling, storing and application (Appendix III – Fig. 2). The idea of dividing the flow of nutrients into these different compartments and to define 'efficiencies' for each of these processes was derived from the approach followed by Rufino et al. (2005) in their review on N transfer efficiencies in mixed crop-livestock systems. Each of these efficiencies depends on the type of animal production system (e.g. cattle vs. shoats, free grazing vs. zero grazing) and on the type of livestock facilities present in the farm (compost pits or heaps, roofed or open-air manure storage facilities, etc.). Manure can be collected from the fields in communal grasslands or form the floor of a zero grazing unit; manure composition and physical properties will vary widely for these different systems. The model considers also the effect of diverse management practices such as adding crop residues with a high C:N ratio to reduce N leaching, rock phosphate additions, or turning over the manure heap to induce 'maturation'. Manure can also be directly dejected in cropping fields when the animals graze standing crop residues. All these practices imply different rates of nutrient losses. At the moment, a prototype fuzzy-logic model is under development, in which all these options (i.e. animal production system, characteristics of the storage facilities, management practices) are considered. A major challenge for developing this sub-model is to identify functional relationships to describe the effect of all this practices on the efficiency of nutrient transfer when different qualities of manure are considered, which will in its turn affect the final quality on the compost applied to the soil for crop production. While there is a considerable amount of information on C flows and balances throughout manure handling and storage, and to some extent for N, less is known for other nutrients.

# 3. FARMSIM: resources, decisions and tradeoffs

Scenarios for different farm types in terms of resource endowments, household goals and production orientation, considering also their internal heterogeneity (field typologies or farmers' field classes) and the particular pattern of resource and labour allocation derived from it, are simulated with FARMSIM. In the current model several decisions operate mainly at farm-scale: e.g. the area of cropped land per season and the yield reduction factor due to weed intensity depend on the amount of labour available at farm scale and on its strategic allocation pattern within the farm. Differential management of the various fields of a farm is also possible, as different decisions are organised in arrays, with each element within the array pertaining to a certain field within the farm. The type of data that needs to be collected to run FARMSIM, through field appraisals and surveys for system characterisation and categorisation of farm heterogeneity (farm typology, local soil quality classification, etc.), and on management practices and resource allocation (e.g. resource flow maps, field transects, etc.) will be detailed in subsequent working documents (working papers 2 to 5).
Another important aspect of the scenario analysis for decision-making on resource and labour allocation is the analysis of tradeoffs between competing farmers' goals and strategies. In FARMSIM, tradeoffs analysis is done by linking dynamic models to non linear optimisation tools, using inverse modelling techniques (van Wijk and Vrugt, 2005). There is currently a

prototype tool linking a dynamic, process-based model for simulation of nutrient balances at field scale (DYNBAL, DYNamic simulation of Nutrient BALances – Tittonell et al., 2005c) to MOSCEM (Multi-Objective Shuffled Complex Evolution Metropolis). This type of analysis are also useful for contrasting objectives of different stakeholders in a village or a region; e.g. while one of the objectives of farmers may be maximising farm profit, local governments (municipalities, districts, *arrondissements*) may be interested in the amount of money that farmers invest in hiring labour, as this creates local job opportunities. However, for a certain farming situation the analysis may show clear tradeoffs between these two objectives (Figure 7).

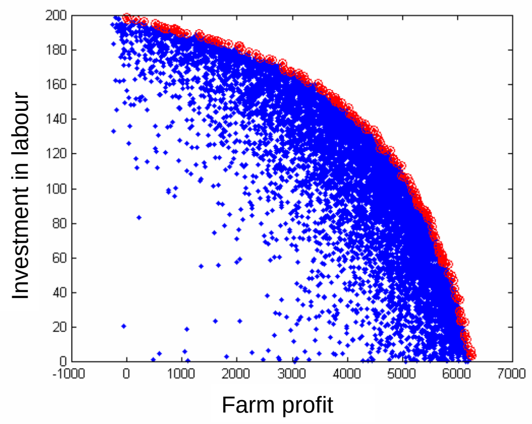


Figure 7: A typical curve for analysis of tradeoffs between objectives (farm profit and investments in labour) at farm scale produced with MOSCEM.

