Documentation LUCIA

1 General remarks

The Land Use Change Impact Assessment tool LUCIA is developed for the 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 watersheds in mountainous areas of Thailand and Vietnam. However, the model aims to be generic. LUCIA is a raster-based spatially explicit dynamic model written in PCRaster code. The model operates on a daily time step and at a pixel size of 25x25m, which corresponds to an average plot size in the research area of Mae Sa, Northwest Thailand. The biophysical LUCIA model is intended to be dynamically coupled with a multi-agent model that simulates decision-making based on economic criteria (MP-MAS).

Different modules of LUCIA were adapted from existing concepts and validated models, see table 1. Calendar functions (planting and management), pore volume, streams and lakes, soil fertility (based on the Trenbath concept in FALLOW and SCUAF) and trees were developed for LUCIA. The Tropical Soil Productivity Calculator TSPC was translated into PCR for compatibility with MP-MAS.

Table 1: Origin of modules in LUCIA

Module	Origin, comments
Radiation, assimilation, crop growth	WOFOST
Dynamic soil properties	GenRiver (reference bulk density concept)
Soil water	Landscape GenRiver, plant WOFOST
Patch water balance	GenRiver
Development	WOFOST
Potential evapotranspiration	WOFOST
Transpiration	WOFOST
LAI, cover	WOFOST
Crop yield	TSPC and WOFOST

Some frequently used abbreviations are listed and explained in table 2.

Table 2: Explanation of model acronyms

PCRaster	Dynamic modelling language used for LUCIA (V. DEURSEN 1995)
MP-MAS 1.0	Multi-agent system, to be coupled with LUCIA (BERGER ET AL. 2006)
TSPC	Tropical Soil Productivity Calculator, an empirical crop module used in MP-MAS (AUNE & LAL 1995)
WOFOST (PCR version)	Process-based crop growth model CGMS by SUPIT (2003)
WaNuLCAS 3.1	Model simulating water, nutrients, light and carbon in agroforestry systems (V. NOORDWIJK & LUSIANA 1999)
GenRiver 1.1	A semi-spatial watershed model (V. NOORDWIJK ET AL. 2005)
FALLOW	A spatially explicit land use model emphasizing socioeconomic and decision-making processes (V. NOORDWIJK 2002)

The present version of LUCIA (Oct 2008) is primarily intended for internal testing. The script has no explicit output section. Instead, report commands are placed directly after each relevant calculation step; they can be switched on / off (placing / removing '#' in front) in order to check the effect of changes in the given context.

In this documentation PCR code and pseudo-code are written in italics.

2 Units

Soil nutrients are given in [kg/ha] (considering only the upper 20cm as in TSPC), while carbon and biomass are in [Mg/ha]. Soil and rooting depth are in cm. Water-related parameters are in [mm], [mm/d] or, for area totals > 1 pixel, in [m^3]. SLA is in [ha/Mg], temperature in [°C]. See also the parameter glossary (section 14).

3 Weather data

3.1 Solar radiation and temperature

Solar radiation [W m^{-2}] and air temperature [°C] are entered on a daily basis (in the case of Mae Sa Noi provided by HUGENSCHMIDT); temperature is modified depending on elevation in the digital elevation model (DEM):

T=timeinputscalar(Temp,AreaMap)+0.005(805-DEM);*

Where 805m asl is the elevation of the weather station and 0.005K/m an assumed elevation-dependent temperature gradient.

3.2 Reference evapotranspiration and rainfall

Daily rainfall data and ET0, both in [mm], are read from one rain gauge in the Mae Sa Noi watershed (provided by HUGENSCHMIDT). Both are assumed to be homogeneous over the area.

4 Soil

4.1 Soil physics

4.1.1 Soil depth and rooting space

Root growth is limited by impermeable soil layers, e.g. rock, hard pan or water logging. Soil Depth is the sum of topsoil + subsoil depth, where topsoil would comprise organic soil horizons and subsoil extends down to the first impermeable soil layer. Soil water available for (capillary rise and) soil evaporation also draws back on the same soil depth.

MaxRoot is the species-specific maximum depth roots can reach.

Both plant available water and nutrient uptake are constrained to rooting depth, the actual root extension at a given time, which is the minimum of MaxRoot, RootingDepth and SoilDepth.

4.1.2 Pore volume

Amounts of water that can be stored in the soil are determined by pore volume. Depending on pore size, water is available for plants, discharge or percolation. The different additive fractions of pores / water and their terminology in different models are illustrated in fig. 1. These fractions refer to potential values; water available for plant growth additionally depends on the water actually infiltrated into the soil.
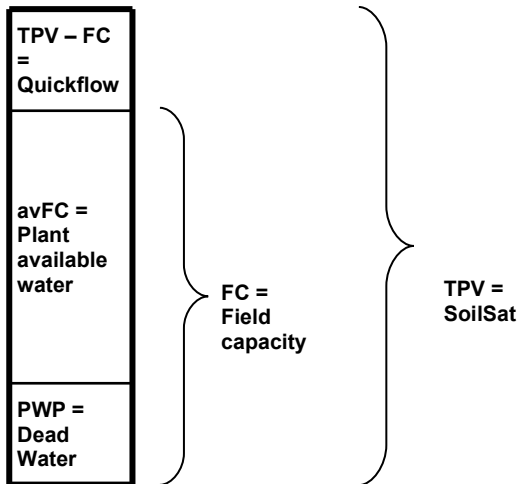
Figure 1: Definitions of pore volumes and corresponding water fractions in the soil. TPV=Total pore volume, FC=field capacity, PWP= permanent wilting point above pF 4.2.

Top- and subsoil are treated separately and pore volume is initialized on the basis of texture, C_{org} and bulk density for topsoils and texture, bulk density and stone contents for subsoils. Tabulated values for TPV (total pore volume), FC, avFC (available field capacity) and PWP (permanent wilting point) are derived from Jahn et al. (2003, after AG Bodenkunde 1994) and read by the model as look-up tables[1].

In the current version, pore volumes were assigned to WRB soil units of existing maps. Alternatively, C_{org}, BD, texture and stone contents could be derived from maps of interpolated measurements.

These calculations require computing time and have been placed in the initialisation section. Consequently, carbon contents as relevant for pores are not updated, however, concerning SOM cycles, they are.

4.1.3 Dynamic pore volume

Roots penetrating the soil create voids once they decompose; thus they have a loosening effect, which differs between land uses. Compared to a given standardised use, different land uses exert a loosening or compacting effect on the soil.

Bulk density and thus pore volume change due to land use as suggested in the GenRiver concept. However, the technical implementation has been modified. Only the rooted part of a soil is modified yearly by a land cover-specific melioration / degradation factor to account for the loosening or compacting effect of land use on the soil. These changes affect TPV as well as FC and PWP of top- and subsoils. As an example, code for topsoil TPV is shown here:

TPVTop=if(JulianDay eq 365,
TPVTop/BDBDRefVeg*min(RootingDepth,TopSDepth)/TopSDepth+
TPVTop*max(0,TopSDepth-RootingDepth)/TopSDepth,
TPVTop);

---

[1] Where texture classes (sand, … , clay) were converted into categorical TextureID values.

The same term is used for TPV, FC and PWP of top- and subsoils. In order to maintain realistic orders of magnitude, dynamic bulk density is updated only once a year. On a daily step too much weight would be given to this factor and parametrisation would require values extremely close to 1 – difficult to measure.

In a following step top- and subsoil parameters are added up. Stone contents of the subsoil are considered, and the loosening effect of roots in the soil is constrained to the rooted zone (coupled to rooting depth in the crop module). TPV, FC and PWP top- and subsoil are summed up. Quickflow (TPV – FC), and avFC (FC – PWP) are subsequently calculated.

4.2 Soil quality and fertility

4.2.1 Soil fertility in the TSPC and FALLOW concept

Development of the soil fertility module in LUCIA was led by two main considerations:

- Compatibility with the Tropical Soil Productivity Calculator (TSPC) used in MP-MAS.
- Including soil degradation and rehabilitation as consequences of land use as implemented in the Trenbath module of the FALLOW model.

