

**Documentation and manual of the LUCIA model,
version 1.2**

state September 2011

C. Marohn and G. Cadisch

The Uplands Program SFB 564, subprojects C4.2 / T6

Institute for Plant Production and Agroecology in the Tropics and Subtropics

University of Hohenheim

Index

1 Introduction.....	3
1.1 Scope.....	3
1.2 Conceptual basis.....	3
1.3 Recent development.....	4
2 Soil.....	5
2.1 Soil physics.....	5
2.2 Changes in soil structure and bulk density.....	6
2.3 Soil chemical characteristics.....	7
2.4 Soil Phosphorus.....	9
2.5 Litter and soil organic matter cycling.....	12
3 Water balance.....	13
3.1 Routing.....	13
3.2 Evapotranspiration.....	14
3.3 Infiltration, deep infiltration and redistribution.....	15
3.4 Soil water stocks.....	17
3.5 Capillary rise.....	18
3.6 Percolation, lateral flow, loss and baseflow.....	18
3.7 Surface Runoff.....	19
3.8 Lakes.....	20
4 Plant growth.....	20
4.1 Net assimilation rates.....	20
4.2 Death rates.....	22
4.3 LAI and cover.....	22
4.4 Phenological stages and differentiation.....	22
4.5 Water uptake and stress.....	27
4.6 Nutrients limiting growth.....	27
4.7 Existing fallow vegetation and natural succession.....	28
5 Nutrient translocation in the landscape.....	29
5.1 Erosion.....	29
5.2 Leaching of nitrogen.....	30
6 Management.....	30
6.1 Cropping calendar and land cover change.....	30
6.2 Tillage.....	31
6.3 Fertiliser and manure.....	31
6.4 Irrigation.....	31
7 Parametrisation from the GUI.....	32
7.1 Maps.....	32
7.2 Scenarios and management.....	33
7.3 Land cover related data.....	34
7.4 Soil related data.....	37
7.5 Weather data.....	37
8 Outputs.....	39
9 References.....	40
10 Appendices.....	43
10.1 Model parameters and units.....	43

1 Introduction

The Land Use Change Impact Assessment tool (LUCIA) is an integrated spatially explicit and dynamic model used to project impacts of land cover change on agricultural productivity and environmental functions at the scale of small catchments up to about 30km². The model was developed for the Special Research Program SFB 564 (The Uplands Program – *Sustainable Landuse and Rural Development in Mountainous Regions of Southeast Asia*) to simulate watershed functions, soil fertility and plant growth in small catchments in mountainous areas of Thailand and Vietnam. The model has been created as a generic tool and was tested in Mae Sa Noi, Chiang Mai, Thailand, and Ban Tat, Hoa Binh, Vietnam.

1.1 Scope

The model aims at assessing consequences of land use change on soil productivity and environmental services. In the given context of mountainous catchments linkages between upland and lowland play a decisive role for equitable resource use, water storage capacity, erosion, siltation and nutrient flows. The risk of resource overuse but also potentials of reduced deforestation and carbon sequestration or soil protection measures can be assessed in scenarios run in LUCIA. While numerous models exist that can depict single processes to a more detailed level, LUCIA aims at an integrated perspective of watershed and plant processes without foregoing a process-based approach. This, in combination with a simulation of decision-making processes, allows to address different user groups: Researchers aiming at assessing the sensitivity of certain impacts to related causes or at projecting future developments, land use planners weighting pros and cons of alternative development scenarios, and students interested in understanding processes in integrated systems.

1.2 Conceptual basis

LUCIA builds on concepts of established, partly more detailed, models. In the beginning of model development, GenRiver (WIDODO ET AL. 2007), a generic semi-spatial cascade model, played an important role in determining the main soil water stocks and flows on the pixel level. In addition, the concept of plant loosening the soil and thus increase water storage capacity was inspired by GenRiver. In order to simulate erosion, a more detailed and spatially explicit representation of infiltration and run-off was needed. This led to the adoption of pedotransfer functions to derive estimates of hydraulic conductivity, developed by SAXTON AND RAWLS (2006) for the SPAW model. Infiltration was implemented following the Parlange (SMITH AND PARLANGE 1978) equations as established in KINEROS 2 (WOOLHISER 1990), while erosion builds on the concept of ROSE ET AL. (1983a) as implemented in WaNuLCAS (V. NOORDWIJK AND LUSIANA 1999). Soil organic matter dynamics closely follow the CENTURY approach (PARTON ET AL. 1987) considering four litter and three soil carbon pools of different recalcitrance. The crop model in LUCIA is based on WOFOST-CGMS (SUPIT 2003), with the

transpiration concept adapted from the FAO irrigation paper 56 (ALLEN ET AL. 1998).

Two approaches are pursued to implement farmers' decision-making on land use and management into the model: a) Dynamic coupling with an existing multi-agent model that optimises decision-making based on economic criteria (BERGER ET AL. 2006), b) a simplified LUCIA-Choice module, under development, based on two sequential steps, suitability and preference.

LUCIA is a raster-based spatially explicit dynamic model written in PCRaster code (V. DEURSEN 1995). The model operates on a daily time step and at user-defined pixel size, which usually reflects average plot size in the research area. Within PCRaster default settings are used except for
#! --radians --unittrue --matrixtable.

In this documentation most formulae are written in pseudo-code as used for the LUCIA model script. Units for soil nutrients, are given in [$\text{kg}\cdot\text{ha}^{-1}$], while carbon and biomass are in [$\text{Mg}\cdot\text{ha}^{-1}$]. Soil and rooting depth are in [cm]. Water-related parameters are in [mm], [$\text{mm}\cdot\text{d}^{-1}$] or, for area totals >1 pixel, in [m^3]. SLA is in [$\text{ha}\cdot\text{Mg}^{-1}$], temperature in [$^{\circ}\text{C}$]. All parameters needed to parametrise the model are listed and explained in the parameter glossary in section 10.3.

1.3 Recent development

Since April 2009, conceptual updates include the more detailed infiltration and routing functions, while the main technical improvements were the change from arrays to look-up tables and the graphical user interface.

One major objective of the model is the simulation of redistribution processes in the landscape, particularly run-off and erosion / siltation.

The previous simplified concept of infiltration based on direct estimates of maximum infiltration was replaced with an explicit calculation of hydraulic conductivity based on SAXTON AND RAWLS (2006), carried out in the user interface. A more process-based concept of infiltration as described by SMITH AND PARLANGE (1978) and in the KINEROS 2 model (WOOLHISER 1990 and online documentation¹) was implemented instead of the previous infiltration constant. In addition, redistribution between soil horizons now considers saturated and hydraulic conductivity and capillary rise. Soil moisture is calculated twice per time step, allowing to determine saturation overflow, which is added to hortonian flow. Shifting to more detailed algorithms implied moving from a daily to an hourly time step. This was achieved using a loop construction native to PCRaster.

Routing algorithms for surface run-off, lateral flow and baseflow were changed from accuflux to accuthreshold functions, allowing to account for infiltration of run-on and saturation of soil horizons before water leaves a pixel.

Technically, parameter arrays for land cover and soil unit parameters were eliminated to make use of the updated pcrcalc software, which does not support arrays anymore. These were replaced with look-up tables. This change was also necessary for the coupling of LUCIA with the multi-agent model MP-MAS (BERGER

¹<http://www.tucson.ars.ag.gov/kineros/> accessed May 5th, 2010

ET AL. 2006). Conceptually, the shift to look-up tables makes did not change the model.

A graphical user interface (GUI) was designed in Python Qt to simplify parametrisation, restrict parameter ranges, carry out calculations and visualise input curves. Recent PCRaster development is directed toward a framework for model coupling and parallelisation of computers, so that LUCIA can make use of synergies.

2 Soil

Soil properties are assigned class-wise in a soil map in PCRaster format. Classes are user-defined, e.g. according to the World Reference Base (WRB) or local soil maps.

Soils in LUCIA consist of two horizons, topsoil and subsoil, each assumed to present homogeneous characteristics and user-defined thickness. Hydraulic conductivity of the parent material below the subsoil horizon determines whether a soil can become stagnant.

2.1 Soil physics

2.1.1 Soil depth and rooting space

Soil depth is the sum of top- and subsoil, while rootable depth, caused by impermeable soil layers such as rock, hard pan or permanent water logging, can be less than soil depth. All nutrient and water resources available for plants are accessible only from the rooted soil. Both soil horizons correspond through percolation, capillary rise and leaching (under construction). Erosion can extend into the subsoil horizon once the topsoil has been completely removed.

2.1.2 Relevant parameters

Horizon thickness, stone contents, bulk density, sand and clay contents and soil organic carbon need to be fed into the model. Additionally, saturated conductivity of the parent material (below the subsoil horizon) must be defined.

2.1.3 Pedotransfer functions

Parameter inputs are used for automatic calculations of further soil characteristics employing pedotransfer functions after SAXTON AND RAWLS (2006). Total pore volume (TPV) is calculated as share of total volume; air capacity (AC), field capacity (FC) and permanent wilting point (PWP) are determined and expressed as shares of TPV.

The pore size distribution index λ is determined from FC and PWP and forms the basis for calculation of saturated hydraulic conductivity (K_{sat}).

As suggested by SAXTON AND RAWLS (2006) AC, FC, PWP and K_{sat} are derived in a two-step procedure of first approximation and adjusted value².

²In the previous model version, TPV, AC, FC and PWP were read from nomograph tables by JAHN ET AL. (2003, after AG Bodenkunde 1994). K_{sat} was not calculated.

2.2 Changes in soil structure and bulk density

Roots penetrating the soil create voids once they die and decompose; they can thus loosen but also compact the soil, which is specific for each land use. Such melioration or degradation effects were accounted for following the concept of the GenRiver model (WIDODO ET AL. 2007). Since Sep 2011 the concept of yearly updates based on land use specific reference bulk density has been updated to a daily approach. Bulk density is now an additive function of root growth, time and – in the topsoil – ploughing, limited to a range between 0.8 and 1.8 g cm⁻³. Changes of bulk density affect total pore volume (TPV), field capacity (FC) and hydraulic conductivity (K θ).

2.2.1 Root growth

The concept builds on the assumption that a higher root volume in a given soil cube creates more pore space. This is valid for fine roots given a continuous short-term turnover, while for coarse roots, (macro) pore space is created only once the root dies and decomposes. However, for infiltration and water storage fine roots are decisive, while macropores rather influence bypass flow. In a first step, daily change in root biomass (dW_{rt}) is split into top- and subsoil horizons, assuming an exponential decrease of roots with rooting depth:

$$dW_{rt_{top}} = dW_{rt} \cdot \left(\frac{Depth_{TopSoil}}{Depth_{Roots}} \right)^{0.25}$$

$$dW_{rt_{sub}} = dW_{rt} - dW_{rt_{top}}$$

For both, top- and subsoil, increase or decrease of root biomass and root volume is added to soil mass and volume, assuming a specific density of roots of 0.35 g cm⁻³.

$$dVol_{Root_{top}} = \frac{dW_{rt_{top}}}{0.35}$$

$$dVol_{Root_{sub}} = \frac{dW_{rt_{sub}}}{0.35}$$

Dividing mass by volume gives the new bulk density, where an increase in roots leads to a decrease in bulk density:

$$BD_t = \frac{(BD_{Top(t-1)} + dW_{rt_{top}}/10000)}{1 + |(dVol_{Root_{top}}/10000)|}$$

Subsoil is calculated in the same way.

2.2.2 Time

With time, soil settles and is compacted. At first bulk density decreases relatively fast, e.g. after ploughing; later on, compaction proceeds much slower. An empirical time-depending function was chosen, that slows down compaction once bulk density approaches 1.8g cm^{-3} :

$$BD = (1.8 - BD) \cdot (1 - e^{0.0001})$$

2.2.3 Ploughing

In a simplified manner, each ploughing operation is supposed to loosen the topsoil reducing bulk density at a fixed amount which itself decreases with bulk density, so that ploughing has less effect in a loose than in a compacted soil:

$$BD_{Top_t} = BD_{Top_{t-1}} - 0.05 \cdot (|0.8 - BD_{Top_{t-1}}|)$$

Subsequently, TPV and FC are updated linearly based on BD:

$$TPV_t = TPV_{t-1} \cdot \frac{BD_{t-1}}{BD_t}$$

$$FC_t = FC_{t-1} \cdot \frac{BD_{t-1}}{BD_t}$$

Theoretically, pore size distribution λ is affected by bulk density, too, however updating λ in the model would require recalculation including texture.

2.3 Soil chemical characteristics

With respect to soil fertility, LUCIA considers plant available N, P and K as macronutrients for plant growth and carbon as factor influencing water holding capacity. The following parameters refer to soil chemical properties and need to be provided by the user for every horizon of all soil units: Soil organic carbon (C_{org}), total nitrogen (N_T), mineral nitrogen (N_{min}), plant available phosphorus (P_{Bray_1}) and plant available potassium (K_{av}). At the current stage pH ($CaCl_2$) is requested in the user interface, but not yet linked to the model.

