Integrated land use modelling in an interdisciplinary project: The LUCIA model

Marohn, C. (1); Siripalangkanont, P. (2); Berger, T. (2); Lusiana, B. (3); Cadisch, G. (1)

(1) Dept. of Plant Production and Agroecology in the Tropics and Subtropics, University of Hohenheim, marohn@uni-hohenheim.de

(2) Institute of Agricultural Economics and Social Sciences in the Tropics and Subtropics, University of Hohenheim

(3) World Agroforestry Centre, Bogor, Indonesia

Abstract: In the mountainous regions of Northwest Thailand and Vietnam political and economic change and demographic pressure have led to intensification of agricultural systems during the last decade. In the uplands, agricultural land expanded at the expense of forests and traditional swidden systems have been replaced by continuous cropping with reduced or no fallow. Subsistence-based systems are shifting towards external input-dependent production for the market, improving income of farmers in the short run, but partly leading to irreversible loss of environmental functions. The LUCIA model was developed in this context to dynamically simulate biophysical processes triggered by land use (change) in small mountainous catchments in a mechanistic and spatially explicit way. This paper describes the role of the model in integrating data generated under different knowledge domains in an interdisciplinary project to simulate scenarios of land use change, potential environmental impacts and alternative pathways towards sustainable land use. The model structure, stakeholder orientation and coupling with an existing multi-agent system are explained in more detail.

Keywords: Land use change; integrated model; coupling; Southeast Asia

Introduction

The Uplands Program (SFB 564) is an interdisciplinary long-term research project led by the University of Hohenheim dedicated to sustainable land use in the mountainous North-western regions of Thailand and Vietnam. Research areas are characterised by rapid transition from subsistence- to market-oriented agricultural systems. While production in some of the Thai areas includes fully commercialised and mechanised systems like bell pepper and cut flower cultivation in greenhouses, land use in Vietnam is characterised by replacement of shifting cultivation-based upland rice by market oriented production of fodder maize associated with nutrient export form the watershed. Land use systems in both countries have in common that market integration led to intensification in the form of expansion of agricultural areas, drastically reduced or omitted fallow periods and high inputs of mineral fertiliser and pesticides. Particularly, clearing of forests on the upper slopes and shifting from swidden to continuous cropping without fallow have led to soil degradation caused by erosion and monocropping. These changes influence ecosystem functions and productivity not only along the slopes, but also in the lowlands. Here, the release of nutrients from typical upland swidden systems, which used to be restored during fallow (Dung et al. 2008), has been converted into extreme events of run-off (Ziegler et al. 2004), erosion and siltation of paddy fields. Formerly sustainable combinations of upland and lowland agroecosystems have in many cases become unbalanced.

Small farmers are the most important agents causing land use change in the research areas. Apart from economic factors such as availability of capital, expected revenue or distance to markets, socio-cultural and political aspects play an important role in land use decisions. Traditional crop rotations, which differ between ethnic groups, perception of soil fertility, attitude toward innovations or influence by neighbours, extensionists and local authorities may influence farmers' decisions.

The Land Use Change Impact Assessment model LUCIA was built for the Uplands Program to address environmental impacts caused by land use change in small mountainous catchments of (sub)tropical regions. Important processes include run-off, erosion, deposition and nutrient mining, which determine soil fertility, carbon seqestration and crop production potentials. In mountainous systems, where linkages between uplands and lowlands, e.g. sediment transport in run-off or irrigation water (Schmitter et al. 2010) play a decisive role for lowland crop production, processes need to be simulated in a spatially explicit way to identify risks and potentials of individual plots.

As a central part of an interdisciplinary research program, the biophysical model contains hydrological, edaphic and plant-related aspects. A soil organic matter module is integrated in the model.

Decision-making routines are currently being developed, that simulate individual farmers' decisions on land use based on availability of resources and prioritisation according to cropping, socio-cultural and economic rules. Alternatively, LUCIA has been dynamically coupled to MP-MAS (Berger et al. 2006), a multi agent model that optimises decision-making based on socio-economic criteria.

While numerous models are available that can simulate single compartments of the system to more detail, LUCIA includes the linkages among processes and among landscape positions. This requires mechanistic approaches at appropriate temporal resolution.

The described integrative approach requires a modelling framework that allows both capturing the most relevant processes and at the same time minimising parametrisation efforts and run time. While data exchange between models and compatibility of programming languages pose less challenges to such frameworks, modular design and user-friendliness become more and more important. This is of particular relevance for a model intended to be sufficiently generic for applications in such contrasting conditions as those in Thailand and Vietnam. Apart from the option to (de)couple modules, the framework was conceived to allow for upscaling. In this paper, we present the current state of LUCIA, examples of outputs and an outlook on model development.