The TSPC proceeds in four general steps to calculate crop yield and nutrient cycling (SCHREINEMACHERS 2007):

1. In the yield determinants section, plant-available nutrients are accounted for: Initial stocks, inputs from residues, atmosphere, fertilizer, manure, exports to markets and as fodder and losses due to erosion.
2. Crop production is calculated based on crop-specific potential yield with crop response curves for N, P, K and pH as reduction factors. Reduction factors influence each other[2].
3. After harvest soil properties are updated.
4. Finally, a balance of soil properties is produced. Exports of harvest and fodder, erosion, fertilizer, manure and atmospheric deposition of N are updated.

The Trenbath concept attributes melioration or degradation to distinct land uses. For undisturbed natural vegetation, land use follows (secondary) succession stages, which recovers soil fertility, while cropping degrades it. Soil fertility is subsumed into one overall factor.

Currently (Oct 2008), TSPC is carried through parallely to the mechanistic strain to warrant compatibility with MP-MAS inputs. LUCIA considers N, P and K as factors influencing soil fertility, but at the same time aims at a more process-based description compared to the merely empirical TSPC approach. The Trenbath approach is reflected mainly in the LUCIA SOM module (section 7).

---

[2] This follows the Mitscherlich approach, in contrast to the minimum concept introduced by J. v. Liebig. Parametrisation of N, P and K crop response factors and an assessment of their interactions has been carried out by Calberto (2008).

Nutrient stocks are initialised from soil maps[3]. The soil balance of plant available nutrient stocks is shown below for K. In the dynamic model section, the cumulative N, P and K pools include inputs from nutrient cycling, fertiliser and manure and outputs through plant uptake; part of the nutrients bound in biomass is lost as harvest and fodder exports. Erosion losses are foreseen once the respective module is fully operable.

K_PlantAvStocks = max(0,K_PlantAvStocks + K_org + K_FertiliserApplication + K_man2Av - K_PlantUptake);

The same balance is applied for N and P adding atmospheric deposition and biological fixation as N inputs and leaching as N losses. For P, availability is reduced by a sorption constant. pH is entered in the initial section as the TSPC recurs on it, but remains stable throughout the dynamic part.

Nutrient uptake by plants is controlled by potential biomass production due to radiation and water as well as nutrient target contents of the respective plant tissue.

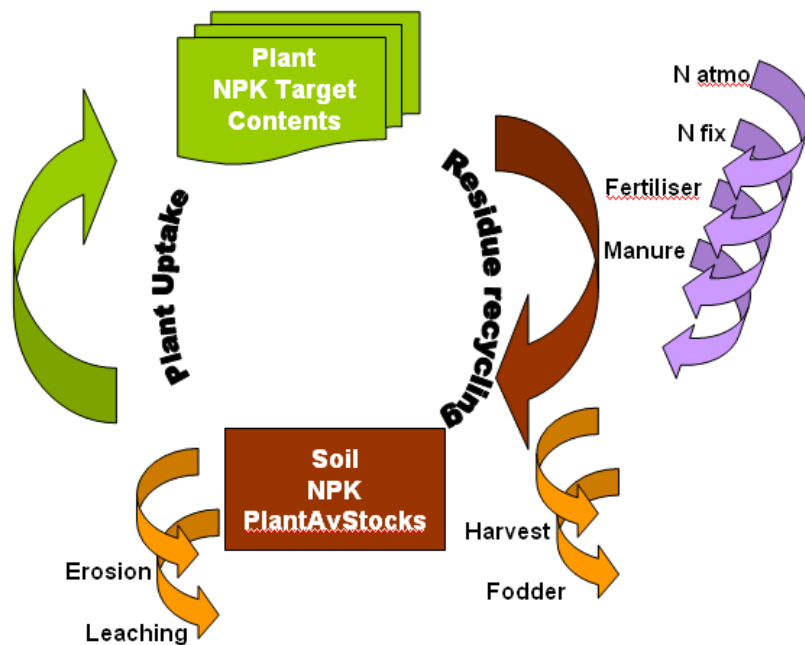*Figure 2: Nutrient cyling between soil and plant, in- and outputs*

Decomposition of plant residues is described to more detail in the SOM section.

---

[3] In the current version, element contents were assigned to soil units in a soil map; this may be updated with interpolated field measurement data.

Different types of fertiliser and manure input are parametrised in the LUCIA input spreadsheet. Amounts and date of application follow farmers' practice: For each specific land use type a representative type of fertilizing is considered across all plots under that land use. Applications are exported on a daily basis as timeinput. Alternatively, a plot-specific approach has been implemented (but not activated) using unique IDs for each plot suitable for agriculture. However, this type of parametrisation would require considerable efforts.

5 Water balance

This model section is based on GenRiver concepts with changes in the patch water balance concerning evapotranspiration and percolation / soil discharge. Flows of soil / groundwater discharge and run-off in the landscape are spatially explicit, an advantage of PCRaster over the Stella platform. Lakes were also conceptualised in a spatially explicit way (referring to a subwatershed).

5.1 Evapotranspiration

Instead of one overall differential parameter (e.g. EvapTransp=ETC-IntEvap, with ETC=ET0*kC), potential evapotranspiration is dissected into soil evaporation and potential transpiration. This accounts better for dynamic LAI as simulated in the crop module and for the sequence Rain → Interception → Infiltration → SoilWaterStocks → ET[4].

Evaporation from plant surfaces is accounted for as InterceptEvap and thus not considered anymore. Evapotranspiration is then calculated as shown in the following pseudo-code:

EvapTrans = (OpenSoilEvap) (1-Cover) + (ShadedSoilEvap)(Cover) + TranspAct and confined by PlantAvWater.

In the following, the single components of evapotranspiration are described in detail.

5.1.1 Evaporation of intercepted water

LUCIA interception builds on dynamic LAI. Maximum water storage on leaves is calculated as in WOFOST, considering plant cover, dynamic LAI and thickness of the water film (0.2 [mm]):

*Storage=LAItot*Cover*0.2;*

InterceptEvap is then a rise-to-maximum function of rainfall and storage:

InterceptEvap=max(Storage(1-exp(-DailyRain/Storage)),0);*

---

[4] If the soil water pool is empty, there will be no ET.

5.1.2 Soil Evaporation

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

Potential bare soil evaporation [cm d^{-1}] is calculated as

$E0_s = ET0 * e^{-Kgb*LAI}$,

where LAI is the leaf area index [ ] and κ_{gb} the extinction coefficient for global radiation [ ]:

κ_{gb} = 0.75*κ_{df}, the latter being the extinction coefficient for diffuse radiation:

κdf = 0.72 (GOUDRIAAN, 1977).

The maximum evaporation rate from a shaded bare soil surface [cm d^{-1}] is calculated as

$E_{Smax} = E0_s * e^{-Kgb*LAI}$. Following this logic and as LAI over bare soil is 0, the term $e^{-Kgb*LAI}$ becomes 1 and $E0_s = ET0$.

Soil evaporation can then be derived from the respective shares of evaporation under shaded and open soil. In LUCIA this reads

*EvapSoil=min(PlantAvWat,(1-Cover)*ET0+Cover*EvapShadedSoil);*

Evaporation from open lake surfaces is calculated in a simplified manner.

5.1.3 Transpiration

Transpiration in LUCIA is primarily demand-driven, depending on biomass increase of the previous time step and water use efficiency (WUE, the amount of water needed to produce one unit of plant biomass):

*TranspAct=min(PlantAvWat,0.1*dWact*WUE);*

As can be seen, actual transpiration is limited by Plant Available Water, a combined term of Soil Water, available Field Capacity and Rooting Depth,

*PlantAvWat=10*SoilWater*(min(RootingDepth,TopSDepth)/SoilDepth*avFCTop/ TPVTop+if(RootingDepth gt TopSDepth, (RootingDepth-TopSDepth) *avFCSub/ TPVSub,0));*

The factor 10 converts rooting depth [cm] into water [mm] units. Pore volumes are differentiated between top- and subsoil, while soil water is a share over the entire soil profile.

For comparison, WOFOST first calculates potential transpiration from ET0, a crop-specific kC factor and plant cover. The resulting value is then multiplied with a reduction factor that represents matric potential Ψ_m, the major force holding back water in the soil pores.

For matric potential to be integrated, calculations should be performed outside the model or simple transfer functions should be derived (e.g. from WaNuLCAS or Rosetta) to obtain pF/θ – curves and other input.

5.2 Infiltration

Infiltration of rainfall into the soil water stock is built on the GenRiver concept. To derive infiltration, rain duration is first estimated from daily rainfall and a uniform random distribution at given mean and CV of rain intensity. The delay of rain getting to the ground leads to time available for infiltration (being the sum of rain duration and delay).