Inputs are inherent soil fertility, fertiliser, manure, litter and crop residues for N, P and K, and atmospheric deposition and biological fixation for N. For P, availability after decomposition is reduced by a sorption constant.

Manure, litter and residues need to be decomposed to be available for plant growth, while fertiliser, atmospheric deposition and biologically fixed N are immediately plant available. Nutrients are taken up only from the rooted soil depth. Fig. 1 shows different in- and outputs of the system in a general form.

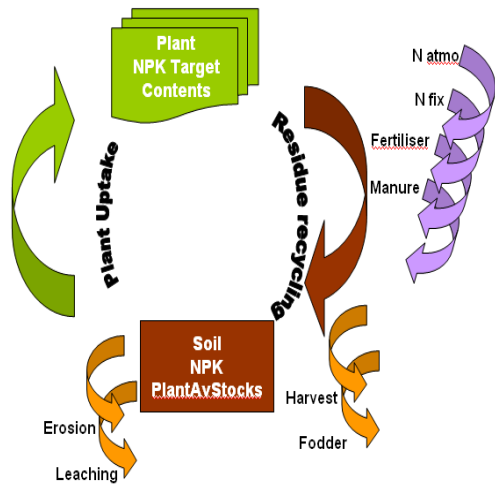


Figure 1: Nutrient cycling between soil and plant, in- and outputs

Plant available N stocks in the top soil are shown in the following equation:

$$N_{available} = N_{available} + N_{atmospheric} + N_{fixation} + N_{min/imm} + N_{fertiliser} - N_{eroded} - N_{leached} - N_{uptake} \cdot \left(\frac{\min(Thickness_{Topsoil}, Depth_{Roots})}{Depth_{Roots}} \right)$$

Available N in the topsoil is cumulative, composed of available N from the previous time step, plus N from atmospheric deposition and biological fixation, N mineralised or immobilised during organic matter decomposition and up to three applications of mineral fertiliser. Manure, litter and residue inputs are considered under mineralised N, because they need to pass the organic matter pool first. Decomposition of plant residues and subsequent release of nutrients is described in the following section. Losses from the plant available pool are eroded and leached N and uptake through plant roots, limited to the rooted zone. The subsoil contains no biological fixation, fertiliser and manure, while erosion can occur only once the topsoil has been completely removed by erosion.

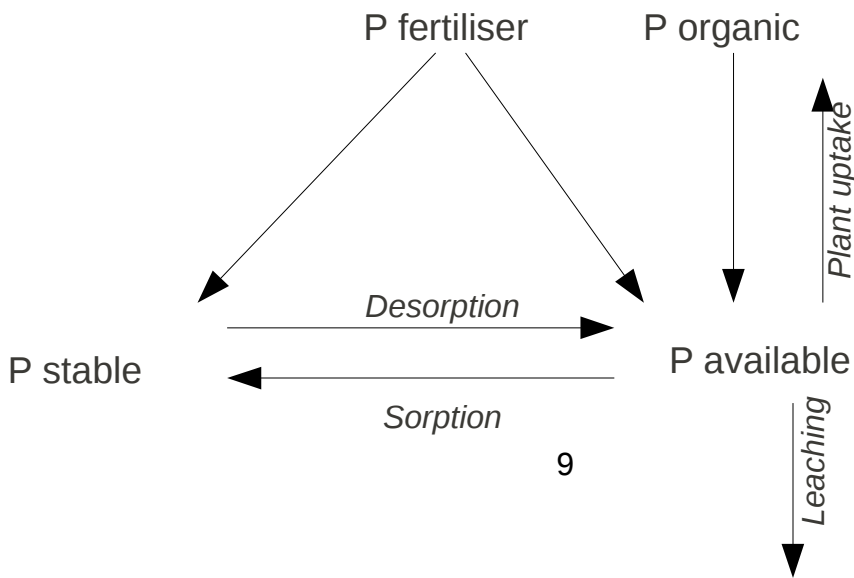
2.4 Soil Phosphorus

2.4.1 Overall concept

Soil inorganic Phosphorus (P) is divided into one stable and one plant available pool per horizon. These correspond to the stable and labile pools in other concepts (e.g. Warren 1994) or the stable and active plus labile pool (Jones et al 1984). Fertiliser inputs are split into available and stable fractions, which feed into the respective topsoil pools. The stable pool acts as a reservoir, which corresponds with the available pool: Desorption is the flow directed from the stable to the available pool while sorption goes into the opposite direction. All other flows are linked to the available pool:

- Leaching, which includes export in vertical and lateral directions;
- plant uptake;
- mineralised and immobilised organic P

Figure 2: Stocks and flows in the LUCIA soil P module



2.4.2 Magnitudes and initialisation of stocks

Figures cited in this paragraph have been taken from Schachtschabel et al (1992) and Sharpley et al (1984) – unless stated otherwise – and are intended to serve as an orientation for model parameterisation and plausibility checks.

Total P reserves in temperate soils up to 1m depth amount to 1,500-2,000kg P ha⁻¹ in podsols, 3,000-3,500kgP ha⁻¹ in acrisols and loess soils. Average values for plant available P in temperate soils range from 20-80 mg kg⁻¹, whereby accumulation takes place in the topsoil (inputs from vegetation) and lower subsoil (weathering). Stable P is in equilibrium at a ratio of about 4:1 with the total of labile plus dissolved P (Jones et al 1984). Not more than about 1% of seasonal plant P demand is available in the soil at any given time, so that not total amounts of soil P but desorption and dissolution rates are the determining factor for plant P supply.

Added soluble fertiliser decreases to about 50% of its original concentration within 1-3 years (Schachtschabel et al 1992), but residual effects of former P fertilizer additions are still effective for years (Warren 1994b). In agricultural topsoils, organic P makes up for 20-65% of total P reserves.

Leaching rates are low (particularly from the subsoil with about 0.003 - 0.1mgP/L soil solution), so that losses are minimized. With repeated desorption, P in solution decreases exponentially to a minimum of 0.06-0.14mgP/L, corresponding to about 3-7mg/kg.

2.4.3 Flows

Sorption and desorption are principally the same for top- and subsoil horizons, while leaching slightly differs according to the underlying water flows. All flows are expressed in [Mg ha⁻¹ time⁻¹], where time in LUCIA is a daily step. Here we describe only topsoil flows.

Sorption

Sorption follows the Freundlich isotherm type of power function³, which has been claimed to be more appropriate than Langmuir equations (Barrow 2008). The model uses empirical factors to scale effects of the main sorbents Al_{oxalate} – supposed to represent Al and Fe oxides/hydroxides⁴ (Warren 1994a) - and clay.

$$Sorption = a \cdot Al_{ox} \cdot P_{av}^{b \cdot Clay}$$

where Al_{ox} stands for oxalate extractable Aluminium oxides/hydroxides [kg/kg] and Clay for clay contents in [dec %]. Coefficients a and b are dimensionless and empirical. In the model they are treated as generic, assuming that most variation in sorption is covered by aluminium and clay contents. In calcareous soils, however, forms of Ca may be the dominant sorbents (Schachtschabel et al 1992). The linear influence of aluminium on sorption was assumed in concordance with the linear relationship found between Al_{oxalate} and fertiliser

³The Freundlich isotherm in its general form: Sorption = a Concentration^b

⁴Better correlations than for pyrophosphate and dithionite-extractable Al- and the corresponding Fe-fractions.

recovery (Warren et al 1994a). Clay as dominant factor for adsorption was used by Farias et al (1994), although as a correlation. At the moment, both a and b coefficients are set to 1, so that Al and clay are pure reduction factors.

Desorption

Solution curves correspond to adsorption curves and can thus be considered as desorption curves (Schachtschabel 1992). Consequently, desorption follows dynamics of the inverse Freundlich isotherm, considering reduction factors for pH and water contents in addition to the empiric a and b coefficients

$$Desorption = s \cdot pH_{factor} \left(\frac{1}{P_{av}} \right)^{WC},$$

where s is an empirical dimensionless scaling factor and the pH and WC factors are dimensionless values between 0 and 1 that control the magnitude of effects of pH and water contents (WC, as a proportion of TPV, total pore volume). Feedback to the exchangeable P pool limits over-accumulation. The influence of pH on P availability was adjusted using the broken stick functions common in most plant nutrition text books. Given that the magnitude of pH and WC factors is limited to a range between 0 and 1, the scaling factor determines potential desorption rates and the factors are reduction factors. The scaling factor was set to 0.00015, which roughly corresponds to time-averaged daily uptake of a crop during a vegetation period of ~150 days.

The role of humic and fulvic acids as well as organic rhizosphere acids, which bind sorbents (Ca, Fe, Al cations) and thus increase desorption, has not been implemented in the model, nor has temperature (e.g. burning) as a factor fostering desorption.

Mineral fertiliser inputs

At the present stage, P sorption in fertiliser is determined by a single constant. As suggested by Wolf et al (1987), fertiliser inputs will be split up into available and stable fractions by the model user, depending on the type of fertiliser defined (s Tab 1). Fractions feed directly into the respective soil pools.

Table 1: Fractions of labile and stable P for common P fertilisers (Wolf et al 1987)

Fertiliser type	Labile fraction	Stable fraction
Ammonium phosphates	1	0
Superphosphates	0.8	0.2
Phosphate rocks	0.1 - 0.2	0.8 - 0.9

Organic amendments are considered separately in the manure and residue sections.

Leaching

P leaching is governed by water flows through the respective horizon (for the topsoil these are percolation and lateral flow, for the subsoil vertical loss below the profile and lateral discharge). A fixed P concentration in leachate is multiplied with each water flow.

2.5 Litter and soil organic matter cycling

The conceptual model for this module has been developed following the CENTURY model (PARTON ET AL. 1987). In addition, potassium has been added and decomposition constants have been adapted.

Seven pools of organic matter exist that are distinguished by placement and turnover rates:

- Surface litter consisting of aboveground plant residues such as fallen leaves and branches. Metabolic and structural surface litter are distinguished according to their decomposition rates.
- Soil litter consisting of root litter and surface litter after ploughing. As for surface litter, metabolic (turnover time 0.5 years) and structural (3 years) pools are treated separately.
- Soil organic matter (SOM), which is differentiated into three pools, active (turnover time 1.5 years), slow (25 years) and passive (1000 years).

Surface litter can be entirely converted into soil litter through tillage. Both surface and soil litter gradually decompose into the different SOM pools at individual decomposition rates. Between SOM pools flows can be bidirectional, organic matter can be stabilised in pools of slower turnover time or decomposed into more available pools. Thus, active SOM can be stabilised into the slow and passive pool, slow SOM can be stabilised as passive SOM and be decomposed into the active pool. Passive SOM, however, can be converted into active, but not into slow SOM (Fig. 3).

Figure 3: Litter and SOM stocks and flows, modified from PARTON ET AL. (1987)

Organic matter cycling is carbon driven. Flows are controlled by specific respiration rates, decomposition rates (k rates) and C:N ratios. Respiration rates determine the share of organic carbon in a stock that is respired versus the share available for decomposition. The standard respiration rate for most flows is 0.55, meaning that 55% of carbon in a given pool, is released as CO_2 , while the rest can be transferred to other pools. Flows between the different stocks are updated every day, but not every day 55% of a pool is metabolised. Flow specific turnover rates (k rates) determine the share converted per time step. The original CENTURY model runs on a monthly time step, so turnover rates in LUCIA are necessarily much smaller than in CENTURY. Soil temperature, soil moisture and lignin contents of litter inputs have regulating functions on turnover rates.

The link back to the plant system is established via release of N, P and K from litter and SOM. Manure inputs need to undergo transformation in the soil, too, before nutrients become available to plants. C:N ratios play a decisive role for N availability. At tight ratios, N is mineralised while at wide C:N ratios, N is immobilised by soil microorganisms and not available for plants. If N supply (more precisely, a target C:N ratio) is not met, the respective process halts. P released from organic matter is subject to sorption on clay minerals at a soil-specific ratio. K released is in its entirety available to plants. C, N, P and K dynamics between all pools at different rates are accounted for and can be reported, but by default, they are summed up. As an example, $N_{\text{min}/\text{imm}}$ is the total

of mineralised and immobilised N flowing between all stocks. This value can become negative for single pools, if immobilisation dominates. Bulk density is not directly affected by organic matter pools, but by rooting.

Top and subsoil processes follow the same algorithms, except for surface litter and ploughing, which are applicable only for topsoils.

Apart from soil C, N, P and K stocks and plant available nutrient inputs, carbon balances for different stocks and CO₂ emissions from respiration can be reported by the model, while CH₄ and N₂O are not implemented.

3 Water balance

3.1 Routing

PCRaster offers a variety of native functions to simulate material flows between pixels. These functions require a digital elevation model (DEM) and a local drain direction map (LDD) derived from the DEM in PCRaster (Fig. 3). The LDD channels all flows originating on a pixel along the direction of steepest slope into the neighbouring pixel. Downstream, flows are added to the material present in the receiving pixel. Simple accumulation (accuflux function), tipping bucket (accutrigger function) or tank approaches (accuthreshold function) can be realised.