## 4. Outlook and future steps

Improvements to this initial modelling approach are expected from the interaction between the different thematic working packages of AfricaNUANCES. Methodological approaches for model calibration and testing are currently being designed by the working team in charge of developing this analytical tool (Plant Production Systems Group, Wageningen University). Progress has been made in identifying process based, biophysical modelling tools and data sets from different regions relevant to the analysis of African farming systems, to underpin the development of descriptive models for use at farm scale. Much progress has been made in developing the basis for CROPSIM, SOILSIM and LIVSIM, though the heap module still needs further attention. The imminent step for the development of these sub-models is their calibration under a wide range of farming system situations for Sub-Saharan Africa.

Prospecting the contribution of modelling to improved farmers decision-making both McCown (2002) and Mathews and Stephens (2002) suggested that simulation modelling using a participative approach may be the future. Thornton and Herrero (2001) pointed out that to avoid “models remaining in academic circles” there is a need to increase the understanding of the behavioural and managerial aspects of the household which, together with the biophysical aspects of the production system, will determine the feasibility of the alternatives proposed (i.e. the ‘Participatory modelling’ approach). Even the definition of system boundary, its sub-components, input and outputs can be done by the farmer (Defoer et al., 1998). Moreover, testing the performance of such an integrated model as FARMSIM, with different processes being dynamically simulated at the same time, constitutes a difficult task. Iterating with farmers and local experts by discussing model results, capitalising their knowledge on the system being modelled, represents a sensible strategy for testing and continuous improvement of the model. In this context, creating opportunities for linking knowledge integration by modelling of farm production processes, feeding on experimental and system analytical research (the ‘hard’ approach), and knowledge generation on decision-making and scenario setting by participatory methods (the ‘soft’ approach) constitutes a major challenge to be embraced throughout the development of the analytical tool for AfricaNUANCES.

*The NUANCES workshop:* Several issues related to improvements of this basic modelling approach were discussed during the NUANCES workshop held in February 2005 at Wageningen University, The Netherlands. For CROPSIM, it was decided to include the effect of K availability on crop production, for which a SOILSIM-K module needs to be developed. The effect of crop rotations and multiple cropping were suggested as key issues the model should be able to consider. A list of main crops to be considered for simulation was also developed (Appendix IV). For SOILSIM and HEAPSIM, the need to simulate not only C but also the $CO_2$, $N_2O$ and $CH_4$ dynamics was also indicated, to be able to investigate possibilities for C sequestration measures at farm scale. For LIVSIM, the main issues discussed were related to the simulation of productivity of the natural grasslands and calculation of the intake rates of free grazing animals. The use of the model RUMINANT was proposed to develop functional relationship for LIVSIM, including the interaction between different quality attributes (i.e. NDF, %Dig., %N) and their effect on feed intake.

**Acknowledgements**

The authors thankfully acknowledge the contributions of Marc Corbeels and Herman van Keulen during the conceptual design of the initial CROPSIM and SOILSIM sub-models, and the fruitful comments of Jo Smith on the modelling of C and nutrient dynamics in SOILSIM. Many of the concepts built into the modelling approach for farm-scale decision making fed on ideas and functional relationships developed by Ed Rowe.

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# Appendix I – Overview of CROPSIM