Infiltration is then the minimum of

- soil capacity for water uptake (*SoilSat – SoilWater*). This has been limited to values ≥0; excess water will percolate, be discharged or run off;
- the maximum hourly infiltration capacity (*DailyMaxInf/24*Time4Infiltration*), and
- the available amount of rain water after intercepted evaporation (*DailyRain – InterceptEvap*).

5.3 Soil water stocks

The cumulative soil water pool is a balance of infiltrated water minus soil evaporation, plant transpiration, percolation into groundwater and soil discharge into the river network:

SoilWater = SoilWater + Infiltration – (max(0,Evapotranspiration-InterceptEvap)) – Percolation – SoilDischarge;

Soil water pool is a potential stock, at this stage not limited to pore volume. Surplus water (*SoilWater – Soilsat*) will be discharged in a later step. Thus soil water redistribution follows the prioritisation EvapTransp, then Percolation and SoilDischarge.

5.4 Deep infiltration

In the GenRiver approach, deep infiltration into the groundwater is assumed to bypass the soil water pool through macropores. Deep infiltration is calculated as the minimum chosen from

- the maximum amount of hourly infiltration [mm/d] multiplied with infiltration hours per day, minus the soil volume available for water:
  *DailyMaxInf/24 *Time4Infiltration[5] – SoilSat + SoilWater,*
- the maximum infiltration capacity of the subsoil *MaxInfSubSoil*,
- available rainfall after intercepted evaporation and infiltration *DailyRain – InterceptEvap – Infiltration*, meaning that infiltration is prioritised,
- the available space in the groundwater body *TPVSub – GWStock*

For LUCIA the first constraint has been omitted.

5.5 Groundwater stocks and discharge

Groundwater stocks are the sum of cumulative deep infiltration plus percolation from soil water minus discharge. Groundwater discharge is governed by a constant fraction released from the groundwater stocks.

---

[5] A weakness of this approach seems that the same infiltration rate is used for infiltration and deep infiltration (which is supposed to occur through macropores).

5.6 Percolation and soil discharge

Percolation is defined here as vertical water flow from the soil water pool[6] into groundwater. Discharge stems from the same pool, but represents lateral flows inside the soil which finally feed into the stream network. Consequently distribution among both flows depends on slope (fig. 3): On a horizontal plain, all available water percolates, while along a vertical wall all available water would theoretically be discharged.
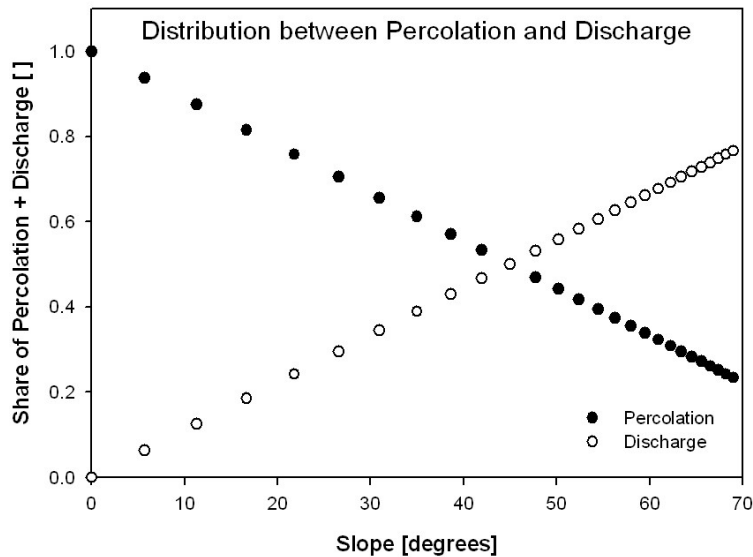

Figure 3: Redistribution of percolation and discharge as depending on slope

Percolation is calculated as the minimum of
- subsoil infiltration capacity (a constant),
- a constant daily soil water percolation fraction (share that can percolate within one day)
  (SoilWater-EvapTransp)*PercolFrac*(1-0.5/45*SlopeDegrees) and
- available volume in the groundwater body (*TPVSub-GWStock*).

Excess water that would not fit into the pore space is now discharged into the stream network:
SoilDischarge=max(0,SoilWater-EvapTransp-Percolation-FCProfile)

5.7 Surface Runoff

Runoff is the remainder of rain minus interception minus infiltration minus deep infiltration. This water has never reached the soil water stocks, it represents water which cannot infiltrate in time. As shown before, excess water surpassing field capacity is discharged.

---

[6] More precisely, a fraction of the soil water pool.

5.8 Patch water balance

To derive hydrographs and other balances integrating the entire (sub)catchment, areatotal functions are used, e.g.:

GWDischargeBalance=maptotal(GWDischarge)*0.625/86400;

Water quantities integrated over the entire watershed reported in this section are given as m^3 per second. For a small watershed such as Mae Sa Noi (<10km^2) a lag phase of less than one day (=time step) is assumed[7]. Data are exported as time series (.out format) and can be opened in nutshell, a text editor or imported to excel (tab and space delimited). These values have been and can be used to validate orders of magnitude of certain stocks and flows and to debug leakage.

5.9 Stream Network

Streams and rivers are fed from soil discharge, groundwater discharge and surface flow from the Patch Water Balance plus overflow from the Lake Section. Streamflows are simulated in a spatially explicit way along a local drain direction map (LDD[8]) using PCRaster accuflux functions, e.g.:

Runoff2Streams=accuflux(LDD,Surface_Flow)*0.625;

where 0.625 converts [mm d^{-1}] or [l m^{-2} d^{-1}] into [m^3 pixel^{-1} d^{-1}]. This unit can easily be changed into [m^3 m^{-2} d^{-1}] dividing by the pixel size of 625 m^{-2}.

As described above, run-off has never infiltrated the soil, due to insufficient infiltration time. This means that there is no superficial run-off due to soil overflow; excess water is discharged. Hereby soil water is understood as an overflowing tank, the pore volume has to be saturated up to field capacity before water can be discharged. This has been considered in a previous step:

SoilDischarge=max(0,SoilWater-EvapTransp-Percolation-FCProfile);

Consequently discharge occurs only, when

SoilWater > (EvapTransp+Percolation+FCProfile),

so that an additional *accuthresholdflux* overflow function would not be justified in the flow section[9].

For groundwater discharge, which is always a constant percentage of groundwater, an *accuflux* function of groundwater discharge has been used; however, *accufractionflux* of groundwater stocks should render the same results.

Having calculated the components of streamflow, a *Streamtotal* balance is formed, that considers a fixed ratio of seepage:

StreamTotal = Runoff2Streams + Soil2Streams + GW2Streams + LakeOver - LeakageFromStreams;

---

[7] and has been reported from the field – HUGENSCHMIDT, pers. comm.

[8] The LDD calculates the slopes of each pixel in 8 directions and leads material flows into the direction of the steepest slope. This procedure generates a transport network in the catchment.

[9] Accuthresholdflux would be the standard approach for a tank concept.

Again, 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 was not necessary to take different residence times and travel distances into account[10].

5.10 Lakes

Lake inflow is derived only from the subcatchment upstream plus rainfall of the lake area, while outflow occurs via evaporation, seepage to groundwater (a fixed fraction of actual lake water) plus overflow in case the lake volume[11] is exceeded. Stocks are initialised from measurements/estimates and calculated as cumulative balance of present stocks + inflows – outflows.

Lake-related evaporation is calculated from the water surface (corrected for present water levels of the lake) and a water-specific kc. 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.

Testing the model using estimated dummy values, overflow does occur. On the other hand, according to HUGENSCHMIDT (personal communication), there is no superficial outflow from the lake in Mae Sa Noi. This discrepancy may be due to the reported extraction of irrigation water for the botanical garden. The simplest way to reduce or avoid overflow in the model is probably setting *MaxResrDepth* in the initial section to a high value.

6 Plant growth

Parts of the LUCIA plant module are built on concepts of a PCRaster version of WOFOST for the EU's Crop Growth Monitoring System (CGMS) by SUPIT (2003). The CGMS version 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 with a concept of target nutrient contents in the biomass that has to be met through plant uptake. The original TSPC module will still be used in the MP-MAS for comparison, possibly running on transfer functions derived in LUCIA from WaNuLCAS. The TSPC-implicit concept of multiplicative effects of nutrient limitations is evaluated apart[12]. For now, soil water does not affect nutrient uptake through diffusion. Phosphorus supply does not yet affect nutrient uptake indirectly through root growth. There are and will be no direct interactions between nutrients in LUCIA. Instead, according to v. Liebig's law of minimum the most limiting nutrient determines growth rates.