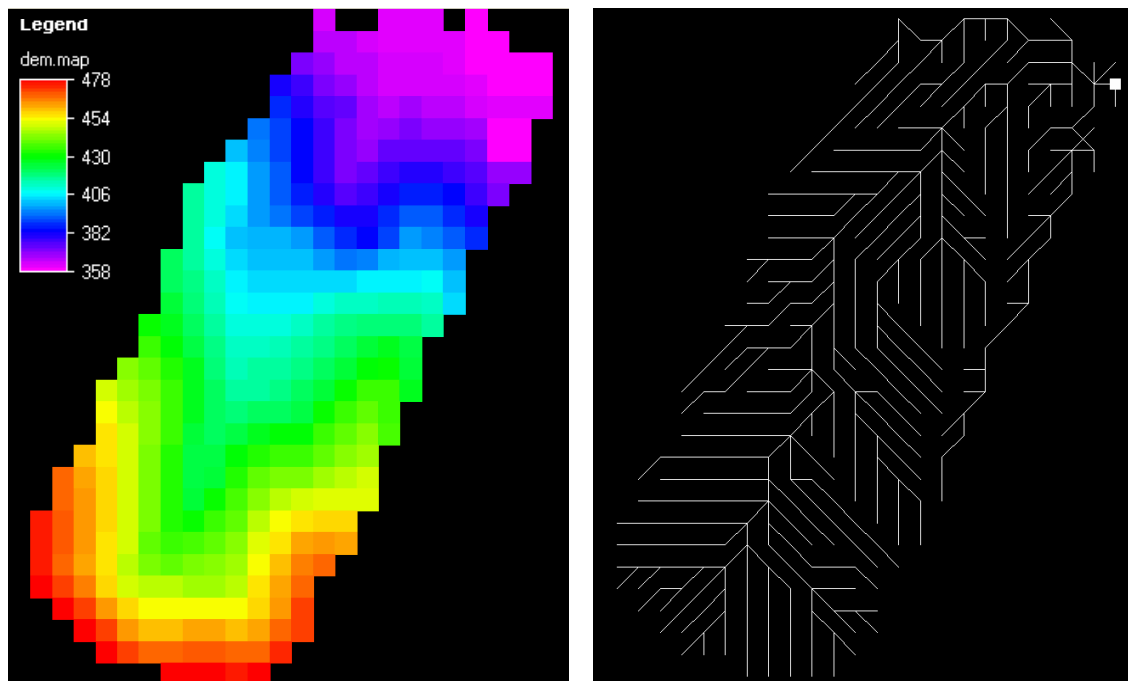


Figure 4: DEM and local drain direction map in PCRaster (catchment Ban Tat, Hoa Binh, Vietnam)

In LUCIA, the accuthreshold function is used to simulate surface runoff, lateral flow in the topsoil and baseflow in the subsoil.

3.2 Evapotranspiration

Potential evapotranspiration is composed of soil evaporation and potential transpiration by plants. Evaporation of intercepted rain from plant surfaces is accounted for as evaporated interception and thus considered in the model script separately before evapotranspiration. The latter is calculated as weighted average of evaporation from bare and covered soil plus transpiration, which is confined by plant available water.

3.2.1 Soil Evaporation

Soil evaporation can be differentiated by bare and shaded soil, the latter being a function of leaf area index (GOUDRIAAN, 1977; RITCHIE, 1972; RITCHIE, 1971 as cited by SUPIT, 2003):

Bare soil evaporation [mm d^{-1}] is calculated following the concept outlined by ALLEN ET AL. (1998), which assumes energy-limited evaporation of readily evaporable water (REW) at high soil saturation and declining rates of evaporation with decreasing soil water contents down to total evaporable water reaching $0.5 \theta_{\text{PWP}}$. Thus bare soil evaporation is a function of ET_0 and a reduction factor kR defined by soil water contents:

$$\text{Evaporation}_{\text{BareSoil}} = \min(1.2 \cdot ET_0 \cdot kR, 0.5 \cdot PWP_{\text{Topsoil}})$$

with kR being 1 at soil water beyond 90% of FC and then decreasing linearly.

Shaded soil evaporation under canopy is derived from bare soil evaporation as reduced by leaf area index:

$$\text{Evaporation}_{\text{ShadedSoil}} = \text{Evaporation}_{\text{BareSoil}} \cdot e^{-k_{\text{global}} \cdot LAI}$$

where LAI is the dimensionless leaf area index and k_{global} a dimensionless extinction coefficient for global radiation:

$k_{\text{global}} = 0.75 \cdot k_{\text{df}}$, the latter being the extinction coefficient for diffuse radiation:

$k_{\text{df}} = 0.72$ (GOUDRIAAN, 1977).

Soil evaporation can now be derived from the respective shares of evaporation under shaded and open soil. Evaporation from open water surfaces is calculated in a simplified manner.

3.2.2 Transpiration

Potential transpiration is calculated as the minimum of plant available water, a combined term of soil water, available field capacity and rooting depth, and a canopy (LAI) dependent function of species-specific evapotranspiration:

$$\text{Transpiration}_{\text{Pot}} = ETC \cdot (1 - e^{-k_{\text{global}} \cdot LAI})$$

where ET_c is a crop-specific empirical modification of ET_0 . Actual transpiration is then derived from potential transpiration and a reduction factor that becomes effective under drought or stagnic conditions. Actual transpiration is described under water stress in section 4.5.

3.3 Infiltration, deep infiltration and redistribution

Following the concept of KINEROS 2 (Woolhiser 1990⁵), infiltration is the minimum of available rain water, available pore space in the topsoil and infiltrability.

Infiltrability is calculated based on the current saturation of the soil and its physical properties:

$$Infiltrability = K_{sat} \cdot \left(1 + \frac{\alpha}{e^{\frac{\alpha \cdot Inf_{Prev}}{SatDef}} - 1} \right)$$

where K_{sat} is the saturated conductivity of the topsoil as a scaling factor, α is a texture-related constant set to 0.85, Inf_{Prev} refers to infiltration depth before the current time step during the same rain event and $SatDef$ stands for saturation deficit defined as follows:

$$SatDef = (G + Inf_{Prev}) \cdot (TPVTop - \theta_{Topsoil})$$

where G is net capillary drive obtained from pore size distribution index and bubbling pressure as a pedotransfer function.

Deep infiltration is water that infiltrates through macropores directly into the lower soil horizon. The range is delimited by available pore space in the subsoil, saturated conductivity of the subsoil, available rain water after subtraction of interception and infiltration and the actual deep infiltration term:

$$DeepInfiltration = \theta_{Topsoil} - \theta_{TPVTop} + K_{sat} \cdot \left(1 + \frac{\alpha}{e^{\frac{\alpha \cdot Inf_{Prev}}{SatDef}} - 1} \right)$$

which is potentially infiltrating water that would surpass available pore space in the topsoil. K_{sat} refers to saturated conductivity of the topsoil.

3.3.1 Hourly updates of rainfall, infiltration, deep infiltration and redistribution of water in the soil

Implementing a loop of higher temporal resolution was considered necessary for the processes related to infiltration and redistribution of water in the soil profile. Not considering redistribution on at least hourly scale would have led to an underestimation of time-critical processes like infiltration, deep infiltration and run-off. These processes, which depend on water that cannot infiltrate in due

⁵Updated manual under <http://www.tucson.ars.ag.gov/kineros/> accessed May 5th, 2010

time during high intensity rain, is now represented more realistically. Hourly values of rainfall are not supplied by the user and have to be estimated from empirical distribution functions of rain intensity for rain events of different magnitudes. Daily rainfall is split into cumulative hourly values along a sigmoid curve. Cumulative infiltration, deep infiltration and percolation+lateral flow are then updated for every hour. The loop is terminated once cumulative rain accounted for in the hourly loop approximates effective daily rain to less than 0.7mm.

3.3.2 Empirical data

Rain intensities were derived empirically from measured⁶ daily amounts of rainfall and intensity and regressions created accordingly. By definition, two rain events were separated for analysis by a lag time of at least 20 min. The model in its current version does not foresee hiatuses during a single day.

Approximating observed rain intensity distribution in Chieng Khoi, empirical functions were designed. In order to avoid differential equations, a sigmoidal cumulative curve shape was chosen, that reaches maximum intensity soon after the beginning of an event and then slowly decreases in intensity. Cumulative hourly rainfall is calculated as follows:

$$Rain_{cumulative} = \frac{Rain_{total}}{\left(1 + e^{\frac{-time - x_0}{b_{int_max}}}\right)}$$

where total daily rain [mm] determines the level of the curve plateau, x_0 [min] stands for the time when maximum intensity is reached, and rain intensity [mm/h] is estimated from observed data (see below). The coefficient b_{int_max} is an empirical factor calculated as

$$b_{int_max} = \frac{25}{intensity_{max}}$$

The field data show, that x_0 and rain intensity vary with the magnitude of event. Therefore, both enter into the cumulative rain function as variables estimated from DailyRain. For rain intensity an exponential function was derived from field data

$$Intensity_{av} = 0.03318 Rain_{total}^{0.9678} \quad 7$$

The lag factor x_0 is approximated following the observation that smaller rain events reach maximum intensity at a relatively later stage of the event as compared to large events:

$$x_0 = Rain_{eff} / 2 + 10$$

Rain duration does not need to be calculated, because the loop stops once at least (effective daily rain - 0.7mm) has been accounted for in the loop.

⁶Using 10 min resolution data for Chieng Khoi 2007 - 8 by Petra Schmitter

⁷Using the original coefficient and exponent without rounding the function gave a coefficient of determination (r^2) of 0.79 for the Chieng Khoi dataset. However, field data refer to average event intensity and the coefficient b in the equation above refers to maximum intensity. In so far, the empirical equation is only a first approximation.

3.4 Soil water stocks

Topsoil and subsoil are principally treated the same way: A preliminary water balance is formed before redistribution in the soil and a final balance after redistribution. For topsoil, infiltration is added to the current water contents and capillary rise from the subsoil of the previous time step, while evaporation and transpiration are subtracted. In a second step, lateral in- and outflow from other pixels and percolation into the subsoil are considered. Topsoil water cannot decrease below permanent wilting point, interpreted as dead water.

Step 1:

$$\theta_{\text{topsoil_prel}_t} = \theta_{\text{topsoil}_{t-1}} + \text{infiltration}_t + \text{capillary}_{t-1} - \text{evaporation}_t - \text{transpiration}_t$$

Step 2:

$$\theta_{\text{topsoil}_t} = \theta_{\text{topsoil_prel}_t} + \text{lateral}_{\text{in}_t} - \text{percolation}_t - \text{lateral}_{\text{out}_t}$$

Regarding subsoil water contents, the preliminary balance contains the stocks of the previous time step plus deep infiltration and percolation from the top soil. This is updated in the final balance adding incoming baseflow from neighbouring pixels and subtracting capillary rise into the topsoil, loss into the parent material, baseflow into neighbouring pixels downhill and overflow in case of saturation.

3.5 Capillary rise

Following the concept by Saxton and Rawls (2006), capillary rise is delimited by available water in the subsoil above PWP, available space in the topsoil, hydraulic conductivity of the receiving top soil and the actual capillary function:

$$\text{Capillary} = K_{\theta_{\text{Topsoil}}} \cdot \left(0.1 \cdot \frac{\Psi_{\text{Topsoil}}}{\text{Depth}_{\text{GW}}} - 1 \right)$$

where K_{θ} stands for hydraulic conductivity, ψ is the matric potential in the top soil and GW depth is groundwater depth. 0.1 is a conversion factor that combines groundwater depth in [cm] and capillary drive in [mm].

3.6 Percolation, lateral flow, loss and baseflow

Similar principles are applied for percolation and lateral flow, which refer to the topsoil, and baseflow and loss from the subsoil. In a first instance, the total available water for both flows is calculated. In the case of topsoil, this the minimum of

- water contents exceeding field capacity,
- saturated conductivity of both horizons and
- available space in the receiving subsoil.

Percolation is a share of this stock determined by different conductivities of both horizons and slope.

$$\text{Percolation} = \text{PercoLat} \cdot \frac{K_{\theta_{\text{Subsoil}}}}{K_{\theta_{\text{Topsoil}}} + K_{\theta_{\text{Subsoil}}}} \cdot \left(1 - \frac{\text{Slope}}{90} \right)$$

where PercoLat describes the water available for both percolation and lateral flow and slope is hillslope in [°]. Percolation is further limited by space in the sub soil and hydraulic conductivity of the sub soil.

Lateral flow of a pixel is the remainder of PercoLat and percolation, which has preference over lateral flow.

Downstream flows between pixels in the landscape are simulated using an accutreshold function in PCRaster:

$$Lateral_{Landscape} = accutresholdflux(LDD, Lateral_{Pixel}, FC_{Topsoil} - \theta_{Topsoil}) \cdot \frac{0.001 \cdot pixel}{86400}$$

where LDD defines the local drain direction map used for the catchment, Lateral is the flow of interest at the pixel level and $FC - \theta$ constitutes the threshold above which lateral flow occurs (field capacity). The entire term is limited to values >0 (not shown in the equation). In the example, constants 0.001 and 86400 are conversion factors from litres to cubic metres and from days to seconds to arrive at the output unit of $m^3 \cdot s^{-1}$. The term pixel refers to the area of a pixel in m^2 and is needed to make the model generic for different user-defined pixels sizes. The same parameter can be reported in [mm] omitting the last fraction term.