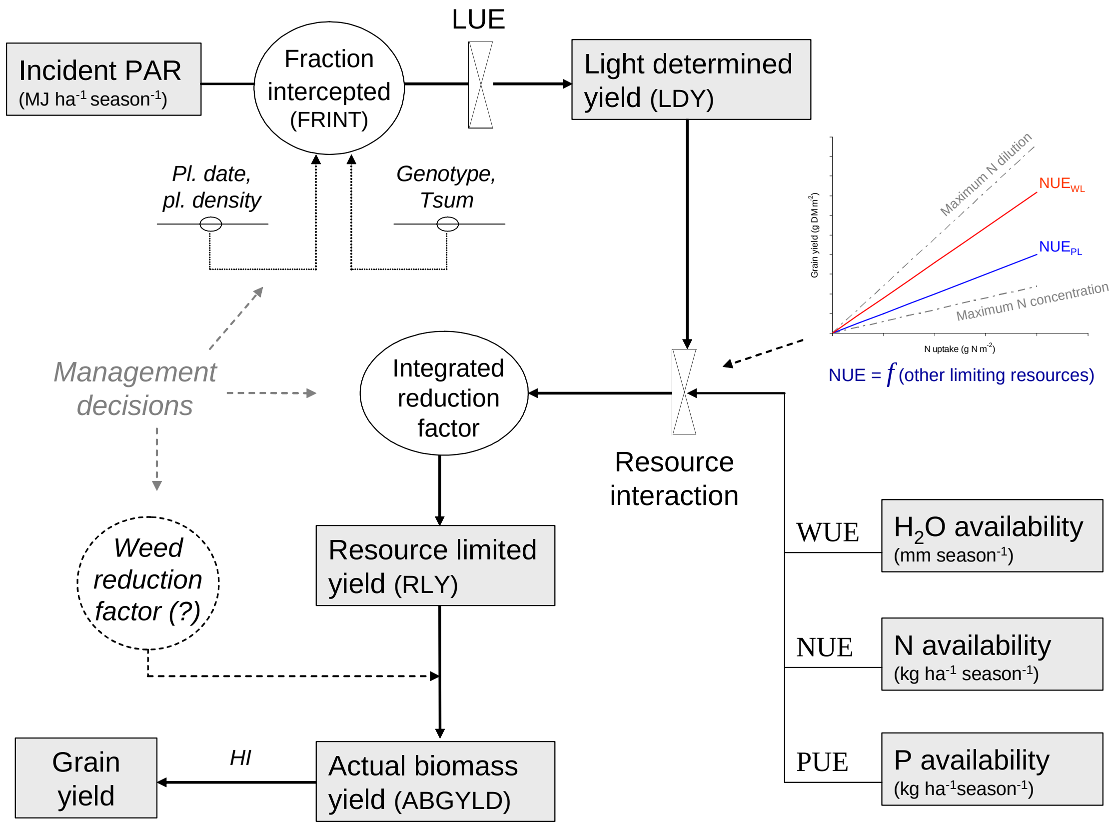



Fig. 1: Simulation of crop production in FARMSIM The approach for the yield reduction factor due to weed competition is still under development. PAR: photosynthetically active radiation; LUE, WUE, NUE, PUE: light, water, N and P use (conversion) efficiencies. Resource 'availabilities' represent potential uptakes; the differences between soil available and crop uptake for water, N and P (recovery coefficients or resource capture efficiencies) are calculated in SOILSIM.

# Appendix II – Overview of SOILSIM

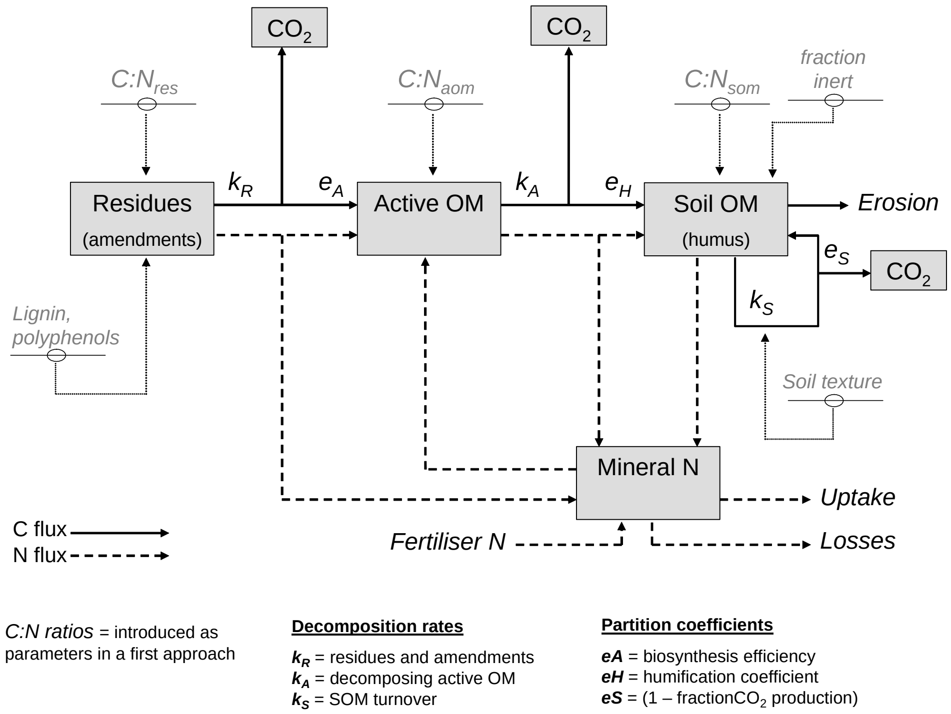



Fig. 1: SOILSIM – CN. Simulation of C and N dynamics in the soil, and N availability to the crop.