While WOFOST and TSPC focus on annual crops, LUCIA includes trees. Necessary changes are described below in the respective context.

---

[10] GenRiver is based on a semi-spatial approach: Routing distance from center of subcatchment to observation points determines how long water travels, which determines into which pool it goes: Direct River and Direct Surface Flow or (retarded) Surface Flow. For this reason, pools are distinguished depending upon routing time.

[11] Calculated as a spherical cap: $V=(h^2*PI/3)*(3r-h)$

[12] Calberto (2008) unpublished

6.1 Initialisation

6.1.1 Initialising individual plant growth

Parametrising plant parameters is straightforward using the excel input file, but two adjustments had to be made in the code to keep the system running:

- LAI must be >0 as it drives assimilation; otherwise no biomass increment will lead to no LAI increase and permanent zero biomass. Consequently LAI is defined as minimum of 0.00001 and LAI.
- The same applies for rooting depth: A minimum value at least slightly >0 needs to be given for Root, otherwise no roots will lead to no plant available water (which is restricted to rooting depth). In this case a minimum value was included in the equation for PlantAvWater: Diffusion of water to the rootless seed can occur now.

6.1.2 Initialisation of biomass stocks

For natural succession and plantations users may want to start from grown-up stands in a landscape as e.g. identified from a satellite image or described by forest inventory rather than grow all types of vegetation from scratch. For this purpose, the LUCIA input file allows to specify initial biomass and LAI for different land uses depending on their current age. Vegetation age, in turn, is associated with the respective land cover class[13].

There are four alternative ways for the user to derive initial biomass (dry matter):

a. Direct measurements in the field. This is recommended for pioneer and non-woody vegetation as well as mixed stands.

b. Based on an age-dependent growth function that follows a rise to maximum (plateau) function. Such growth dynamics have been suggested for forest community ecosystems by ODUM (1969) and for nutrient-limited growth in THORNLEY & FRANCE (2007). Maximum biomass and a coefficient k need to be provided.

c. Based on stand age, more mechanistic sigmoid growth curves of trees have been described by ACKER ET AL. (2002) and MAROHN (2007). The Gompertz function as described in THORNLEY & FRANCE (2007) starts sigmoid and ends in a plateau, accounting for senescence. This approach follows the form: $W=W_0*exp((\mu_0/D)(1-e^{-Dt}))$, where W_0 is initial weight, μ_0 growth dependent on W and D decay rate. W_0, μ_0 and D need to be provided by the user.

d. Based on allometric equations. These are frequently used in forestry inventories and follow the form Biomass = a dbh^b. Diameter at breast height (i.e. 1.3m) as well as species (and site)-specific a and b need to be provided by the user.

LAI is obtained from biomass in a similar way, with its function passing through the origin at biomass zero and then rising proportionally up to a given maximum LAI.

---

[13] Alternatively, vegetation age could be read pixel by pixel from a map layer, but generating such maps would probably be too much effort for most users.

While the abovementioned steps are executed in the LUCIA input file, development stage D for perennials is calculated in the dynamic part of the model script. Stand age is related to time until first flowering (rendering a fraction of 1) and after first flowering D is derived in the usual seasonal approach based on degreedays.

In analogy to pure stands, natural vegetation can theoretically be classified and parametrised as one land use type. Such a natural succession would start with grasses and other herbaceous pioneers, proceed through bush fallow to pioneer, young, old and finally primary forest[14].

6.2 Cropping calendar

Moving from a yearly decision intervals in MP-MAS to a daily time step is needed for process-based simulation of weather and plant growth. Due to the higher temporal resolution, dates for planting and application of inputs must be defined. Annuals as well as perennials are planted on defined land cover-specific Julian days (farmers' practice) once an agent's decision in MP-MAS has reserved the respective pixel/plot for the respective land use.

When land use on a pixel changes from an annual to a perennial crop, the perennial is planted (e.g. onset of rainy season), so that an a priori definition of planting years is not needed. Vice versa, change from perennial to annual crops requires cutting the perennials first; this happens automatically as soon as a pixel's land use switches accordingly.

Inputs of fertilizer and manure are also imported as land cover-specific time series from the LUCIA input spreadsheet and queried as timeinputs in the script: *P_FertiliserApplication=timeinputscalar(P_FertApp,I_LandCover);*

6.3 Plant development stages

Obviously, development of plants is delineated by the vegetation period, which starts at sowing / planting and ends with cutting. Cutting of plants is at harvest for annuals and on a certain Julian day[15] once a decision has been taken to replace a perennial land use by another one.

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 as in the concept of temperature sums implemented in WOFOST. At stage D=2 plants are mature and immediately harvested. Degreedays are accounted for as soon as the daily temperature surpasses a species-specific minimum. Translation of temperature sums into development stages is effectuated dividing actual temperature sums by species-specific degreedays required for flowering and harvesting, respectively:

D=(Temperature sum)/(Degreedays to Flowering) for the vegetative phase and
D=1+((Temperature sum)/(Degreedays to harvest)) for the generative phase.

---

[14] As implemented in FALLOW

[15] This could be in the middle of the dry season, when people use to slash and burn. For now it is '1' for all land uses, meaning Julian day one after land use change.

In contrast to annuals, trees do not necessarily flower during the first year and are not necessarily cut after harvest, but fall back into the beginning of the generative phase[16]. They continue growing, while annuals will only grow if planted again. In both cases, counting of degreedays starts from zero after harvest[17]. Flowering periods for trees are not constrained to certain seasons in order to enable testing of off-season fruit production.

Plant growth parameters that depend on the phenological development stage of the plant are specified in look-up tables: These include biomass partitioning between plant organs, maximum assimilation rate, target nutrient contents per plant organ and specific leaf area. Development-depepnding parameters follow broken-stick functions and can be parametrised from two cardinal points in the parametrisation spreadsheet.

DD2Flow	DD2Harv
0 < D < 1	1 < D < 2

DD2FirstFlower		DD2Harv	DD2Flow	DD2Harv	DD2Flow
0 < D < 1		1 < D < 2	0 < D < 1	1 < D < 2	0 < D < 1

Figure 4: Development stages of annuals (upper bar) and perennials (lower) in LUCIA.

In LUCIA differentiating annuals from perennials is solved by split iteration over the array of land covers (annuals and perennials separately). Periods before and after planting and before and after flowering and harvest are segregated by if… then terms as illustrated by the decision tree in figure 5.

---

[16] This means flowering immediately after harvest is possible. It has been intended to build in a vernalisation trigger that induces flowering again, however data on required number of chilling days are not easily available (pers. Information Prof. Wünsche, Dr. Hegele). In a simplified fashion, a six month delay will block flower induction after harvest.

[17] This leads to the phenomenon that plants can fall back in terms of development: However, biomass formation would still go on.
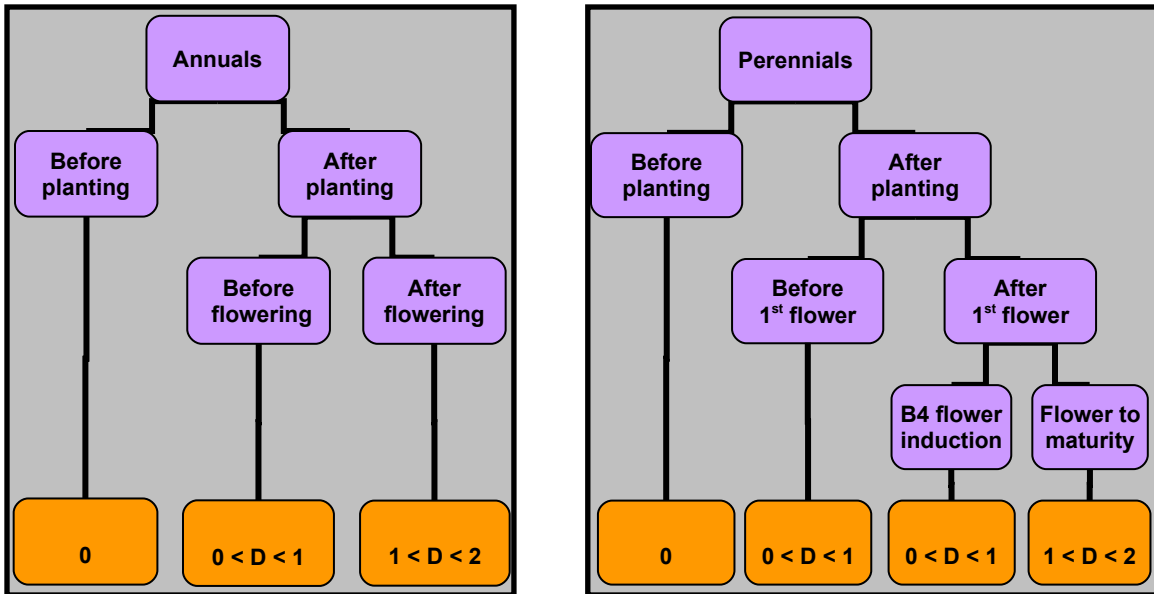
Figure 5: Decision tree for plant development stages, extended for perennials. Note that stages 0-1 for perennials distinguish trees before and after 1st flowering. However, both vegetative phases follow different dynamics.