In the subsoil, loss and discharge are calculated in analogy to percolation and lateral flow.

3.7 Surface Runoff

Before run off sets on, water accumulates on the soil surface. Ponding is the parameter that determines the amount of this surface storage. Ponding depends on several factors like surface roughness, but is set to a fixed value in LUCIA.

Hortonian flow is now the remainder of rainfall after interception, infiltration, deep infiltration and surface storage have been subtracted. Saturation overflow after the final soil water balance is added to this if the soil profile is filled with water.

On the landscape scale runoff is quantified using a procedure of several steps. First, potential infiltration is the minimum of available pore space in the topsoil and the actual potential infiltration term:

$$Infiltration_{Pot} = K_{sat Top} \cdot \left(1 + \alpha \cdot e^{\frac{\alpha \cdot InfCumPrev}{SatDeficit} - 1} \right)$$

Potential deep infiltration is derived in the same manner, taking into account pore space in the subsoil and saturated conductivity of the subsoil. This exponential term has been additionally limited to a minimum value of 0.01 for technical reasons (numerical overflow).

$$DeepInfiltr_{Pot} = \theta_{Topsoil} - TPV_{Topsoil} + K_{sat Topsoil} \cdot \left(1 + \frac{\alpha}{e^{\frac{\alpha \cdot Inf_{prev}}{SatDeficit} - 1}} \right)$$

In a following step, available space in the soil is updated, before runoff is calculated for the landscape scale:

$$Runoff_{Landscape} = accutresholdflux(LDD, Runoff_{Pixel}, Space)$$

As for lateral flow, LDD refers to the local drain direction map of the catchment, $\text{Runoff}_{\text{Pixel}}$ to the flow under consideration and Space to the threshold that needs to be exceeded to cause overflow of the stock into the neighbouring downstream pixel. Finally, water contents of both top- and subsoil are updated, accounting for runoff.

For a relatively small watershed it is assumed that all excess rain water reaches the subcatchment outflow within the model time step of one day, so that it is not necessary to take different residence times and travel distances into account.

3.8 Lakes

The current lake section is based on a simplified concept that derives lake volume as a spherical cap with user-defined depth. Stocks are initialised from measurements or estimates and updated as cumulative balance of present stocks + inflows – outflows. Lake inflow is derived only from the subcatchment upstream plus rainfall of the lake area. Among outflows, lake-related evaporation is calculated from the water surface (corrected for present water levels of the lake) and a water-specific k_c . Leakage is a fixed rate of water in the lake. Overflow occurs when the simplified geometric volume of the lake is exceeded by the balance of stocks, inflows and losses.

4 Plant growth

Parts of the LUCIA plant module are built on concepts of the Crop Growth Monitoring System (CGMS) by SUPIT (2003), a PCRaster version of WOFOST. CGMS simulates process-based plant growth on a daily time step depending on photosynthesis and water, while nutrient constraints are not considered. This approach is combined in LUCIA with a concept of target nutrient contents in the biomass that has to be met through plant uptake. The plant module in LUCIA is hierarchical with potential growth determined by radiation, constrained first by water and in a second step by nutrients. Further, some additions to WOFOST were made in LUCIA regarding perennial plants.

In the following sections the plant growth module is described starting with photosynthesis and the production of assimilates. This part follows closely the steps undertaken in CGMS and is not explained in much detail here. Allocation of assimilates to different plant parts and phenological development stages are described more closely. The section concludes with growth constraints imposed by suboptimal water and nutrient supply.

4.1 Net assimilation rates

As in WOFOST, daily assimilation depends on day length, photosynthetically active radiation (PAR), leaf area index (LAI), and crop- and development-specific maximum assimilation rates (AMD).

In a first step, day length is calculated based on geographical latitude and declination of the Earth on the respective Julian day. A Gaussian interpolation method proposed in WOFOST to derive $\sin \beta$ (sine of solar elevation) is not used

here, because global radiation data are expected to be measured as average over the day.

Incoming radiation is attenuated by the plant canopy (calculated by Gaussian interpolation as in WOFOST) and direct sunlight distinguished from diffuse light. Global radiation is converted into PAR by multiplication with 0.5.

Orders of magnitude of Net Assimilation Rates extracted and converted from Larcher (1980)⁸ are presented in Table 1 for comparison.

Table 2: NAR of selected plant species (Larcher 1980). Original values in [mg d⁻¹ dm⁻²] converted to [kg h⁻¹ ha⁻¹] as used in LUCIA.

Plant type	NAR average growth season [kg.h ⁻¹ .ha ⁻¹]	NAR main growing phase [kg.h ⁻¹ .ha ⁻¹]
C 4 grasses	> 8.3	16.6-33.33
C 3 grasses	2-6	3-8
C 3 dicotyledon	2-4	4-25
(Sub)Tropical woody dicotyledon	0.4-0.8	1.2-2
Crassulaceae Acid Metabolism	0.08-0.16	0.4

Respiration, apart from assimilation, depends on temperature. Maintenance respiration is modeled as a species-specific factor multiplied by actual dry matter of the plant. As an orientation, the range of values for the maintenance coefficient over several species found by IRVING & SILSBURY (1987) ranged from 1.6 to 2.9 per cent of the dry weight per day as determined by different methods respectively. Potential growth is then a function of growth and maintenance respiration and conversion efficiency of carbohydrates into biomass.

The parameter $Efficiency_{C2Biomass}$ describes the conversion efficiency of assimilated carbohydrates into biomass. Efficiency differs between plant organs and development stages. In LUCIA, the basic term for potential growth is governed by conversion efficiency.

$$\Delta W = Efficiency_{C2Biomass} \cdot (Respiration_{daily} - Respiration_{Maintenance} \cdot W)$$

where W is cumulative biomass and ΔW is biomass increase per time step. Parameter ranges were adapted from LAMBERS ET AL. (2008). As in the model biomass production takes place before biomass partitioning, one overall value for all plant tissues was chosen (Table 2). Conversion efficiencies, the reciprocal of construction costs, are not dependent on development stage.

Table 3: Conversion efficiency after LAMBERS ET AL. (2008)

Efficiency of glucose conversion into biomass				
Leaf	Stem	Root	Fruit	Mean
0.64	0.69	0.75	0.61	0.67

⁸ As cited under:

<http://generalhorticulture.tamu.edu/hort604/lecturesuppl/growthkinetics/growthkinetics05.htm>

4.2 Death rates

In LUCIA, three different causes for leaf fall can occur: Senescence (a certain share of leaf biomass shed at $D > 1.5$), self-shading and drought due to water stress. These fractions are added up to ΔWD_{leaf} (Δ weight of dead leaves during a time step). For stem and root litter only senescence plays a role. All these fractions move to the residue pool, whereby retranslocation of nutrients before abscission are considered for leaf shedding due to age, but not to water stress. Leaves produced per time step after subtraction of leaf fall are denominated as ΔWn_{leaf} or net leaf growth.

4.3 LAI and cover

LAI is determined by net leaf growth and specific leaf area (SLA), a measure of leaf thickness expressed in $\text{m}^2 \cdot \text{kg}^{-1}$. The respective equation reads:

$$LAI_t = LAI_{t-1} + \Delta Wn_{\text{leaf}} \cdot SLA \cdot 0.0001$$

As mentioned before, LAI must never become zero and is delimited to a minimum of 0.00001 – even after harvest or before sowing – as otherwise all growth processes would be disrupted. Maximum LAI, too, is constrained externally and determines levels of shading and self-thinning. Potential leaf biomass exceeding MaxLAI is shed into the litter pool. MaxLAI for natural vegetation is supposed to be real maximum LAI, while for cultivated crops it is optimum LAI. Otherwise farmers are supposed to prune plants or choose wider spacing, as additional leaf production would be at the expense of yield.

Soil canopy cover is formed as an asymptotic function approaching 1, determined by LAI. Both, cover and LAI, have impacts on interception, evaporation, transpiration, erosion, albedo and assimilation.

4.4 Phenological stages and differentiation

4.4.1 Plant development stages

LUCIA adapts the temperature sum concept for plant phenological development as introduced by the SUCROS-WOFOST school of models.

Plant development is quantified along a scale from 0 (planting) through 1 (flowering) to 2 (maturity). Development stages (D) of all plants are expressed as a continuum subdivided into a vegetative ($D=0$ to 1) and a generative ($D=1$ to 2) phase. At maturity plants are immediately harvested.

Progress on the development scale is triggered by air temperature: Once actual temperature surpasses a species-specific minimum (base temperature), phenological development starts, increasing linearly with the difference between actual and base temperature. From a certain upper threshold temperature upwards, growth is limited and, at a second threshold, stops. Translation of temperature sums into development stages is effectuated dividing actual

temperature sums by species-specific degreedays required for flowering and harvesting, respectively.

For the vegetative phase development stage is calculated as follows:

$$D = \frac{T_{cum}}{DD_{flower}}$$

where T_{cum} stands for the (cumulative) temperature sum and DD_{flower} for a user-defined number of degreedays required for the plant species to reach flowering stage.

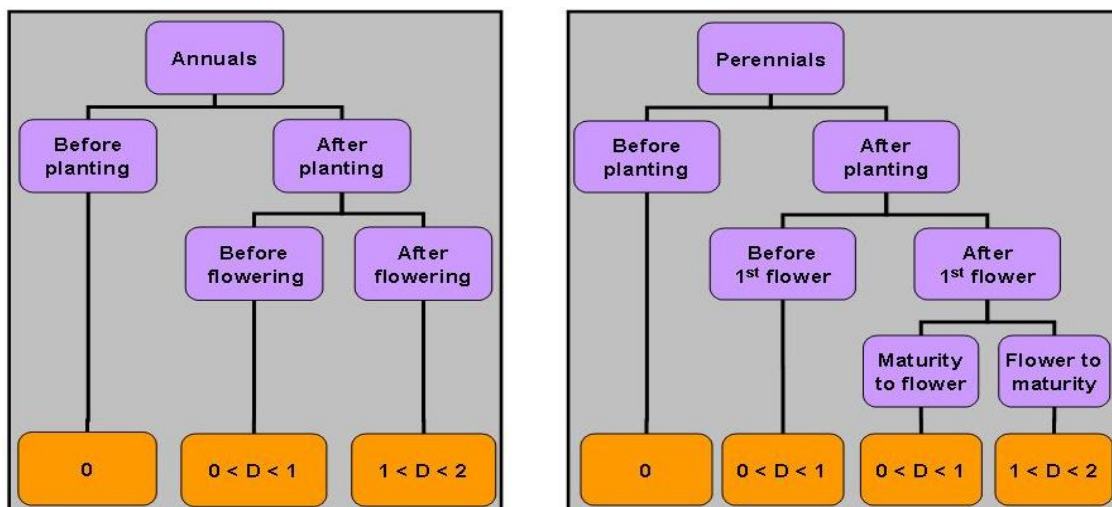
Accordingly, for the generative phase, starting by definition at development stage 1, development is calculated as shown below:

$$D = 1 + \frac{T_{cum}}{DD_{maturity}}$$

In contrast to annuals, trees do not necessarily flower during the first year. In this case, a day of first flowering needs to be defined by the user. Further, trees are usually not cut after harvest, but fall back into the beginning of the generative phase. They continue growing, while annuals will only grow if planted again (Fig. 4). In both cases, counting of degreedays starts from zero after harvest.

Figure 5: Development stages of annuals (upper bar) and perennials (lower) in LUCIA.

Plant growth parameters that depend on the phenological development stage of the plant include biomass partitioning between plant organs, maximum assimilation rate, target nutrient contents per plant organ and specific leaf area. Development-depending parameters have been simplified to broken-stick functions that can be parametrised from two cardinal points (see sections 7.3.2, 7.3.3). Development stages for annuals and perennials are shown in Figure 5.



Assimilation as starting point for growth is controlled by D (which needs to be >0). For annuals, $D > 2$ marks the endpoint of growth, while perennials continue growing after harvest, except harvestables, for which weight is reset to zero. Theoretically, fruits can grow at any season.

4.4.2 Biomass partitioning

From the model perspective, biomass is first formed as pluripotent cells and then differentiated into four types of plant tissues, leaves, stems, roots and harvestables. The latter term includes fruits as well as tubers. Stems are understood *sensu lato* as any woody aboveground material including bark, branches, twigs, infructescence not harvested etc. Partitioning of annuals (grown from seeds) and perennials (planted as seedlings) is initialised at different levels. This refers also to the initialisation of biomass as given for existing perennial land covers.

Depending upon allocation of resources to different organs, these grow at different rates (Fig. 6). Technically, partitioning of assimilates to different plant organs is read from a user-defined function for each land cover and differs between development stages. Resource fractions allocated to root and shoot add up to 1, and in a second step aboveground fractions StemRatio + LeafRatio + HarvestRatio add up to 1 again.