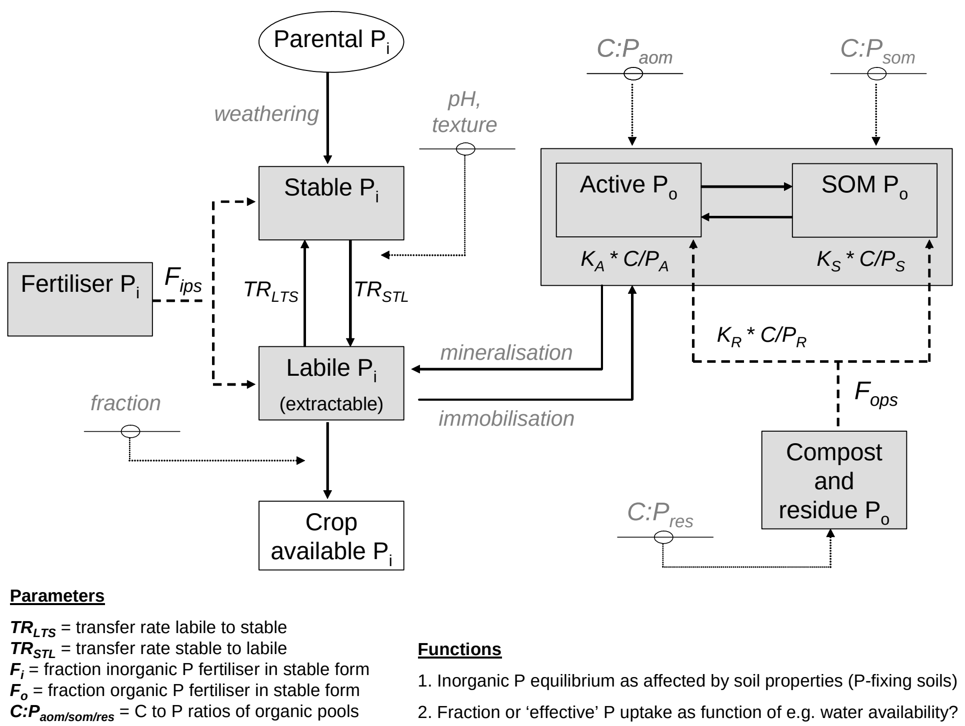
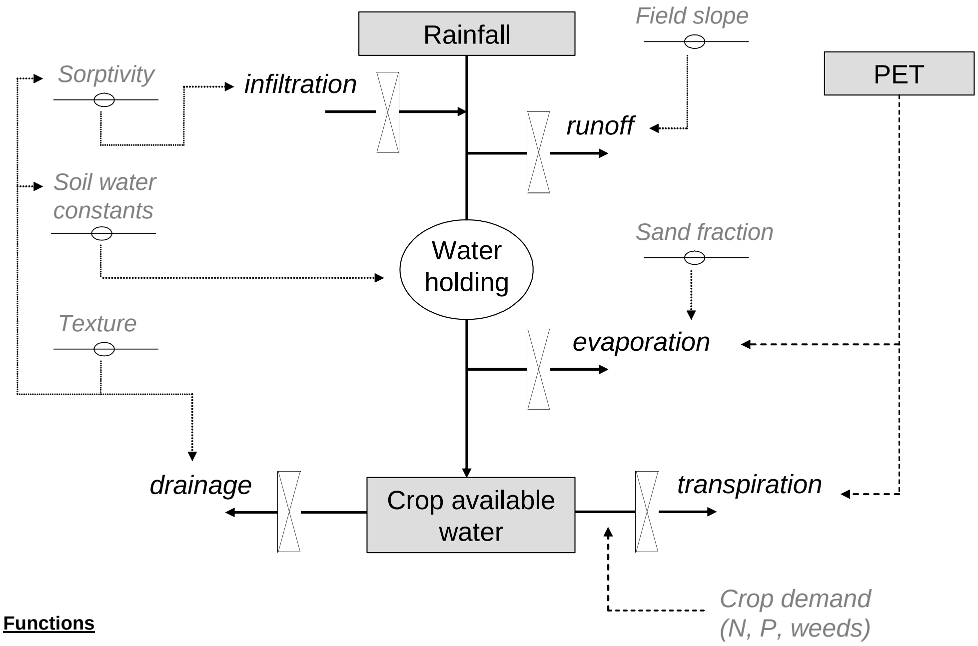