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 storage organs, whose weight is reset to zero. Theoretically, fruits can grow at any time.

6.4 Net assimilation rates

As in WOFOST, daily assimilation depends on PAR, LAI, crop- and development-specific maximum assimilation rates (AMD) and day length. Orders of magnitude of Net Assimilation Rates were extracted and converted from Larcher (1980)[18] for comparison.

Table 3: NAR of selected plant species (Larcher 1980). To come to the target unit [kg h^{-1} ha^{-1}] in LUCIA, original values in [mg d^{-1} dm^{-2}] were divided by 24.

Plant type	NAR average growth season	NAR main growing phase
C4 grasses	>8.3	16.6-33.33
C3 grasses	2-6	3-8
C3 dicots	2-4	4-25
(Sub)Tropical woody dicots	0.4-0.8	1.2-2
CAM	0.08-0.16	0.4

Respiration, apart from assimilation, depends on temperature. Both are not cumulative.

---

[18] As cited under:
http://generalhorticulture.tamu.edu/hort604/lecturesuppl/growthkinetics/growthkinetics05.htm

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 (respiration - maintenance respiration)*0.67, where 0.67 is a constant chosen to represent the conversion efficiency of carbohydrates into biomass (explained under 6.7.1).

6.5 Death rates

In LUCIA, three different causes for leaf fall are foreseen: Senescence (a certain share of leaf biomass shed at D>1.5), drought as depending on water stress and self-shading. These fractions are added up to dWDlv (Δ weight of dead leaves, where Δ stands for increase during a time step). For the corresponding stem and root litter only senescence plays a role. All these fractions move to the residue pool, retranslocation of nutrients and dead leaves attached to the living plant are not considered so far.

6.6 LAI and cover

LAI is determined by net leaf growth and specific leaf area SLA. The respective equation reads:

*LAItot=if(D lt 2,max(0.00001,min(MaxLAI,LAItot+dWnlv*SLA*0.0001)),0.00001);*

As mentioned before, LAI can never become zero, but decrease only to a minimum of 0.00001 – even after harvest or before sowing – because otherwise all growth processes would be disrupted.

Maximum LAI, too, has to be constrained externally, and determines levels of shading and self-thinning. Potential leaf biomass exceeding MaxLAI is led 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 or choose wider plant spacing (because additional leaf production would be at the expense of yield).

Soil 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.

6.7 Biomass production

6.7.1 Efficiency of assimilates-to-biomass conversion

The parameter *Eff_C2Biomass* describes the conversion efficiency of assimilated carbohydrates into biomass. Efficiency differs between plant organs and development stages. Guideline values were adapted from LAMBERS ET AL. (1998): Construction costs of glucose to biomass [g g^{-1}] for leaves 1.56 (mean of n=123), stems 1.44 (n=38), roots 1.34 (n=35), fruit/seed 1.65 (n=31). As biomass production in WOFOST_LUCIA is located before biomass partitioning, one

overall value for all plant tissues was chosen. Conversion efficiencies, the reciprocal of construction costs, are not dependent on development stage.

In WOFOST-LUCIA, the basic term for potential growth is governed by conversion efficiency.

dW=if(D eq 0 or D ge 2,0,
max(0,Eff_C2Biomass*(DailyRespiration-MaintResp*W)));

Efficiency of glucose conversion into biomass

Leaf	Stem	Root	Fruit	**Mean**
0.641026	0.694444	0.746269	0.606061	**0.67195**

6.7.2 Biomass partitioning

6.7.2.1 Partitioning during the growing period

Partitioning of plant parts begins at planting: Depending whether annuals (grown from seeds) or perennials (assumed to be planted as seedlings) are planted, these ratios are initialised at different levels. This refers also to the initialisation of biomass as given for existing perennial land covers.

In the dynamic section, different plant organs have different growth rates (example: fig. 6), which are read from a user-defined function for each land cover and development stage. In the excel input file, root and shoot are distinguished first, where shoot = 1 - root. In a second step, aboveground fractions make up to 1 again: StemRatio = 1 – LeafRatio – HarvestRatio.
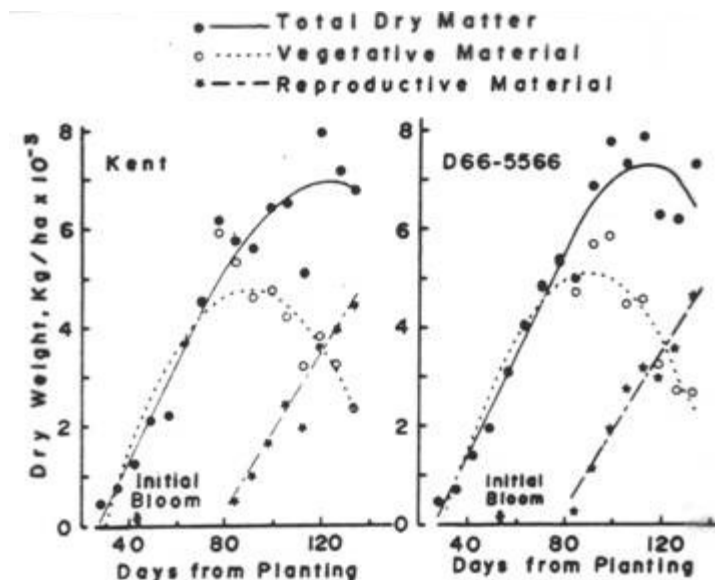

Figure 6: Examples for growth rates of different plant organs (Egli and Leggert 1973)

The separation of harvest allocation also allows resetting fruit weight to zero after harvest.

20

6.7.2.2 Partitioning after growth

After harvest, different plant parts go to different pools: For annuals, at D≥2, the whole plant is uprooted. Storage organs move to the harvest pool, while all roots as well as user-defined shares of stems and leaves form part of the residue pool (fig. 7)[19].

---

[19] As shown in figure 7, stems is a generalised term for all lignified aboveground and fruit for all kind of harvestable parts including tubers. For timber extraction it may be necessary to redefine partitioning for part of the land uses.
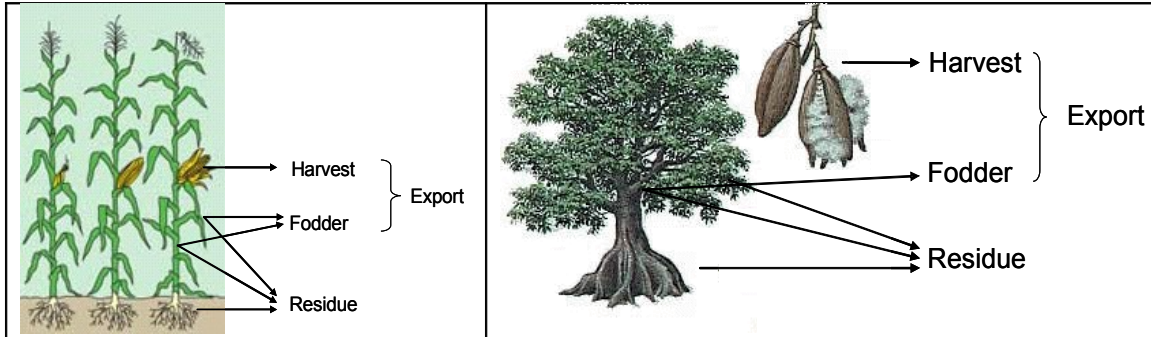
Figure 7: Biomass partitioning after harvest, in the case of perennials after cutting

The same applies to plant organs that die off due to senescence or drought, so that the overall equation reads:

Residue = Wrt + (Wst+Wlv)*ResidueIndex + dWDlv + dWDst + dWDHarvestable + dWDrt + Resi_Remain.