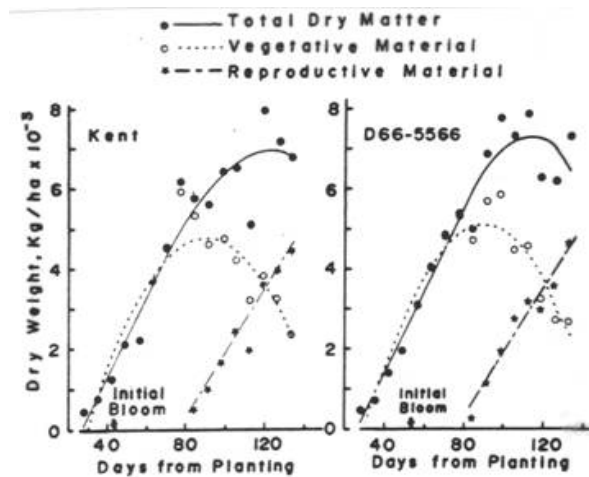


Figure 7: Examples for growth rates of different plant organs (Egli and Leggert 1973)

After harvest, different plant parts go to different pools (Fig. 7): For annuals, at $D \geq 2$, the whole plant is uprooted. Harvestables move to the harvest pool, while parts of the leaves and stems can be exported as fodder and the rest becomes surface litter. Roots become soil litter after harvest. For perennials, only harvestables are removed from the plot, while for the other fractions normal abscission continues while plants are growing.



Figure 8: Biomass partitioning after harvest, in the case of perennials after cutting

Distribution of plant material from various sources into different litter pools is shown below for metabolic and structural surface litter of annual plants. Composition of the metabolic carbon part of surface litter is governed by falling leaves and fruits during the vegetation period and leafy crop residues after export of fodder from the plot after harvest.

$$C_{SurfaceLitterMetabolic} = \Delta WD_{leaf} \cdot LitterFraction_{metabolic} + \Delta WD_{harvestables} \cdot 0.42 +$$

$$W_{leaf} \cdot LitterFraction_{metabolic} \cdot (1 - FodderIndex_{leaf}) \cdot 0.42$$

whereby the second line refers only to annual crops after harvest. 0.42 is an empirical conversion factor from biomass to carbon.

For the structural surface litter pool, leaf and stem litter during the vegetation period and leafy and woody residues after export of fodder are accounted for.

$$C_{SurfaceLitterStructural} = (\Delta WD_{leaf} \cdot (1 - LitterFraction_{metabolic}) + \Delta WD_{stem}) \cdot 0.42 +$$

$$(W_{leaf} \cdot (1 - LitterFraction_{metabolic}) \cdot (1 - FodderIndex_{leaf}) + W_{stem} \cdot (1 - FodderIndex_{stem})) \cdot 0.42$$

Again, the second line applies only for annual crops after harvest. Fruits move entirely into the metabolic and stems into the structural litter fraction, while leaves are composed of both a metabolic and a structural fraction.

As for annuals, fodder is a user-defined share of aboveground biomass; stems may include twigs fed to goats as an example. For perennials, both residue and fodder indices for (roots), leaves and stems do not need to add up to 1 as they do for annuals, because fractions are rather small relative to the total plant biomass.

4.4.3 Root growth

Root biomass is derived from biomass partitioning ratios per development stage. Assuming a half-ellipsoid shape of the rootstock, rooting depth is updated from existing cumulative root weight (W_{root}) taking into account additional user inputs on planting density, average fine root weight density⁹ and a root shape factor $\gamma = a/b$, which determines the ratio of rootstock depth to radius.

In a first step the rootstock volume is calculated assuming fine root expansion at a continuous fine RWD. Rooting depth is then obtained by solving the rootstock volume at given γ for depth a . The calculation process and examples for rootstock shapes at different γ are shown in Fig. 8.

⁹ Assuming that fine roots extend excentrically at a constant RWD. A twofold simplification: First, RWD decreases towards the margins of the ellipsoid. Second, RWD is easier to measure in the field than RLD. While for availability of water / nutrients only fine RWD (e.g. $\leq 2\text{mm}$ diameter) should be taken into account, total RWD can be determined at the same time for belowground biomass / carbon.

Figure 9: Calculation of rooting depth and examples for rootstock shape at different γ (a/b).

4.5 Water uptake and stress

LUCIA uses a concept based on WOFOST to simulate water limitation for plant growth:

Potential transpiration is calculated from Penman reference evaporation corrected for a crop factor (ETc) and then reduced by an exponent combining LAI and a light extinction factor of leaves:

$$Transpiration_{Pot} = ETc \cdot \left(1 - e^{-k_{global} \cdot LAI}\right)$$

Actual transpiration is derived by a reduction factor based on an empiric relationship of water depletion by crops from the soil under different soil moisture regimes. First, an empirical depletion factor is used to estimate how much water a plant can extract from a dry soil. Next, critical water contents are determined at which stomata close and assimilation stops. Plant available water takes this value and the rooted space into account.

Next, two reduction factors are formed that relate constrained growth to dry and stagnic conditions, respectively.

$$Reduction_{Drought} = \frac{\theta_{Topsoil} - \theta_{PWPTopsoil}}{\theta_{CritTopsoil} - \theta_{PWPTopsoil}} + \frac{\theta_{Subsoil} - \theta_{PWPSubsoil}}{\theta_{CritSubsoil} - \theta_{PWPSubsoil}}$$

This factor is limited to the range between 0.001 and 1.

$$Reduction_{Stagnic} = \frac{\theta_{TPVProfile} - \theta_{Topsoil} - \theta_{Subsoil}}{\theta_{TPVProfile} - \theta_{FCProfile}}$$

The factor is limited to the range between 0 and 1 and causes a linear reduction once soil water contents surpass field capacity.

Actual transpiration is now derived as the minimum of both reduction factors multiplied by potential transpiration:

$$Transpiration_{Actual} = \min(TranspRedDrought, TranspRedStagnic) \cdot Transpiration_{Pot}$$

Water stress again is a reduction factor – calculated as actual transpiration over potential transpiration – affecting assimilation. In addition to reduced growth, water stress causes leaf death.

4.6 Nutrients limiting growth

Constraints for plant growth in LUCIA follow a hierarchical approach: Potential growth is determined by incoming radiation, LAI and light extinction coefficient. This potential growth is then constrained by water availability (see previous section). Finally, water-constrained growth is multiplied with reduction factors for available N, P and K in the topsoil over plant N, P and K demand. PlantN, P and

K demand is calculated as N, P, K concentration in leaf, stem, root and harvestables multiplied with the dry weight of the respective plant parts. In the model, gross instead of net biomass increase are considered for this purpose as nutrient constraints are positioned after biomass partitioning but before leaf death rates. Total plant demand for potential growth is calculated summing up compartment demands. This total demand is then related to available stocks forming a reduction factor. The least of all obtained ratios among N, P and K is used to restrict actual biomass increment. This implies the Liebig law of minimum, not a Mitscherlich approach of mutual interactions between nutrient supply levels.

4.7 Existing fallow vegetation and natural succession

Usually, an initial land cover map of a catchment is derived by remote sensing and subsequent land cover classification. This stage represents a certain point in time which can be used as a starting point for modelling scenarios or linked to measured weather data of the following period (e.g. for reverse modelling). In both cases existing vegetation biomass and leaf area index must be initialised. Four alternatives are offered to estimate initial total biomass:

1. Destructive measurements or other direct estimates, preferably for grasslands and bush fallows.
2. Allometric equations of the form

$$W = a \cdot dbh^b \cdot PlantingDensity \cdot ShootRatio^{-1}$$

where W [Mg ha⁻¹] represents biomass, dbh diameter at breast height [cm] and a, b are dimensionless empirical user-defined coefficient and exponent; both are ideally species- and site-specific. As this type of estimate refers to aboveground biomass of individual trees, multiplication with planting density [ha⁻¹] and a dimensionless shoot factor is needed. Allometric equations are common for forest inventories and preferably used for even-aged stands of one or few similar species, as is the case for plantations.

3. Plateau curves of the form

$$W = W_{max} \cdot (1 - e^{-k \cdot StandAge})$$

are used to estimate total biomass of mixed stands such as natural forests. They are based on an age-dependent growth function that forms a rise to maximum curve. Such growth dynamics have been suggested for forest community ecosystems by ODUM (1969) and for nutrient-limited growth by THORNLEY & FRANCE (2007). W_{max} [Mg ha⁻¹] stands for the maximum biomass at climax stage, k is a dimensionless empirical factor determining curve slope and stand age [a] denotes the age of the vegetation.

4. Gompertz curves of the form

$$W = W_0 \cdot e^{\frac{\mu_0}{D} \cdot (1 - e^{-D})}$$

as described by THORNLEY & FRANCE (2007) start sigmoid and end in a plateau, accounting for senescence. Such empirical functions for biomass have been described by ACKER ET AL. (2002). W_0 [Mg ha⁻¹] stands for initial weight, μ_0 is a dimensionless empirical growth dependent factor on W and D for specific decay rates representing death of individuals or plant organs.

This kind of equation is more mechanistic than the previous one and allows for more precise estimates of natural vegetation, but requires more input parameters, which may be difficult to obtain.

After any of these estimates of W , total biomass is allocated to leaves, stems, harvestables and roots following the ratios determined beforehand. Rooting depth is calculated from root weight. Leaf area index (LAI) is calculated from leaf weight and a user-defined maximum LAI.

5 Nutrient translocation in the landscape

5.1 Erosion

LUCIA uses the Rose concept of erosion (ROSE ET AL. 1983a and b, HAIRSINE & ROSE, 1993, ROSE ET AL. 2007), a process-based approach originally developed for semi-arid environments. In contrast to USLE and other empiric models, Rose accounts for deposition, in addition to erosion. This makes the concept particularly useful for spatially explicit models. The Rose concept considers the main processes of detachment, entrainment, re-entrainment¹⁰ and deposition of particles from soil surfaces (ROSE ET AL. 2007). Model simulations in WaNuLCAS (V. NOORDWIJK AND LUSIANA 1999), built on the Rose model, have been validated for plots in NE Thailand by PANSACK ET AL. (2008). The conceptual model in WaNuLCAS has been used to set up the erosion module in LUCIA. However, as a plot-level model WaNuLCAS is not spatially explicit. For LUCIA PCRaster the *accutreshold* operator is used. Different basic equations are required to derive respective parameters:

1. Sediment concentration:

$$K = \frac{0.1 \cdot \rho_{Sed} \cdot S \cdot L^{0.4}}{\frac{\rho_{Sed}}{1000} - 1 \cdot 0.06} \cdot \left(\frac{\sqrt{S}}{n} \right)^{0.6}$$

with ρ_{Sed} standing for sediment density, a calibration factor with values ranging from about 1500 kg/m³ for large aggregates to 2650 kg/m³ for primary particles

¹⁰ This term is introduced, because particles that have been detached before are not bound to the soil as strongly as in their 'original' state.

(FOSTER, 1982), S for hillslope in [degrees], L for slopelength in [m] and n for the dimensionless Manning's roughness coefficient,

2. Flow velocity:

$$V = \left(\frac{\sqrt{S}}{n} \right)^{0.6} \cdot L^{0.4} \cdot Q^{0.4}$$

depending on slope, slopelength, runoff (Q) and Manning's n, and

3. Transport capacity:

$$C_{trans} = \left(k^{\beta} \cdot (Q^{0.4})^{\beta} \right) \cdot e^{Cover_{surf}}$$

Surface cover is derived from the LUCIA plant section and is related to LAI and SLA. The parameter β represents an erodibility factor (ROSE, 1993), a value between 0 and 1 that varies with soil cohesive force or soil strength. It is currently a calibration factor within the LUCIA framework. Further improvements in this direction will focus on removing this calibration into a more precise soil physical concept, e.g. f(shear strength, bulk density, C_{org}). The Rose approach was developed to take erosion by sheet and overland flow processes into account. So far, splash detachment is not considered, and further developments in this direction will follow suggestions by DE ROO ET AL. (1995) and VAN DIJK & BRUINZEEL (2003).

5.2 Leaching of nitrogen

Following a simplified approach, leaching is calculated in LUCIA as N concentration in the soil matrix multiplied by the respective flow (percolation, lateral flow, base flow). This module is not yet fully operable.

6 Management

All management activities are bound to land uses, i.e. they are applied to all pixels in the land cover map under the given land use. Theoretically, each individual plot could receive a specific treatment, which is not feasible for parametrisation of larger areas. To apply different treatments to the same land use type, the respective crop should be parametrised in different land use classes.

6.1 Cropping calendar and land cover change

Up to three planting dates (Julian days) per year can be defined for annual crops. However, the second and third planting are ignored if the previous crop has not been harvested until the planned planting date.

Two options for land cover change as main driver of environmental impacts have been developed so far. First, a sequence of yearly land cover maps defined before the model run is initialised. If a perennial land cover is replaced by another

land cover type, an appropriate slashing day must be defined (e.g. end of dry season).