1. Model structure and use

Regarding the biophysical parts of the model, processes are simulated in a mechanistic manner. On the socio-economic side, a two-step approach is followed, which assesses available resources first, to prioritise among the possible land uses for each area unit.

1.1. Model concepts

LUCIA (Marohn 2008) is a spatially explicit dynamic model written in PCRaster (van Deursen, 1995), a non-programmer-friendly modelling language with integrated raster GIS and routing functions. The model runs on a daily time step; pixel size is user-defined and usually set to the minimum size of a smallholder plot. LUCIA builds on established model concepts, which have been extended and partly modified. The current model version consists of a hydrological part originally based on the cascade model GenRiver (Widodo et al., 2007; van Noordwijk et al., 2003), which has been amended for mechanistic infiltration and redistribution algorithms based on KINEROS 2 (Woolhiser et al., 1990). Necessary inputs such as hydraulic conductivity are derived using pedotransfer functions from SPAW (Saxton & Rawls, 2006); calculations are performed outside the model in the parametrisation interface. Transport processes between pixels are simulated using the routing algorithms provided by the PCRaster language; these are basically flow or tank algorithms calculated along a local drain direction network based on a digital elevation map.

Plant growth at stand level is simulated based on CGMS-WOFOST (Supit, 2003). The hierarchical model concept first estimates potential biomass growth as given by assimilation in a layered canopy and temperature-sensitive respiration. Air temperature also affects plant phenological development through degreedays. Daily readings from a weather station are extrapolated into the landscape as a function of elevation. In a second step, limitations imposed by water, nitrogen, phosphorus and potassium constrain potential growth. In addition to WOFOST and CGMS, LUCIA can simulate perennial crops and natural (forest) vegetation at the stand level. Assimilates are partitioned into different plant organs with specific N, P and K target contents. Feedback of plants to the soil, apart from uptake of nutrients and water, are loosening or compacting, thus affecting bulk density and infiltrability, and nutrient recycling via litter. Aboveground litter fall can be induced by phenological stage, shading or water stress. Aboveground residues form metabolic and structural litter, which is transformed into active or slow soil organic matter following specific decomposition rates. Roots and ploughed surface litter add to the soil litter pools. Soil organic matter is separated into active, slow and passive pools with distinct decomposition rates. Decomposition is carbon driven, thus N and P can be mineralised or immobilised, depending upon C:N and C:P ratios. Litter and SOM transformations follow the CENTURY approach (Parton et al., 1987). Additionally, potassium is recycled. In a simplified manner, a uniform user-defined K release rate is applied for mineralization; mineralised K is stored in the plant available pool, which subsumes soluble as well as exchangeable potassium in mineral interlayers as both correspond closely. Erosion and deposition follow the Rose approach (Rose et al. 1983; Yu et al. 1999), based on a concept of detachment, entrainment factor and sediment concentration in run-off.

1.2. Parametrisation

Required inputs include rasterised maps of land cover, soil types and elevation; based on the latter slopes and local drain directions are calculated. Daily data on solar radiation, air and soil temperature, rainfall and reference evapotranspiration are required to calculate plant development and decomposition of organic matter.

Input parameters on plant and soil characteristics are entered into an external spreadsheet that generates the actual parametrisation files and look-up tables required by PCRaster. Parameters entered are mostly easy to measure or estimate. Standing biomass of natural vegetation can be initialised in the spreadsheet through alternative empirical methods depending on vegetation type. These include data derived from destructive measurements, allometric equations, plateau or Gompertz functions. More complex soil physical characteristics like saturated conductivity are calculated using pedotransfer functions.

The model has been parametrised using soil and weather data from Tat hamlet, Ban Tat, Northwest Vietnam and calibrated using rice yield data from the same catchment (Dung et al., 2008).

1.3. Coupling

MP-MAS is a well-established multi-agent model that contains a solver (linear programming), which optimises decision-making for economic parameters (Berger et al., 2006). The model runs on a yearly time step. MP-MAS can be dynamically linked to LUCIA using Typed Data Transfer (TDT; Linstead 2004) and simulations can be carried out on two communicating machines (Fig. 1). Once a year, LUCIA delivers a map with simulated yield for the respective land use on every pixel. The PCR-specific map format is converted into ASCII by a wrapper and read in by MP-MAS. In the following optimisation process, agents take decisions on land use directed by expected and actual yields, cost factors and revenues. This process can lead to land use change and consequently an updated land use map, which is converted and handed back to LUCIA.