Fig. 2: SOILSIM – P. Simulation of organic and inorganic P dynamics in the soil and P availability to the crop

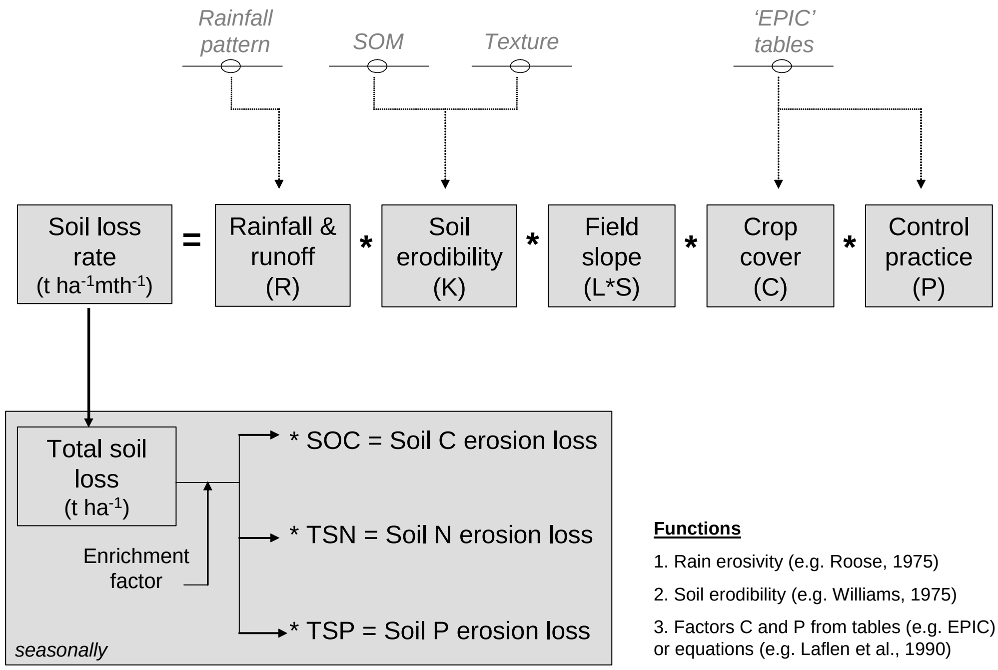
Appendix II – Overview of SOILSIM (Cntd.)




**Functions**

1. Sorptivity as fc of soil texture and management (Driessen, 1986)
2. Runoff as fc of field slope (Lal, 1976)
3. Evaporation rate as fc of sand fraction (van Keulen, 1975)
4. A drainage coefficient as fc of texture for sandy soils (van Keulen, 1975)

Fig. 3: SOILSIM – W. Simulation of water balances in the soil and crop available water




**Functions**

1. Rain erosivity (e.g. Roose, 1975)
2. Soil erodibility (e.g. Williams, 1975)
3. Factors C and P from tables (e.g. EPIC) or equations (e.g. Laflen et al., 1990)

Fig. 4: SOILSIM – E. Calculation of soil losses by water erosion using an adapted version of the universal soil loss equation (USLE)