Fodder is calculated as the stem and leaf biomass remaining apart from harvest and residues:

Fodder=(Wst+Wlv)*(1-ResidueIndex).

For perennials, storage organs are entirely harvested at stage D≥2. In contrast to annuals, only part of leaves, stems and roots accumulate as residues / litter during the entire growing period

Residue=Wrt*ResidueIndex+Wlv*ResidueIndex +Wst*ResidueIndex

Stems are understood *sensu lato* as any woody aboveground material including bark, infructescence not harvested etc. As for annuals, fodder is a defined share of aboveground biomass; stems may include twigs fed to goats as an example. 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.

6.7.3 Root growth

Root biomass is derived from biomass partitioning ratios per development stage. Assuming a half-ellipsoid[20] shape of the rootstock, rooting depth is dynamically calculated from existing cumulative root weight (Wrt) taking into account additional user inputs on planting density, average fine root weight density

---

[20] One might argue that a rootstock depart from the root neck and thus form a full ellipsoid; on the other hand, roots of plants in nutrient-poor soils mainly extend along the surface to capture nutrients released from surface litter.

(fRWD)[21] and a factor γ = 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.

Given:

Wrt$_{cum}$ [Mg/ha]

User inputs:
•**Planting density [ha^{-1}]**
•**γ = a/b [ ]**
•**fine RWD [Mg/m^3]**

$V = \tfrac{2}{3} (\pi\, a\, b^2)$

$\gamma = 0.5$ $\gamma = 1$ $\gamma = 2$

V = Wrt$_{cum}$ / RWD x Planting density
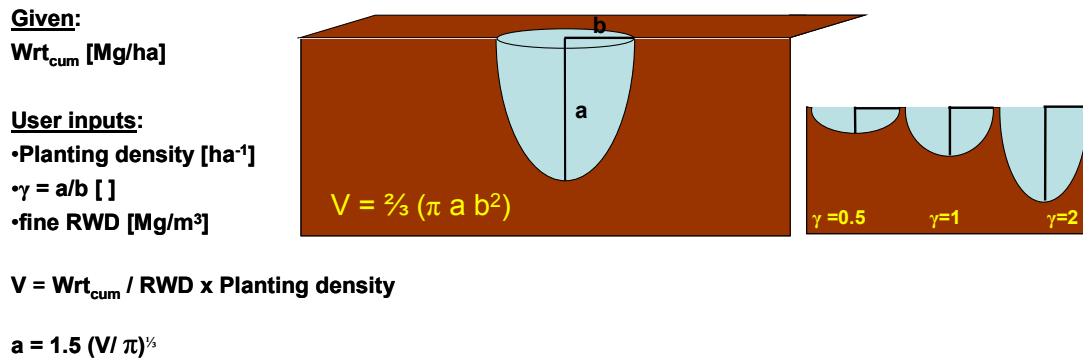
a = 1.5 (V/ π)$^{1/3}$

Figure 8: Calculation of rooting depth and examples for rootstock shape at different γ.

6.8 Water uptake and stress

LUCIA in tis current state (Oct 08) makes use of a simplified concept based on WaNuLCAS and WOFOST to simulate water limitation for plant growth:

Demand-driven water uptake, determined by biomass W and water use efficiency WUE determines potential water uptake. Water stress is expressed as a reduction factor between 0 and 1, calculated by water demand over plant available water, which considers rooting depth. Plant growth, or better respiration, is then reduced by multiplication with this reduction factor. In addition to reduced growth, water stress causes leaf death.

In comparison, WaNuLCAS first calculates potential transpirational demand from potential dry matter production and species-specific WUE. Then plant water potential is estimated from soil water potential, resistance soil/root surface, root entry resistance and axial transport resistance; these are combined into a transpiration reduction factor, which is then multiplied with potential transpirational demand.

Rhizosphere potential necessary for transport until stem base is calculated. This allows deriving potential water uptake rates and matric flux potentials (depending on unsaturated conductivity). Uptake is now the minimum of demand and supply in the soil. After uptake soil water is updated. After all, a water stress factor is calculated as actual over potential transpiration. This concept is mechanistic but

---

[21] 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. ≤ 2mm diameter) should be taken into account, total RWD can be determined at the same time for belowground biomass / carbon.

requires extensive calculations on soil water, which are solved outside the model in an excel file.

WOFOST comes to the same reduction factor, called TaTpfraction, in a simplified way: Departing from potential transpiration (see above) and a fraction actual over potential transpiration, actual transpiration is calculated as

*Ta = Tp * TaTpfraction;*

TaTpfraction is derived from soil matric potential Ψ and $\Psi50$, a constant of 800cm water column:

TaTpfraction = 1/(1+(Ψ / $\Psi50$)**3);

Table 4 gives values for TaTp at different matric potentials following the formula suggested in WOFOST.

Table 4: Transpiration reduction factors and matric potentials in WOFOST

TaTp	WS [cm]	Ψ [pF]
1.000	1	0
0.998	100	2
0.940	320	2.5
0.804	500	2.7
0.599	700	2.8
0.413	900	3.0
0.060	2000	3.3
0.000	15000	4.2

Apart from matric potential, Ta is constrained by soil moisture and rooting depth. Water stress, expressed as TaTpfraction, reduces daily respiration, which in turn controls biomass increment. To adapt the complete WOFOST concept to LUCIA, matric potential would be needed to be linked to texture and organic matter (for example employing a nomograph or second order equation).

6.9 Nutrients limiting growth

In the TSPC approach as part of MP-MAS and LUCIA, only nutrients are considered as limiting factors, water can be considered optionally as a linear reduction function from CROPWAT. All nutrients influence each other by multiplication of equations of the form:

Potential yield*(rf N) *(rf P) *(rf K) *(rf pH) *(rf C), where rf are reduction factors (range 0 to 1) in the form of exponential or second order equations.

The process-based LUCIA approach, which runs parallely to TSPC, is a hierarchical model: Potential growth is determined by incoming radiation, LAI and light extinction coefficient. This potential growth is then constrained by water availability (see previous section). Then, 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/KDemand 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 script, 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 then used to restrict actual biomass increment. In contrast to the TSPC approach, this part of LUCIA implies the Liebig law of minimum instead of a Mitscherlich approach of mutual interactions between nutrient supply levels.

6.10 Differences between trees and crops

To segregate annual and perennial plants, arrays for certain functions are iterated only partially in the dynamic section; sub-arrays are defined in the binding section. The following terms differ between annuals and perennials plants:

- TreeNow, CutPlant and Tree: These determine planting and cutting dates. Cutting occurs after harvest (D≥2) for annuals and when the underlying land use map changes from an annual towards a perennial plant in the case of perennials.
- Development: Trees have a vegetative stage until first flowering that is usually longer than 1 year. This is reflected in the parameter Day1stFlower, the number of degreedays until first flowering. The Setback term defines that perennials return to growth stage 1 after harvest, while annuals need to be planted again.
- Residue production in perennials is a more or less continuous process while annual crops accumulate biomass, which is only released at harvest.
- Residue and fodder make up for a small share of perennial biomass only, while residue, fodder and harvest indices of annuals add up to 1.

7 SOM and nutrient cycling

Partitioning of biomass into residues, harvest and fodder has been described under 6.7.2.2. To these, dead plant parts as well as undecomposed residues and immobilised nutrients of the previous timestep are added. Humification of residues is carbon-driven and determined by the ratio of C available for respiration vs. humification as well as a (so far constant) decomposition factor kF.

Litter quality is coupled to carbon dynamics of biomass C as well as N, P and K target concentrations which depend on plant species, tissue and development stage. N, P and K available for decomposition are summed up from the products of concentrations and weight of the respective plant organs.