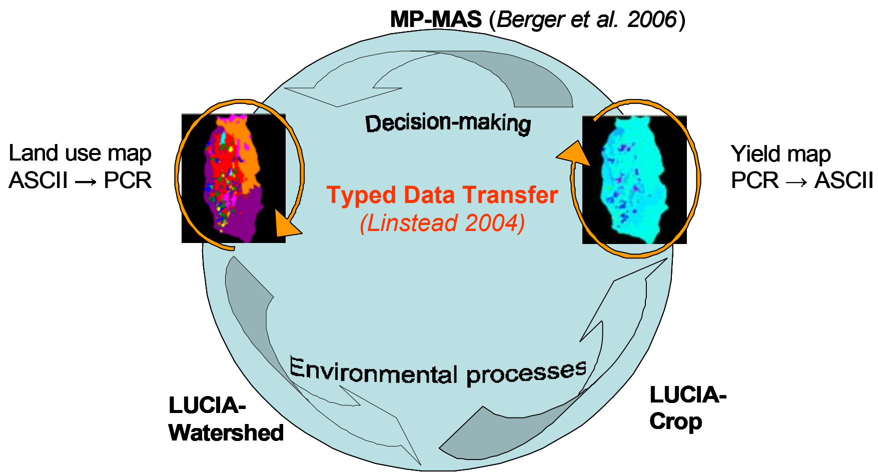

Figure 1. Schematic depiction of the coupled models and the TDT interface; apart from yields, other parameters can be exported to MP-MAS.

MP-MAS in its standalone version includes the Tropical Soil Productivity Calculator (TSPC; Aune & Lal, 1995), an empirical crop model. TSPC can be switched off in MP-MAS so that no overlap of functions or stocks occurs between the coupled models.
Apart from yield and land use, additional parameters can be exchanged as currently performed for management options like fertiliser and manure application imported to LUCIA. This exchange takes place in form of land cover-specific look-up tables or pixel maps, which are produced by MP-MAS and processed in LUCIA.

1.4. Model outputs

Model outputs can be generated as animated map layers or time series for single predefined pixels. Visualisation in 2 or 3D maps allows identifying spatial features like erosion hotspots (Fig. 2) and facilitates communication of results to stakeholders.

Plant growth reacting to management and environmental factors is shown in Fig. 3. for Chieng Khoi in Vietnam (for calibration, soil and yield from the watershed were used).

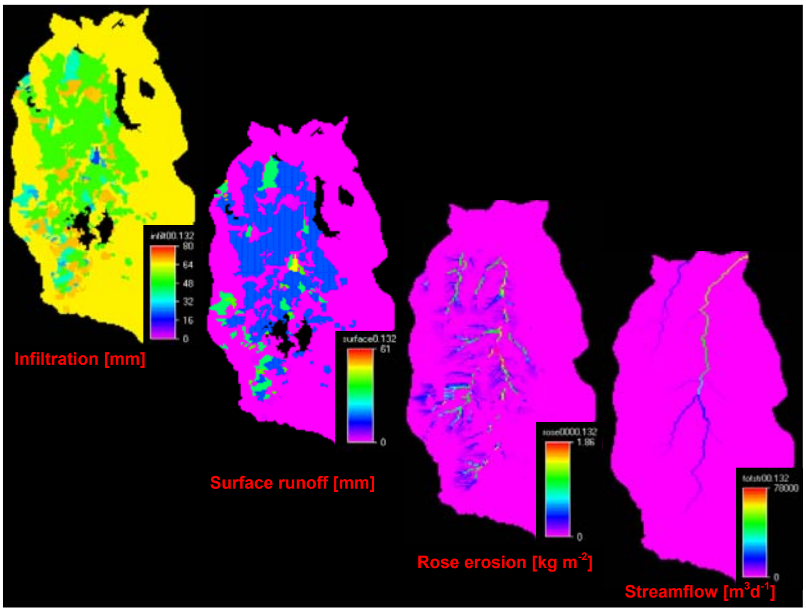

Figure 2. Water-related model outputs in Mae Sa Noi watershed, Thailand, after a rainfall event of 67.9mm/d. Infiltration and run-off are shown as independent pixel values (with settlements excluded from the map), while erosion and streamflow include PCR routing functions.