# Appendix IIII – Overview of LIVSIM and HEAPSIM

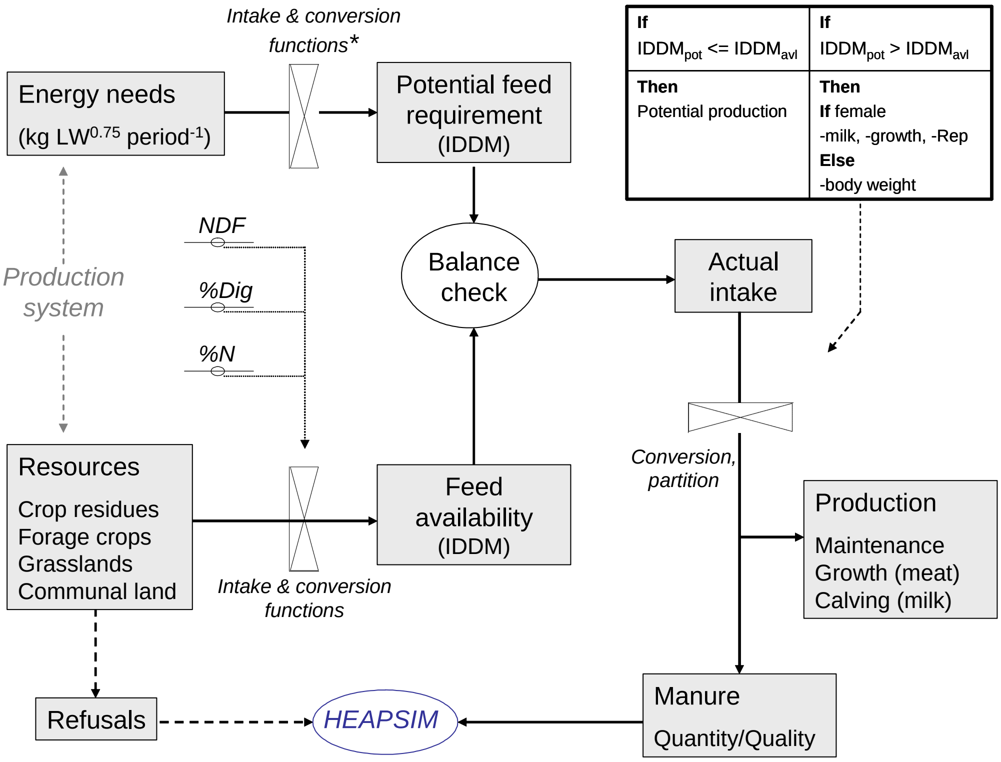



Fig. 1: LIVSIM. Simulation of livestock production and feed demands. The unit of analysis is the animal, while the number of animals and their characteristics (species, type) are simulated by a module called STOCKSIM, in which the net rate of change of the herd size depends on reproduction, mortality and market decisions. IDDM: ingested digestible dry matter.

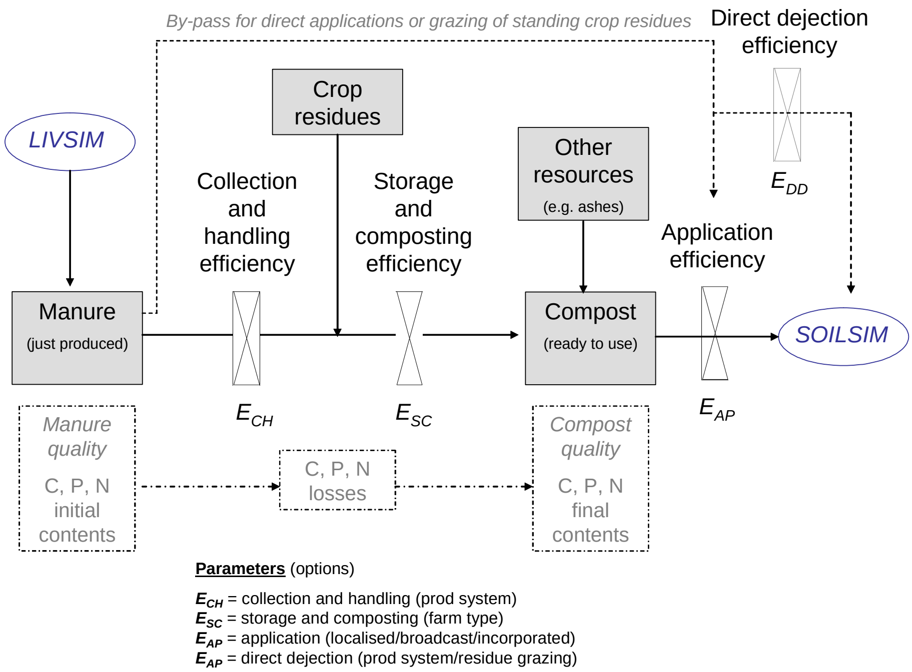



Fig. 2: HEAPSIM. Simulation of C, P and N dynamics during manure production, collection and handling, storing and application. Empirical relationships are abundant for C transfers in literature, whereas N and P dynamics require further consideration.

## Appendix IV – List of crops to be considered for CROPSIM

List of main crops in the eight AfricaNUANCES locations that will be considered for simulation using CROPSIM

| Cereal crops | Legume crops | Root/tuber crops | Perennial crops | Strictly cash crops |
|---|---|---|---|---|
| Maize | Common beans | Cassava | Bananas | Cotton |
| Sorghum | Bambara beans | Sweet potatoes | Coffee | |
| Finger millet | Ground nuts | Yams | Palms | |
| Pearl millet | Cowpea | Taro | Tea | |
| | Soybean | Potatoes | Trees (woodlots) | |
| | Pigeon pea | | | |