C:N and C:P ratios govern mineralisation and immobilisation in the soil. For example, cycling of nitrogen is governed by the respective C:N-ratios of the residue and SOM pools (the latter being tighter). If N requirements for the amount of SOM potentially formed by available residue C cannot be met from N contents of litter, then nitrogen from the soil mineral N pool will be immobilized;

otherwise nitrogen is mineralized. Thus, humification goes before mineralization. For respired C, nitrogen bound to the respective fraction of residues goes directly into the mineral N pool.

Phosphorus is subject to the same mechanisms, but potassium is not. In this case all K in the decomposed residues will be released directly into the mineral pool; there is no coupling to C contents and consequently no immobilization[22, 23]. Mineral N, P and K are now in the plant available state (*N/P/K_PlantAvStocks*); further inputs can be added for the next time step as described above.

Not all residues are necessarily transformed within a time step. Remaining residues as well as plant available stocks are cumulative.

Manure also enters the SOM cycle, provisionally at identical kF as residues.

8 Coupling watershed and crop modules

Linkages between the separately developed watershed and plant modules are formed by relief-dependent growth determinants such as temperature, soils and hydrology as well as influences that plants exert on water stocks, nutrient translocation and cycling processes

Interception, shaded/open soil evaporation and transpiration in the watershed module, which recur on LAI and cover from the crop module are examples of plant influence on the water balance. Vice versa LAI recurs on water-constrained growth, which is driven by plant-available water as influenced by the watershed functions.

Nutrients extracted from the plant available stocks determine plant growth, while part of these nutrients as residues and biologically fixed N feed back into the soil nutrient stocks.

An amendment in this respect will be the physical role of plant residues as topsoil protection against splash erosion.

9 Land Use Change

LUC will be implemented through new land use maps provided by MP-MAS every 365 days (timeinput function). Perennials will continue growing, if the land

---

[22] In the future, a link of soil water contents influencing K^+ availability might be implemented. According to Pagel et al. (1984), availability depends on water contents of the soil (also tortuosity of pores etc), contents of 3-layered clay minerals and cations competing for binding sites (Ca, Mg, Al).

[23] K pools (Scheffer & SCHACHTSCHABEL 1992): 0.2-3.3% total K in soil, 25-30kg Kmic /ha given a microbial biomass of 3000kg/ha, 2-6kgK/ha atmospheric deposition (Germany), soluble K (Bodenlösung) -100mgK/l, leaching (NW Germany, sandy soils) 20-50kgK/ha/a, especially in sandy acidic soils (Al replaces K from binding sites), OM does not effectively prevent leaching. PAGEL ET AL (1984): <0.1% of all K exists as Korg. Depletion in soils by plants to 0.4mgK/g clay or 0.1mgK/l Bodenlösung, replenishment by buffer stocks.

Exchangeable K refers to NH_4Ac extraction, which does not represent plant availability well.

K balance and buffering in soils between K in silicates (feldspars, illite, glimmer) ←→ interlayer K in clay minerals ←→ soluble K.

use remains the same, otherwise they are cut and other crops are planted on the foreseen planting date.

9.1 Erosion

LUCIA uses the Rose concept of erosion (Rᴏꜱᴇ ᴇᴛ ᴀʟ. 1983a and b, Rᴏꜱᴇ ᴇᴛ ᴀʟ. 2007), a process-based approach originally developed for semi-arid environments. In contrast to USLE and other empiric models, Rose accounts for deposition, not only erosion. This makes the concept particularly useful for spatially explicit models. WaNuLCAS builds on Rose and can be used to generate transfer functions; extensive experiences with WaNuLCAS erosion in Thailand are available (e.g. Pᴀɴꜱᴀᴋ ᴇᴛ ᴀʟ. 2008). However, as a plot-level model WaNuLCAS is not spatially explicit.

The Rose concept considers three main processes, being detachment, re-entrainment[24] and deposition of particles from surfaces. Sediment loads are calculated from water flows and sediment concentration.

Currently (as of Oct 2008) the erosion module of LUCIA is being developed by M. Lippe.

9.2 Leaching of nitrogen

Leached nutrients are not recoverable for plants, but play a role in the landscape. Following a simplified approach, leaching is calculated in LUCIA as N concentration in the soil matrix * (Percolation + Deep Infiltration).

In WaNuLCAS, leaching is computed as percolation multiplied by nutrients in the soil solution, which in turn is determined by soil water contents, inorganic nutrient stocks and adsorption constant. Analogous to percolation and deep infiltration in LUCIA (which originates in the GenRiver concept), preferential vs. bypass flow in WaNuLCAS is ruled by a distribution factor; both contribute to leaching.

10 Coupling

LUCIA exports yield and, if required, other information to the MP-MAS component. Decision-making processes simulated on this basis in MP-MAS will lead to a renewed land use map for the coming simulated year. Technically, the conditional iteration function

repeat {idle loop} until

will keep the biophysical component in idle loop until a new land use map has been created that matches the current year.

11 Parametrisation

11.1 Maps

Relevant maps for LUCIA Mae Sa Noi are a digital elevation model, soil units according to WRB 2006 (Sᴄʜᴜʟᴇʀ 2008) and a land use map based on satellite imagery (ground truthing by M. Lɪᴘᴘᴇ and P. Eʟꜱᴛɴᴇʀ). The soil classification, in

---

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

combination with representative sampling, was used to derive maps of specific soil parameters such as texture, C, N among others. All maps were pre-processed in ArcGIS and exported as ASCII files.

Map edit, on the nutshell GUI, was used, to edit maps. This was the case where known GPS points were used to generate output maps used for timeoutputs.

11.2 Time series, lut, par – the LUCIA input file

Files needed to parametrise models in PCRaster comprise time series (.tss), look-up tables (.lut) and par files (.par). Examples of these files, opened in a text editor, are shown in tab. 5.

par files are used to define values for arrays of classes such as land uses or soil types. Table 5, left column shows examples of degreeays until flower (parameter name, column 1) for different vegetation types (category name, column 2) with their respective values (column 3). Lychee needs 190 degreedays to reach the flowering stage, while fruit trees require 270 degreedays and so on. In the second example, the array is soil types, and values of nitrogen concentrations (Nt) are shown for different WRB soil untis such as Gleysol, Regosol etc. PCRaster will iterate over the land use and soil maps as defined in the previous section and attribute the given values to each land use or soil class.

Table 5: Examples of LUCIA files for parametrisation

Par files for arrays	**Look-up table**	**Time series**
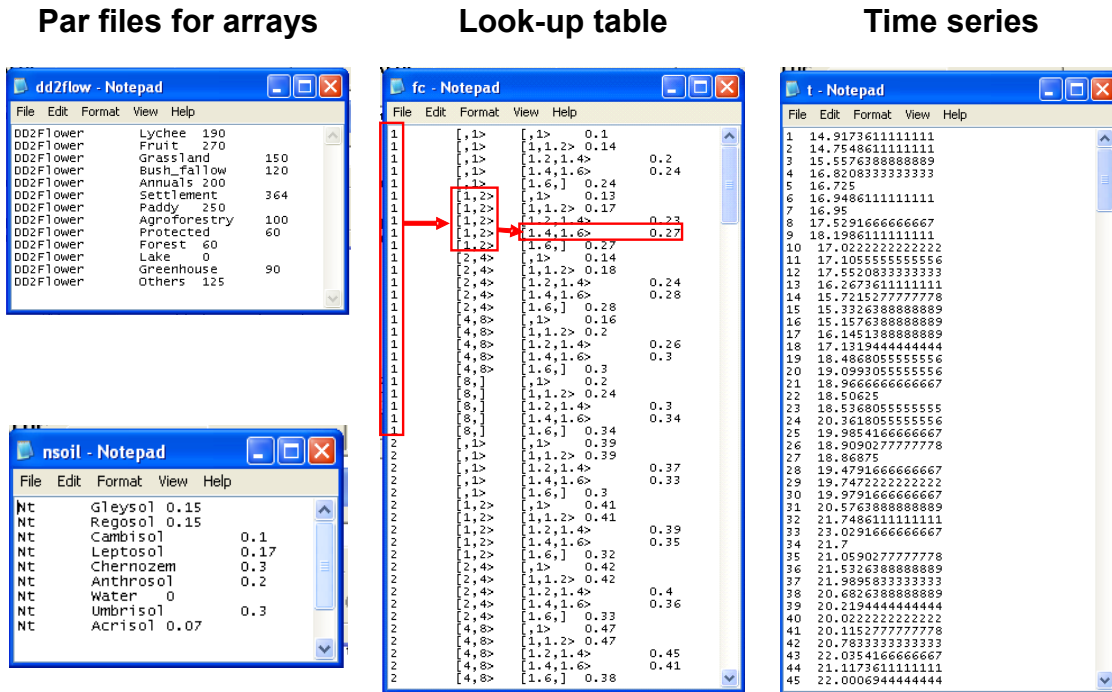
Look-up tables follow a similar principle, but considering several hierarchical levels of classes; they can be seen as decision trees. The example in the center column of table 5 shows field capacity as depending on texture (column1), organic matter (column 2) and bulk density (column 3): Textures have been

encoded in a previous step, so that the code '1' stands for sand, 2 for loamy sand etc. (until 11, cut off in the image). PCRaster iterates over the first qualifier texture; if texture is '1', organic matter contents are revised: Assuming organic matter contents of 1.5% would lead us to rows 6-10. In the next step, bulk density is checked: For a given bulk density of 1.5g/cm3, we end up in row 8 which leads to field capacity of 0.27 or 27% in column 4.