Second, land use can change dynamically as consequence of farmers' decisions in response to crop performance, soil degradation or as part of typical cropping or crop-fallow rotations. At the moment, dynamic decision-making is realised through coupling to MP-MAS (BERGER ET AL. 2006), a multi-agent system that optimises decision-making based on economic criteria, taking into account typical decision rules regarding land suitability. A standalone version for LUCIA is under development, which allows to simulate these processes internally with relatively low input requirements as compared to MP-MAS.

6.2 Tillage

Tillage affects only the top soil horizon and leads to mixture and thus transfer of surface litter into the respective soil organic matter pools. For erosion, impacts of ploughing will be implemented once empirical functions are available from the study region. Only one input parameter, day of ploughing, is related to tillage.

6.3 Fertiliser and manure

For up to three applications of mineral fertiliser per year, Julian dates of application and fertiliser type can be specified. Amounts of fertiliser are converted into elemental N, P and K and are immediately plant available.

Only one manure application is foreseen per year. In analogy to mineral fertilisers, manure type (N, P, K contents) are user-defined and converted into elemental contents. In contrast to mineral fertiliser, manure needs to undergo transformations in the soil organic matter pools to become available for plants.

6.4 Irrigation

Two different types of irrigation can be selected, deficit-oriented and fixed applications. In the first case, required water for potential growth is added automatically, while for the second type dates and amounts of irrigation water need to be specified. For both types, the water source has to be selected: Groundwater, stream / lake, reservoir (e.g. cistern or pond of a given volume) or pipe. Irrigated water is deducted from the respective stocks, so that water competition can be simulated. In the case of pipe it is assumed that water supply is unlimited. This module is currently under construction.

7 Parametrisation from the GUI

Explanations in this section refer to the Graphical User Interface (GUI) of LUCIA and follow the tab structure of the GUI. Previous versions of text files or spreadsheets used for parametrisation still work but are not developed anymore. The graphical user interface for LUCIA has been developed in Python Qt. However to parametrise the model, a `lucia.exe` file allows to call all required software, open and operate the GUI.

In a first step, the user is asked to define a new or point to an existing folder, where all data for the coming model runs are stored. This is called a profile, which can be imagined as a project area or, in hydrological terms, a catchment. Consequently, the GUI asks in the next step for the location of all maps needed for this catchment. Once the respective folder is identified, all maps are automatically copied into the profile folder.

Next, a scenario name is defined and a folder with the scenario name generated by the GUI. All scenarios refer to the same catchment, but differ in certain assumptions. The scenario name should reflect these assumptions. Usually, a baseline scenario is defined first. In addition to the baseline, different alternative scenarios are defined, e.g. climate change, agricultural intensification, deforestation, among others. Scenario building is one of the most important steps in modelling and thus scenarios should be discussed thoroughly before entering values into the model.

Now, parametrisation, i.e. entering values for model parameters, starts by clicking on the Maps tab.

7.1 Maps

Using the LUCIA GUI, defining maps is the first step for parametrisation of a model scenario. Maps are selected from the profile folder, they can be opened and edited from the GUI calling standard PCRaster applications `Aguila` and `Mapedit`. The following maps need to be provided in PCRaster (`.map`) format to run the model.

1.Area: A boolean map defining the catchment to be simulated. All calculations refer to pixels on this map. All maps must have the same attributes as the `area.map`, i.e. the same number of rows and columns, same cell length and projection. If the maps do not match exactly, the model will produce missing values, which may propagate downstream.

2.Rain: A scalar map defining the area subjected to rainfall (the same as `area.map`, but continuous data format).

3.Land cover: Nominal map defining land cover types. These maps can be produced in any Geographical information System or spreadsheet and exported as ASCII files. In a following step the ASCII files, without header are converted into PCRaster format using the `asc2map` application of the PCRaster package (for use of `asc2map`, see PCRaster documentation).

4.Soil: Nominal map defining the soil types in the catchment. As for `landcover.map` the legend corresponds with the tables used for parametrisation.

- 5.DEM: Scalar digital elevation model of the catchment.
- 6.LDD: Local drain direction map defining the routing direction for each pixel. Water or sediments are transported along this routing direction to a pit cell, i.e. a cell without outflow, and eventually to the catchment outflow. The LDD is generated from the DEM using the `Iddcreate` function native to PCRaster.
- 7.Test points: Nominal user-defined map of observation points for which outputs of all parameters can be reported as time series.
- 8.Outflow (optional): In principle an additional testpoint at the hydrological catchment outlet that is used to observe watershed balances, particularly for validation.

All maps are loaded into the map tab of the GUI. Land cover and soil types found in the legends of the land cover and soil maps are automatically copied into the tables, which are described in the following sections. Vice versa, changed land cover or soil unit names in one of the tables will be written to the respective map legend.

7.2 Scenarios and management

For all parameters explanations, units and minimum / maximum values are shown as tool tips when moving the cursor over the respective column header.

7.2.1 General settings

- Time steps [d] refers to the number of days the model simulation takes and must not be < the number of observations for any parameter under Weather. Attempts to run a simulation with insufficient weather data will evoke an error message in PCRaster.
- Geographic latitude of the catchment is needed to calculate day length, which is used to estimate daily radiation. Latitude is given in [radians] and may need to be converted from [degrees].
- Pixel size refers to the side length of each pixel in [m].
- Perennials? This box must be checked for each land cover dominated by perennial plants.
- Present vegetation? This box is checked for vegetation present before the simulation starts, e.g. natural forest or fallow
- Tilage? Checked for land uses which are ploughed
- Fertilised? Manure? Irrigated? Boxes need to be checked for land covers which receive fertiliser, manure or irrigation water.
- Aquatic? This box is activated for aquatic plants and land covers like fish ponds (but not paddy rice).
- For test purposes water, N, P, and K as growth constraints can be separately switched off by checking the respective box.

7.2.2 Fertiliser and manure application

Only land cover types that have been selected as fertilised in the scenario tab are displayed here. Starting with an empty fertiliser tab, a fertiliser type is added (+ button) and optionally named on the left side; next N, P and K contents in [%]

are entered. On the right side of the tab, the Julian day of application is defined in the calendar and a fertiliser type selected on the drop-down menu in column 3. The amount of fertiliser added is entered into the following column and elemental N, P and K are calculated automatically. This can be repeated for up to 3 application dates.

Manure parametrisation works analogously to fertiliser.

7.2.3 Irrigation

One of two modes, deficit or fixed date and amount are selected first from the drop down menu in column 2. Next the source of irrigation water and the loss fraction due to leakage or evaporation are determined. Now different application dates and the respective amount of irrigation water can be entered.

7.3 Land cover related data

Although land cover classes have been loaded into the table from the map, new land covers can be added clicking the New button. However, this does not imply that the new land cover is represented in the land cover map. Land cover types not needed can be deleted, as long as they are not represented in the land cover map. Fully parametrised land cover classes can be saved as defaults with extension *.land and loaded later on, using the respective buttons.

7.3.1 Land cover

The land cover tab contains general plant-related and physiological parameters. Management inputs refer to up to three yearly planting dates. Note that in the model the second and third planting date are skipped if the previous crop has not reached maturity stage (harvest) until the scheduled planting date. Slashing date refers to farmers practice of cutting fallow or natural vegetation during the dry season. Timing of slashing can have impacts on nutrient availability for the following crop.

Initial and maximum leaf area index (LAI) are crutches needed by the model to delimit plant growth. Initial LAI can be understood as a small number representing cotyledons; it cannot become zero by definition, otherwise no biomass would develop. Maximum LAI is used mainly for the parametrisation of natural succession. During normal plant growth LAI is limited by self-shading.

Root Max determines the species-specific maximum rooting depth in cm. Additionally, rooting depth can be limited by soil properties. RWD fine is the root weight density or root weight per soil volume of fine roots. This parameter serves for calculating rooting depth taking root shape, the shape of the individual rootstock as vertical divided by horizontal extension, into account.

Erosion cover describes the protective effect of vegetation cover preventing soil erosion. A value of 1 indicates full protection, meaning no erosion.

KC is an empiric factor to derive crop-specific evapotranspiration rates (ALLEN ET AL. 1998) from ET₀, reference evapotranspiration. Drought adaptation is another empiric factor that describes the ability of plants to extract water from dry soil. On a range from 1 to 5, 1 stands for drought-sensitive and 5 for drought-tolerant

crops. WUE or water use efficiency quantifies the amount of water in litres metabolised to produce one kg of biomass.

TDbase, TDmax1 and TDmax2 are cardinal points for plant phenological development, which is determined by degreedays. They determine the minimum air temperature for development, threshold temperature with restricted development and maximum temperature that stops phenological development. Following the same concept, DD2flower and DD2harvest determine the numbers of degreedays needed for flowering and maturity, respectively.

Start and end of flowering period refer to seasonal phenology of flowering and are given in Julian days. Both are not yet fully implemented in the model and should be parametrised as 1 and 365, respectively. In contrast, Day 1st flower is an ordinal number, not a Julian day, for perennial plants that do not reach flowering stage during the first year after planting.

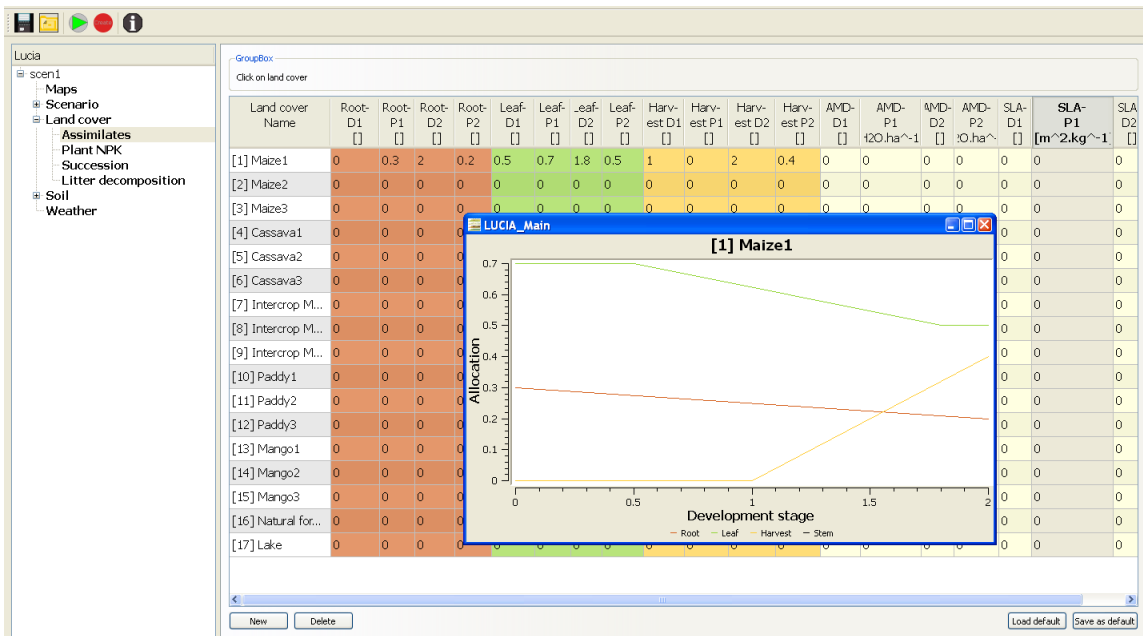
Albedo max plant gives the maximum proportion of solar radiation reflected by the plant surface. Photosynthesis is reduced for this share of radiation. Fodder index of leaf and stems determines the proportions of each of these plant parts exported from the field as fodder. These correspond to the harvest index, which in LUCIA is the total of Wha, the weight of harvested organs.

Maintenance respiration is the amount of CO₂ in kg per hectare and day, respired to maintain vital functions of the plant.

7.3.2 Assimilates

In this tab, parameter values related to assimilation are set. These include the maximum assimilation rate, allocation of assimilates to the different plant organs – leaves, stems, harvestables¹¹ and roots – and specific leaf area.

Each of these parameters changes with plant development stage. To facilitate parametrisation, values are entered for only two cardinal points, i.e. characteristic plant development stages (in the range between 0 and 2), and interpolated along broken stick functions (Fig. 9).



The linear equation for root ratio RR_i at a given development stage D_i is shown in below. D_1RR_1 and D_2RR_2 are the x,y coordinates of the two cardinal points.

$$\begin{aligned}
 RR_i &= RR_1 && \text{for } D_i < D_1 \\
 RR_i &= RR_1 - \left(\frac{RR_2 - RR_1}{D_2 - D_1} \right) \cdot D_1 + \left(\frac{RR_2 - RR_1}{D_2 - D_1} \right) \cdot D_i && \text{for } D_1 < D_i < D_2 \\
 RR_i &= RR_2 && \text{for } D_i > D_2
 \end{aligned}$$

Allocation to leaves + stems + roots + fruits cannot exceed 1. Stems are not explicitly parametrised but calculated in the model as
 Stems = 1- leaves- roots- fruits.