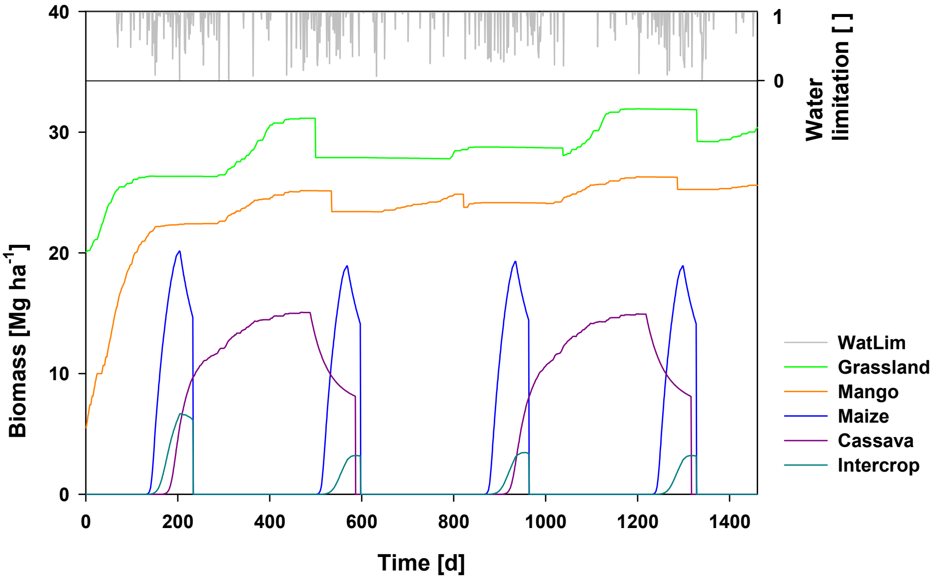

Fig. 3. During four years of continuous cropping, biomass and yields of fertilised maize (not shown, around 3Mg ha-1) remain stable, while unfertilised cassava and mango yields decline (from 6.2 to 5.9 and from 1.7 to 1 Mg ha-1, respectively). Grassland growth is affected by water stress (scale from 1 = no limitation to 0. No growth below 0.3).

2. Outlook

Erosion and deposition affect topsoil thickness and composition as well as crop productivity. With run-off, they are the main processes that link uplands to lowlands. A process-oriented concept of erosion based on the Rose / GUEST approach (Yu et al., 1997) is being incorporated into LUCIA. In contrast to the USLE approach the Rose concept allows to spatially simulate erosion and deposition and identify erosion hot spots in the landscape. Outputs will be validated using run-off and erosion data from Wischmeier plots and catena analysis (sedimentation) collected in a twinned project. To better account for erosivity of rainfall, intensity of events needs to be temporally downscaled to an hourly time step. Further modules will focus on sediment transport in paddy cascades and on irrigation and reservoir siltation.

Plant related modules to be developed include multi-cropping, which considers competition between crops for light, water and resources. Biodiversity as important ecosystem function will be included based on concepts of habitat fragmentation and seed dispersal.

For the socio-economic part, LUCIA-Choice will represent individual farmers' decisions on land use determined by cropping rules, market access, costs, expected benefit, institutional regulations and tradition. In a first step, indispensable factors needed for each land use will be parametrised. These include soil physical and chemical data, elevation, different types of capital, available land and regulations, among others. This will lead to a suitability map per crop and to a list of potential land uses for each pixel. Among the possible land uses the most favourable one will be selected. This, however, requires user inputs on weighting between selection criteria.

To optimise parameterisation and run-time, parsimony of parameters and calculations is imperative. A flexible modular structure will allow users to compose models for specific research questions by coupling single modules and decoupling unnecessary ones. The framework includes a user-friendly interface for parameterisation, map editing, input validation and visualisation. All components will be linked using the free and platform-independent Python language, which is supported by the PCRaster developers (Schmitz et al. 2009).

Conclusion

In the preceding sections we outlined the scope, structure and functionalities of the LUCIA tool. The model has been run combining field data from different subprojects and can be employed to test scenarios such as crop diversification, changing agroecological zonation or management options. Validation has been carried out for yield data in Ban Tat and a previous version of the hydrological submodel. After an initial phase of rapid model development and expansion, extensive testing and validation, particularly of the run-off and erosion related outputs is now needed. Parallely, modules will be further developed. The model has been used by individual students for case studies, but will also serve as a teaching tool to introduce land use change modelling. Outputs will be presented at stakeholder meetings in the research areas to evaluate acceptance, relevance and credibility.

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