A time series for air temperature is shown in the right column of table 5: Column 1 indicates the time step (here: day) and column 2 the measured temperature in °C.

Entering data into parametrisation files requires opening each file separately. To facilitate parametrisation, an input spreadsheet was created that allows entering all parameters in a few data sheets. This makes it easier to compare parameter orders of magnitude at a glance and to modify entire land use or soil classes at once, not file-by-file.

A second example of time series generated is shown in fig.9. Here, fertiliser inputs are defined: The type of fertiliser is determined by the user first, entering the name and elemental contents (percentages) of N, P and K for each type (cells B9:E18). Then the applied type and amount of fertiliser is entered in the respective row(s) corresponding to each application date (yellow cells) and elemental nutrient quantities are calculated automatically in the purple cells, which are finally exported as time series.

Figure 9: Fertiliser inputs in the LUCIA input spreadsheet: In the grey fields, fertilizer types and their respective elemental N, P and K contents are defined. In the yellow cells, application of

29

fertilizer type and amount are specified per time step (column G). These are converted into elemental contents (e.g. user inputs in cells H7:I7 become quantities of N, P and K in AH7:AJ7).

Apart from inputs, land use and soil characteristics, development-dependent parameters regarding biomass partitioning, nutrient target concentrations of plant tissues, initial biomass and weather time series are all parametrised in the spreadsheet. Export to .par, .lut and .tss files is automatised, when the respective button on the front sheet is pressed.

12 Validation of model outputs

12.1 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 when moving the mouse on the respective grid cell. Multiple time series can be generated defining a map of output pixel or set of pixels and creating *timeoutputs* (fig. 10).
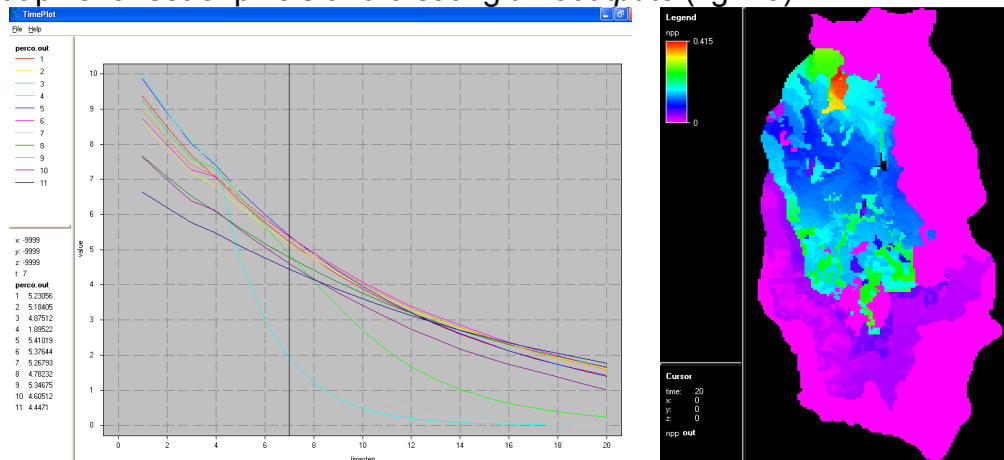

Figure 10: Outputs as map or multiple time series, left: Percolation at pre-defined points; right: Biomass in the entire watershed.

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). If reports should not be shown 'report' can be replaced by '# report', meaning the line is commented and will not be read by the software. If Nutshell is used as a GUI, the red fonts of the report command turn to grey, indicating deactivation of the command. 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.

12.2 Validation of LUCIA hydro

So far, plausibility checks for most parameters have been undertaken whilst developing the code. Some more advanced validation mechanisms have been elaborated for the watershed functions.

12.2.1 Flow balance using map totals

Areatotals allow calculating balances of different stocks over the entire water shed.

A simple example for a maptotal, which adds up rainfall over the entire map area and converts [mm] into [m³ per timestep] is:

RainBalance=maptotal(DailyRain)*0.625;

Balances over several maptotals can be used to detect unintended outflows from the system, one example is:

Balance1=(RainBalance-IntEvapBalance-InfiltrationBalance-DeepInfBalance-SurfaceFlowBalance-SoilDischargeBalance-GWDischargeBalance);

This balance, once divided by the number of cells, should be close to zero, as all flows subtracted from incoming rainfall should add up to zero – at least on the first day and under the boundary condition that soil- and groundwater stocks are initialised empty or subtracted from the total.

12.2.2 Comparing measured and modeled outflow

A further validation function has been built in to compare simulated with measured water outflow. For the Mae Sa Noi case, simulated outflow was validated against data measured by Hugenschmidt (unpublished). The position of the measuring point was imported into a PCRaster map and a timeoutput series produced and compared to the measurements:

report outflow.out=timeoutput(Outflow,StreamTotal/86400);

As for the meaasurement, simulated outflow data refer only to the area upstream of the measuring point (not the entire watershed) and are related to rainfall quantities of the same area. Data are reported as $[m^3s^{-1}]$ in a time series (.out format).

13 Known bugs

Fixed:

Settlements and lakes had to be 'planted' – best on day 1, year 1 – otherwise they created missing values, which affected LDDs and accu functions. This was solved by excluding settlements from array iterations and defining a subarray 'Terrestrial' which does not consider the lake area for most functions.

A dummy parameter (do not remove!!!) is needed after VegPer to avoid crashing of the system:

VegPer=if(PlantPlant eq 1,1,VegPer);
VegPer=if(CutPlant eq 1,0,VegPer);
Dummy=if(D eq 2,1,0);

LAI must never become 0, otherwise photosynthesis and biomass production will not work. This was solved (inelegantly) by limiting to a small minimum value.

14 Model parameters and their units

Coming soon

15 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.

AUNE, J.B. & R. LAL (1995): The Tropical Soil Productivity Calculator—A Model for Assessing Effects of Soil Management on Productivity. In Lal, R. & B.A. Stewart (eds.): Soil Management. Experimental Basis for Sustainability and Environmental Quality. Lewis Publishers, London.

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.

CALBERTO, G. (2008): Parameterization and calibration of the Tropical Soil Productivity Calculator (TSPC) for cabbage, bell pepper and litchi in Mae Sa watershed, Northern Thailand. Master thesis Institute for Agroecology and Plant Production in the Tropics and Subtropics, University of Hohenheim. Unpublished.

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.

AG BODENKUNDE (1994): Bodenkundliche Kartieranleitung. Hannover.

LAMBERS, H., CHAPIN, F.S. & T.L. PONS (1998): 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.

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.

Schaap, M.G., J.L. Feike & M.T. v. Genuchten (2001): Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. Journal of Hydrology 251:163-176.

Schachtschabel et al. (1992): Lehrbuch der Bodenkunde, 13.ed. Enke, Stuttgart.

Schreinemachers (2007): The (Ir)relevance of the Crop Yield Gap Concept to Food Security in Developing Countries With an Application of Multi Agent Modeling to Farming Systems in Uganda. Dissertation University of Bonn. Cuvillier, Göttingen.

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

Thomley J H M: 1995 Shoot:root allocation with respect to C, N and P: an investigation and comparison of resistance and teleonomic models. Ann. Bot. 75:391-405.

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

Wösten J.H.M., Lilly A., Nemes A., Le Bas C. (1998): Using existing soil data to derive hydraulic parameters for simulation models in environmental studies and in land use planning, Final Rep. Eur. Un., Wageningen.