7.3.3 Plant NPK

Plant contents of N, P and K in the different tissues leaf, stem, root, fruit are variable during the life cycle of a plant and differ between developments stages. As a general rule, nutrient concentrations of the phloem-mobile N, P and K decline with development stage after a potential initial peak. Organ concentrations are ranked in the order leaf > root > stems (LAMBERS ET AL. 2008) for the three nutrients.

As for assimilates, parametrisation is simplified through linear functions crossing two cardinal points. As an example, for D_1, K_{leaf_1} and D_2, K_{leaf_2} as the x,y coordinates of the two user-defined cardinal points the K_{leaf_i} value for a given development stage D_i is derived from a broken stick function.

$$\begin{aligned}
 K_{leaf\ i} &= K_{leaf\ 1} && \text{for } D_i < D_1 \\
 K_{leaf\ i} &= K_{leaf\ 1} - \left(\frac{K_{leaf\ 2} - K_{leaf\ 1}}{D_2 - D_1} \right) \cdot D_1 + \left(\frac{K_{leaf\ 2} - K_{leaf\ 1}}{D_2 - D_1} \right) \cdot D_i && \text{for } D_1 < D_i < D_2 \\
 K_{leaf\ i} &= K_{leaf\ 2} && \text{for } D_i > D_2
 \end{aligned}$$

Such two-point parametrisation needs to be completed for N, P, K of leaves, roots, stems and harvestables, all in all 24 points.

7.3.4 Succession

Four alternative methods for estimation of present biomass and natural succession are offered (direct measurements, allometric equations, plateau and Gompertz functions) as described in section 4.7. Selecting the type of estimation from a drop-down menu highlights the required data inputs. Calculation of total biomass and biomass of leaves, stems, roots and harvestables is automated. LAI is approximated based on leaf biomass and user-defined maximum LAI.

7.3.5 Litter decomposition

Data for organic matter cycling are entered in two different tabs. Properties of organic matter in the litter stage depend on the litter source and are parametrised under Land cover / Litter decomposition. Once organic matter has transgressed from the litter into the soil organic matter stage, generic decomposition constants

and C:N and C:P ratios for soil organic matter are parametrised under SOM in the soil tab. Transition from litter to SOM occurs gradually, depending on decomposition rates between the pools or when litter is ploughed into the soil. Day of ploughing is the first parameter to be defined under litter decomposition. Cover efficiency of litter is a reduction factor relevant for soil erosion rates, at cover efficiency 1 maximum protection is offered to the soil and no erosion takes place.

In the following, fractions of surface litter and litter in SOM are defined and the active and slow fractions of SOC are quantified. The passive fraction is calculated as $1 - \text{active} - \text{slow}$.

Lignin fractions in metabolic and structural surface litter, in fine and coarse roots are specified in the following columns. Finally, remobilisation efficiencies for N, P and K in leaves and fine roots before abscission are requested. These are not well-known for most species, but remobilised nutrients not available for recycling can be of importance for NPK stocks. A default proportion of 0.5 for all three elements is suggested after LAMBERS ET AL. (2008) unless measured data are available.

7.4 Soil related data

As for land covers, new soil types can be added clicking the New button. Soil types can be deleted, as long as they are not represented in the land cover map. Fully parametrised soil types can be saved as defaults with extension *.soil and loaded later on, using the respective buttons.

Soils in LUCIA can have two homogeneous horizons, referred to as top- and subsoil. Standard profile data such as horizon thickness, stone, clay and sand contents, bulk density and organic carbon are used to automatically estimate the soil hydraulic parameters of total pore volume, water contents at field capacity and permanent wilting point, pore size distribution index λ and saturated conductivity. K_{sat} of the parent material determines permeability of the underground and thus stagnic properties of a soil. In depressions a small value for this parameter can lead to the formation of a lake.

For total and mineral N and available K values are given in g.kg^{-1} and for P Bray I in mg.kg^{-1} . pH CaCl_2 is not yet implemented in the model.

Under SOM, generic decomposition constants (k rates) and respiration rates for different soil carbon pools are required. C:N and C:P ratios are also entered here.

7.5 Weather data

More than one weather station can be parametrised, but the current model reads only data from the first one. Elevation of each weather station must be given, because temperatures per pixel are calculated as a function of altitude. The number of daily observations must not be $<$ than the number of timesteps selected under Scenarios for the model run. Values for air and soil temperature, rainfall, reference evapotranspiration and solar radiation can be copied into the mask from spreadsheet files. The graphs on the right side serve as data quality check, they cannot be edited.

1. Rainfall is measured in [mm]
2. Reference evapotranspiration is estimated or measured in [mm] and used to calculate transpiration and evaporation.
3. Air temperature is given in [°C] and modified for each pixel depending on elevation in the digital elevation model (DEM):

$$T = T_{station} + 0.005 \cdot (Elevation_{Station} - Elevation_{Pixel})$$

Phenological plant development follows the degreedays concept. Every degree on a certain day that surpasses a plant-specific constant threshold temperature is counted as one degree day. Plants require specific totals of degreedays to reach the flowering and maturity stage.

4. Soil temperature is measured / estimated in [°C] and an important driver for SOM cycling processes.
5. Solar radiation [$W m^{-2}$] is distributed in the model over day length as defined by latitude and Julian day. Photosynthetically active radiation (PAR) is estimated as half of the global radiation. PAR drives assimilation in LUCIA.

8 Outputs

Two types of outputs are mainly used in LUCIA: Map and time series. Maps are opened in Aguila, a software component included in PCRaster. Maps can be animated and illustrate changes as colour scale per time step in the entire map area. Exact values can be read pixelwise. Multiple time series can be generated defining a map of testpoint and creating *timeoutputs* (Fig. 10).

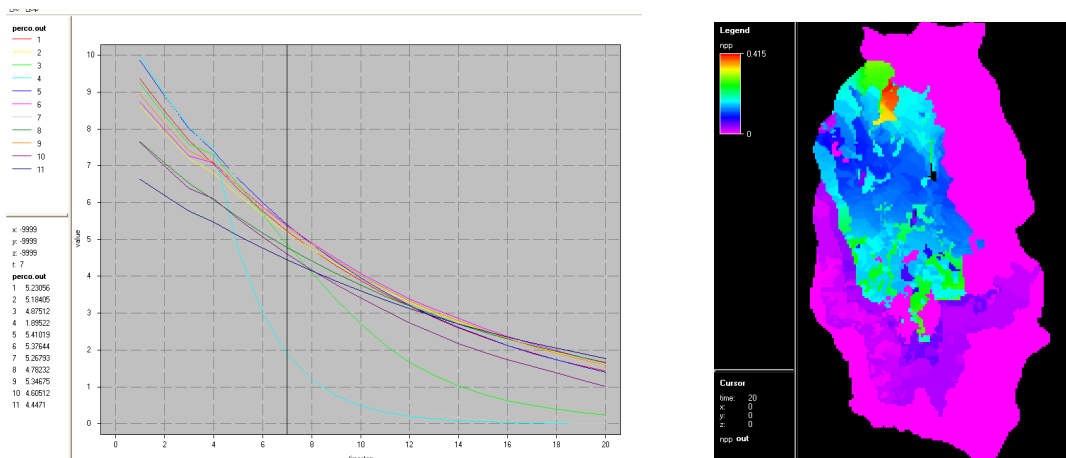


Figure 11: Outputs as map or multiple time series, left: Biomass in the entire watershed, excluding forest areas; right: Percolation at pre-defined points.

In the model script, most parameters are preceded by the 'report' command and can be produced as outputs. There is no explicit output section in the script, instead every output report is placed immediately after the respective parameter equation. This arrangement is supposed to give a good overview of where a parameter is located (which may matter for the output). Formats of output files can be defined by the user; in LUCIA .001 etc is used for map stacks and .out for multiple time series.

9 References

- ACKER, S.A., C.B. HALPERN, M.E. HARMON & C.T. DYRNESS (2002): Trends in bole biomass accumulation, net primary production and tree mortality in *Pseudotsuga menziesii* forests of contrasting age. *Tree Physiol.*, 22(2-3):213-7.
- AG BODENKUNDE (1994): Bodenkundliche Kartieranleitung. Hannover.
- ALLEN, R.G., L.S. PEREIRA, D. RAES & M. SMITH (1998): FAO Irrigation and Drainage Paper No. 56. Crop Evapotranspiration (guidelines for computing crop water requirements). FAO, Rome.
- BARROW, N.J. 2008. The description of sorption curves. *Eur J Soil Sci* 59:900–910.
- BERGER T., SCHREINEMACHERS P. & T. ARNOLD (2006): Mathematical Programming-based multi-agent systems to simulate sustainable resource use in agriculture and forestry. Internal document, University of Hohenheim, Stuttgart, Germany.
- V. DEURSEN, W.P.A. (1995): [Geographical Information Systems and Dynamic Models: development and application of a prototype spatial modelling language](#). Doctor's dissertation, Utrecht University, [NGS 190](#).
- GOUDRIAAN, J. (1977): Crop micrometeorology: A simulation study. Simulation Monographs. Pudoc, Wageningen.
- IRVING, D. E. & J. H. SILSBURY (1987): A Comparison of the Rate of Maintenance Respiration in Some Crop Legumes and Tobacco Determined by Three Methods. *Annals of Botany* 59: 257-264.
- JAHN, R., H.P. BLUME & V.B. ASIO (2003): Students guide for soil description, soil classification and site evaluation.
- JONES, CA, COLE, CV, SHARPLEY, AN, WILLIAMS, JR. 1984. A simplified soil and plant phosphorus model: I. Documentation. *Soil Sci Soc Am J* 48:800-805.
- LAMBERS, H., CHAPIN, F.S. & T.L. PONS (2008): *Plant Physiological Ecology*. 2nd ed. Springer.
- V. NOORDWIJK, M. (2002): Scaling trade-offs between crop productivity, carbon stocks and biodiversity in shifting cultivation landscape mosaics: the FALLOW model. *Ecological Modelling* 149:113-126.
- V. NOORDWIJK, M. & B. LUSIANA (1999): WaNuLCAS 1.0, a model of water, nutrient and light capture in agroforestry systems. *Agroforestry Systems* 45: 131-158.
- ODUM, E.P. (1969): The strategy of ecosystem development. *Science* 164:262-270.
- PAGEL, H., J. ENZMANN & H. MUTSCHER (1982): Pflanzennährstoffe in tropischen Böden: Ihre Bestimmung und Bewertung. Dt. Landwirtschaftsverlag, Berlin.
- PANSAK, W., T.H. HILGER, C. MAROHN, T. KONGKAEW & G. CADISCH (2008): Assessing soil conservation strategies for upland cropping in Northeast Thailand with the Water Nutrient Light Capture in Agroforestry Systems Model. Submitted to *Agroforestry Systems*.
- PARTON, W.J., D.S. SCHIMEL, C.V. COLE & D.S. OJIMA (1987): Analysis of factors controlling soil organic levels of grasslands in the Great Plains. *Soil Science Society of America Journal*. 51:1173-1179.
- RIBEIRO DE FARIAS, D, TAVARES DE OLIVEIRA, FH, SANTOS, D, ALVES DE ARRUDA, J, BEZERRA HOFFMANN, R, FERREIRA NOVAIS, R. 2009. Fósforo em solos representativos

do estado da Paraíba. i - Isotermas de adsorção e medidas do fator capacidade de Fósforo. R Bras Ci Solo 33:623-632.

RITCHIE, J.R. (1971): Dryland evaporative flux in a subhumid climate. II. Plant influences. Agronomy Journal, 63:56-62.

RITCHIE, J.R. (1972): Model for predicting evaporation from a row crop with incomplete cover. Water Resources Research, 8:1204-1213.

ROSE, C.W., J.R. WILLIAMS, G.C. SANDER & D.A. BARRY (1983): A mathematical model of soil erosion and deposition processes: II. Theory for a plane land element. Soil Science Society of America Journal 47:991-995.

ROSE, C.W., J.R. WILLIAMS, G.C. SANDER & D.A. BARRY (1983): A mathematical model of soil erosion and deposition processes: II. Application of data from an arid-zone catchment. Soil Science Society of America Journal 47:996-1000.

ROSE, C.W. B. YU A, H. GHADIRI, H. ASADI, J.Y. PARLANGE, W.L. HOGARTH & J. HUSSEIN (2007): Dynamic erosion of soil in steady sheet flow. Journal of Hydrology 333:449– 458.

SAXTON, K.E. & W.J. RAWLS (2006): Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. Soil Sci. Soc. Am. J. 70:1569–1578.

SCHACHTSCHABEL, P, BLUME, H-P, BRÜMMER, G, HARTGE, K-H, SCHWERTMANN, U. 1992. Lehrbuch der Bodenkunde, 13th ed. Enke, Stuttgart.

SHARPLEY, AN, JONES, CA, GRAY, C, COLE, CV. 1984. A simplified soil and plant phosphorus model: II. Prediction of labile, organic, and sorbed phosphorus. Soil Sci Soc Am J 48:805-809.

SMITH, R.E., & J.-Y. PARLANGE (1978): A parameter-efficient hydrologic infiltration model. Water Resources Research, 14(3):533-538.

SUPIT, I. (2003): Updated system description of the WOFOST crop growth simulation model as implemented in the crop growth monitoring system applied by the European Commission. Treemail Publishers, Heelsum, The Netherlands. <http://www.treemail.nl/download/treebook7/start.htm>

THORNLEY, J.H.M. & J. FRANCE (2007): Mathematical models in agriculture; 2nd ed. CABI, Wallingford.

WARREN (1994a). Influence of soil properties on the response to phosphorus in some tropical soils: I. Initial response to fertilizer. Eur J Soil Sci 45:337-344.

WARREN (1994b). Influence of soil properties on the response to phosphorus in some tropical soils: II. Residual P and yield response. European Journal of Soil Science 45

WIDODO, R.H., B. LUSIANA, FARIDA, D. SUYAMTO, M. v. NOORDWIJK & N. KHASANAH (2007): GenRiver - Generic River Flow Model. User Manual, Version 1.1.. ICRAF Southeast Asia Programme, Bogor, Indonesia.

WOLF, J, DE WIT, CT, JANSSEN, BH, LATHWELL, DJ. 1987. Modeling Long-Term Crop Response to Fertilizer Phosphorus. I. The Model. Agron J 79:445-451.

WOOLHISER, D.A., R.E. SMITH & D.C. GOODRICH (1990): KINEROS, A kinematic runoff and erosion model: Documentation and user manual. US Department of Agriculture, Agricultural Research Service, ARS-77, 130p.

10 Appendices

10.1 Model parameters and units

Parameters, their units and ranges are explained following their appearance by section in the model script and in the LUCIA GUI by tab.

10.1.1 Maps

Contents of the required maps have been listed under 7.1. All of these maps must use the same map attributes to be consistent:

- Numbers of rows and columns
- Projection
- X and Y value of the upper left corner
- Cell length
- Angle (as related to standard coordinate systems)
- ID value

10.1.2 Weather data

Parameter	File	Unit	Range
Rainfall	rain.tss	[mm]	≥0
Reference evapotranspiration ETO	et0.tss	[mm]	≥0
Air temperature	airtemp.tss	[°C]	-10 to 60
Soil temperature	soiltemp.tss	[°C]	-10 to 60
Solar radiation	rad.tss	[W m ⁻²]	≥0

10.1.3 Look-up tables

landcover.lut			
Parameter	Unit	Range	Explanation
Planting day 1	[Julian day]	1 to 365	Day of sowing, planting, transplanting
Planting day 2, 3	[Julian day]	1 to 365	Optional, for 2 or 3 crops per year
Slashing day	[Julian day]	1 to 365	Day for clearing standing <i>perennial</i> biomass before cultivation
LAI Initial	[m ² .m ⁻²]	0.0001 to 20	Initial leaf area index; automatic for natural succession

landcover.lut			
LAI Max	[m ² .m ⁻²]	0.0001 to 20	Maximum leaf area index
Root Max	[cm]	0 to 1000	Species-specific maximum rooting depth
RWD fine	[Mg.m ⁻³]	0.001 to 0.05	Fine root density
Root shape	[]	0.1 to 10	Vertical extension over horizontal radius of rootstock
N fixation	[kgN.ha ⁻¹ .d ⁻¹]	≥0	Biological N fixation
Parameter	Unit	Range	Explanation
Erosion cover	[]	0 to 1	Cover factor erosion, 1 = full protection
kC	[]		Empiric single crop coefficient for evapotranspiration
Drought adaptation	[]	1 to 5	Empirical factor from WOFOST: Ability to extract water from the soil. 1=drought sensitive, 5=drought tolerant
WUE	[l.kg ⁻¹]	0 to 2000	Water use efficiency
T base	[°C]	-10 to 30	Minimum air temperature for assimilation
T max 1	[°C]	15 to 50	Upper threshold for assimilation, reduced growth beyond
T max 2	[°C]	20 to 70	Upper threshold for assimilation, no growth beyond
DD2 flower	[°C d]	>0	Degreedays until flowering
DD2 harvest	[°C d]	>0	Degreedays until maturity
Day 1 st flower	[day]	>0	First flowering day, if not during 1 st year
Start flowering period	[Julian day]	1 to 365	Phenological first flowering date
End flowering period	[Julian day]	1 to 365	Phenological last flowering date
Albedo plant	[]	0 to 1	Proportion of sunlight reflected by plant surface
Fodder index leaf	[]	0 to 1	Proportion of leaves used as fodder (annuals only after harvest)
Fodder index stem	[]	0 to 1	Proportion of woody parts used as fodder (annuals only after harvest)
Maintenance respiration	[kgCO ₂ .ha ⁻¹ .d ⁻¹]	0.01 to 0.1	

assimilates.lut			
Parameter	Unit	Range	Explanation
Root D1	[]	0 to 2	Development stage for P1
Root P1	[]	0 to 1	Proportion of assimilates allocated to roots at D1
Root D2	[]	0 to 2	Development stage for P2
Root P2	[]	0 to 1	Proportion of assimilates allocated to roots at D2
Parameter	Unit	Range	Explanation
Leaf D1, P1, D2, P2	[]		As for roots
Harvest D1, P1, D2, P2	[]		As for roots
AMD D1, D2,	[]	0 to 2	Development stages for AMD
AMD P1, P2	[kgCH ₂ O.ha ⁻¹ .h ⁻¹]	5 to 100	Maximum assimilation rates at D1, D2
SLA D1, D2	[]	0 to 2	Development stages for SLA
SLA P1, P2	[m ² .kg ⁻¹]	10 to 100	Specific leaf area at D1, D2

npkplant.lut			
Parameter	Unit	Range	Explanation
N leaf	[g.g ⁻¹]	0.0001 to 0.04	Target content of N in leaves
N root	[g.g ⁻¹]		Target content of N in roots
N stem	[g.g ⁻¹]		Target content of N in stems
N harvest	[g.g ⁻¹]		Target content of N in harvestable parts
P leaf	[g.g ⁻¹]		Target content of P in leaves
P root	[g.g ⁻¹]		Target content of P in roots
P stem	[g.g ⁻¹]		Target content of P in stems
P harvest	[g.g ⁻¹]		Target content of P in harvestable parts
K leaf	[g.g ⁻¹]		Target content of K in leaves
K root	[g.g ⁻¹]		Target content of K in roots
K stem	[g.g ⁻¹]		Target content of K in stems
K harvest	[g.g ⁻¹]		Target content of K in harvestable parts

succession.lut			
Parameter	Unit	Range	Explanation
W	[Mg.ha ⁻¹]	≥0	Total biomass, dry matter
Wlv	[Mg.ha ⁻¹]	≥0	Leaf biomass, dry matter
Wrt	[Mg.ha ⁻¹]	≥0	Belowground biomass, dry matter
Wst	[Mg.ha ⁻¹]	≥0	Stem biomass, dry matter
Wha	[Mg.ha ⁻¹]	≥0	Harvestable biomass, dry matter
dbh	[cm]	0 to 500	Stem diameter at breast height
Parameter	Unit	Range	Explanation
a	[]	empiric	Coefficient for allometry
b	[]	empiric	Exponent for allometry
Planting density	[ha ⁻¹]	≥0	Plants per hectare
Shoot ratio	[]	0.1 to 0.9	Proportion of shoot to total biomass
Max biomass	[Mg.ha ⁻¹]	10 to 800	User-defined maximum for biomass
k	[]	empiric	Empirical exponent
Stand age	[a]	≥0	Age of vegetation
W0	[Mg.ha ⁻¹]	≥0	Initial weight
μ0	[]	empiric	Empirical growth factor
Decay	[]	empiric	Decay rate

litter.lut			
Parameter	Unit	Range	Explanation
Ploughing day	[Julian day]	1 to 365	Day of tillage
Cov Eff Litter	[]	0 to 1	Protective effect of litter layer against erosion (1 = full protection)
Surf Litter	[]	0 to 1	Fraction of surface litter in topsoil SOM
Litter Frac SOM	[]	0 to 1	Fraction of litter in SOM
Act Frac SOM	[]	0 to 1	Fraction of active C in SOM
Slow Frac SOM	[]	0 to 1	Fraction of slow C in SOM
LigninSurfLittMet	[]	0 to 0.6	Lignin concentration in metabolic surface litter
LigninSurfLittStruc	[]	0 to 0.6	Lignin concentration in structural surface litter
Lignin fine roots	[]	0 to 0.6	Lignin contents in fine roots
Lignin coarse roots	[]	0 to 0.6	Lignin contents in coarse roots
RemobEffN	[]	0 to 1	Remobilisation efficiency for N
RemobEffP	[]	0 to 1	Remobilisation efficiency for P
RemobEffK	[]	0 to 1	Remobilisation efficiency for K

soil.lut			
Parameter	Unit	Range	Explanation
Thickness Top	[cm]	0 to 99	Topsoil thickness
Thickness Sub	[cm]	0 to 999	Subsoil thickness
Stones Top	[]	0 to 1	Stone contents topsoil
Stones Sub	[]	0 to 1	Stone contents subsoil
BD Top	[Mg.m ⁻³]	0.3 to 2.8	Bulk density topsoil
BD Sub	[Mg.m ⁻³]	0.3 to 2.8	Bulk density subsoil
Sand Top	[]	0 to 1	Sand contents topsoil
Sand Sub	[]	0 to 1	Sand contents subsoil
Clay Top	[]	0 to 1	Clay contents topsoil
Clay Sub	[]	0 to 1	Clay contents subsoil
C _{org} Top	[%]	0 to 50	Soil organic carbon topsoil
C _{org} Sub	[%]	0 to 50	Soil organic carbon subsoil
N _T Top	[g.kg ⁻¹]	0 to 10	Total nitrogen topsoil
N _T Sub	[g.kg ⁻¹]	0 to 10	Total nitrogen subsoil
N _{min} Top	[g.kg ⁻¹]	0 to 2	Mineral nitrogen topsoil
N _{min} Sub	[g.kg ⁻¹]	0 to 2	Mineral nitrogen subsoil
P _{Bray I} Top	[mg.kg ⁻¹]	0 to 500	Phosphorus Bray I extract topsoil
P _{Bray I} Sub	[mg.kg ⁻¹]	0 to 500	Phosphorus Bray I extract subsoil
K _{av} Top	[g.kg ⁻¹]	0 to 10	Plant available potassium topsoil
K _{av} Sub	[g.kg ⁻¹]	0 to 10	Plant available potassium topsoil
pH Top	[]	2 to 14	pH CaCl ₂ extract topsoil
pH Sub	[]	2 to 14	pH CaCl ₂ extract topsoil
K _{sat} parent	[mm.d ⁻¹]	2 to 3000	Saturated conductivity of parent material
Water Top	[]	0 to 1	Topsoil water content (proportion of TPV)
Water Sub	[]	0 to 1	Subsoil water content (proportion of TPV)

Estimated parameters (pedotransfer functions)			
TPV	[]	calculated	Total pore volume (proportion of soil volume)
FC	[]	calculated	Volumetric water contents at field capacity
PWP	[]	calculated	Volumetric water contents at permanent wilting point
Lambda	[]	calculated	Pore size distribution index
K _{sat}	[mm.d ⁻¹]	calculated	Saturated conductivity
PsiETop	[mm.d ⁻¹]	calculated	Water potential in topsoil at bubbling pressure

som.lut			
Parameter	Unit	Default	Explanation
k_SurfLitterMetab	[]	0.025	Decomposition rate of metabolic surface litter
k_SurfLitterStruc	[]	0.0042	Decomposition rate of structural surface litter
k_SoilLitterMetab	[]	0.031	Decomposition rate of metabolic soil litter
k_SoilLitterStruc	[]	0.0052	Decomposition rate of structural soil litter
k_Active	[]	0.0085	Decomposition rate of active C pool
k_Slow	[]	0.0002	Decomposition rate of slow C pool
k_Passive	[]	0.00001	Decomposition rate of passive C pool
RespFracGeneral	[]	0.55	Respiration fraction (share of SOC respired as CO ₂)
RespFracSurfLitterStruc2Active	[]	0.45	Respiration fraction structural surface litter to active C pool
RespFracLitterStruc2Slow	[]	0.3	Respiration fraction structural litter to slow C pool
CNtarget_Metab	[]	10	C:N target ratio of metabolic C pool
CN_Struc	[]	150	C:N ratio of structural C pool
CN_Active	[]	8	C:N ratio of active C pool
CN_Slow	[]	11	C:N ratio of slow C pool
CN_Passive	[]	11	C:N ratio of passive C pool
CP_SurfLitterMetab	[]	180	C:P ratio of metabolic surface litter
CP_SoilLitterMetab_Top	[]	200	C:P ratio of metabolic topsoil litter
CP_Struc	[]	1500	C:P ratio of structural soil C pool
CP_Active	[]	250	C:P ratio of active soil C pool

som.lut			
CP_Slow	[]	300	C:P ratio of slow soil C pool
CP_Passive	[]	400	C:P ratio of passive soil C pool
FineRoots_N	[]	0.01	N concentration in fine roots
SurfLitterMetab_N	[]	0.02	N concentration in metabolic surface litter pool