International Environmental Modelling and Software Society (iEMSs)
2012 International Congress on Environmental Modelling and Software
Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany
R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.)
http://www.iemss.org/society/index.php/iemss-2012-proceedings

Interpreting Outputs of a Landscape-Scale Coupled Social-Ecological System

Carsten Marohn[1], Pepijn Schreinemachers[2], Dang Viet Quang[2], Prakit Siripalangkanont[2], Simon Hörhold[1], Thomas Berger[2], Georg Cadisch[1]
[1]*University of Hohenheim, Institute for Plant Production and Agroecology in the Tropics and Subtropics, 70593 Stuttgart, Germany*
[2]*University of Hohenheim, Institute for Land Use Economics in the Tropics and Subtropics, 70593 Stuttgart, Germany*
[1]*marohn@uni-hohenheim.de*

Abstract: Coupled specialised models have the advantage of high flexibility; processes represented, input requirements and precision levels can be tailored specifically to a given research question. However, as more parameters become endogenous to a coupled model system, tracing back causal relations of processes can become challenging, because conditions vary over time and between scenarios. Such complexity is still increased in spatially explicit representations of fluxes in landscapes, where pixels are not spatially independent. We present the case of a coupled system composed of a pixel-based biophysical and a farm-based socio-economic model. The coupled model system was employed to assess resource degradation, yields and land-use decisions in a mountainous catchment of 31 km^2 and 490 households in Northwest Vietnam. Specifically, we looked into impacts of farmers' adoption of different soil conservation techniques on erosion, yields and incomes. From the perspective of the biophysical model, land use change and management were dynamically influenced by crop yields when adding the decision component. After a common starting point the scenarios developed into very different directions and only overall outcomes could be compared. In order to be able to draw conclusions on biophysical processes – as usual in pure biophysical models under stable or at least comparable treatments (here: land uses and management) – we employ tools used for spatial analysis and geostatistics. This paper presents first results of ongoing research.

Keywords: Coupled social-ecological model; spatial analysis; process-based model; agent-based models.

1 INTRODUCTION

Coupling specialised models from different scientific domains has the advantage of high flexibility; processes represented and precision levels can be tailored specifically to a given research question, so that input requirements are minimised. Several applications of coupled socio-economic and simplified crop models have been described, e.g. by Schreinemachers et al. (2007) – the combination of the Mathematical Programming Multi Agent Systems model MP-MAS with the empirical Tropical Soil Productivity Calculator (TSPC), or loosely coupled approaches by Bithell and Brasington (2009) or Bulatewicz et al. (2010). Once two detailed process-based components are coupled, interactions between the human and environmental sphere can be better represented. On the other hand, tracing back causal relations of processes can then become challenging, because conditions vary over time and between scenarios.

The case study presented is based on a simulation of MP-MAS coupled with the Land Use Change Impact Assessment tool (LUCIA) described in Marohn et al. (2012).

It was expected that – once decisions and mechanistic biophysical routines become endogenous to the model – feedback mechanisms between both human and environmental spheres, which are often non-linear, could be better accounted for. The detailed information fed into the system from both sides would particularly lead to insights regarding agents' consideration of inherent soil fertility during decision-making, which is of importance under low input conditions.

From a biophysical perspective, scenarios ideally resemble an experimental design with stable treatments. Either impacts of land use or management or climate change, among others, are quantified under experimental (*ceteris paribus*) conditions. Socio-economic models are run on more integrated scenarios, which usually include land use change, but do not account for biophysical feedback.

In the coupled model, our goal is to maintain the strengths of the biophysical model, enabling mechanistic understanding of landscape-scale processes, while running complex scenarios. The objective of this study was to assess impacts of soil conservation measures on crop yields within the given framework of changing land uses and management.

As an example of output complexity we highlight two connected issues raised by outputs of the coupled model system: What is the underlying causality for declining average maize yields in the baseline and for extensification – increase of unfertilised relative to fertilised maize area – in all scenarios? Two main hypotheses were explored to explain model behaviour: a) Maize yields were reduced because of soil degradation (erosion and nutrient export) so that cultivation was not profitable and farmers invested less inputs, reducing fertiliser. b) Farmers reduced fertiliser first, so that yields declined.

2 MATERIALS AND METHODS

2.1 Model structure

MP-MAS (Schreinemachers and Berger 2011) seeks to maximize agent household income under various technical and social constraints, using mathematical programming. Each farm is represented as an agent, who takes decisions based on expectations, which evolve dynamically. In its standalone version, MP-MAS includes the empirical TSPC model, which calculates pixel-based crop production on the basis of empirical nutrient response curves. Typical scenarios cover testing land and resource use under certain policy premises.

LUCIA (Marohn and Cadisch 2011) represents water and C, N, P, K fluxes between soil, organic matter and plants in small catchments. The model runs on pixels of user-defined size and on a daily time step. Typical simulations compare effects of predefined land use sequences or climate time series on natural resource availability and food security.

Both models were loosely coupled using the Typed Data Transfer (TDT) protocol (Linstead 2004). After each year of biophysical simulation in LUCIA, a yield map is passed to MP-MAS, which updates agents' expectations on yield levels thus influencing decisions on land use and fertiliser application based on household resources and yield expectations. MP-MAS then sends an updated land use map and look-up table, containing fertiliser application levels, back to LUCIA (Fig. 1).

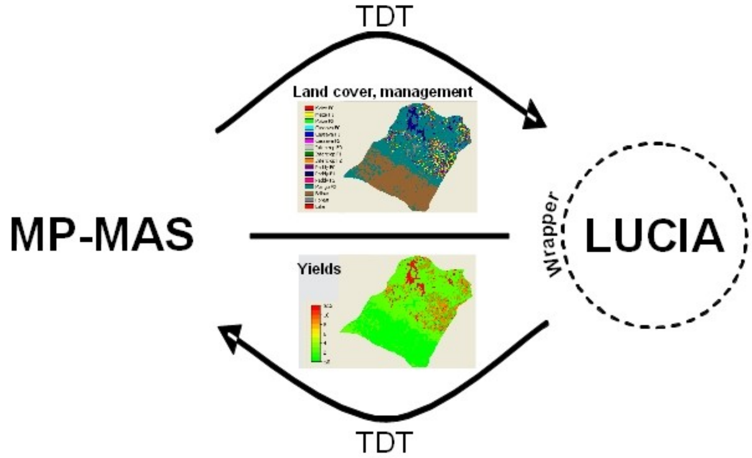

Figure 1 . Coupling of the Land Use Change Impact Assessment tool and Mathematical Programming Multi Agent System.

2.2 Study area

The research area was Chieng Khoi commune, located in Son La province, Northern Vietnam. During the last decade a transition to market economy as well as population growth have been strong drivers replacing traditional rice-based swidden systems with maize under high fertiliser input. Maize is monocropped on steep slopes, leading to severe soil erosion. Our simulation of 25 years looked into the potentials of soil conservation measures to reconcile economic profits (influenced by yields and fertiliser costs) and environmental sustainability (reducing erosion levels).

The baseline simulated farmers' current practice of maize cultivation with burning and ploughing. The alternative scenarios offered three different soil conservation techniques alongside the baseline option, so that farmers could choose their preferred management.

Table 1 . Available management options for maize cultivation in the scenarios tested.

Scenario	Burn	Plow	Cover crop	Labor use (hours/ha)	Explanation
A. Baseline: Current practice	Yes	Yes	No	207	Fallow vegetation slashed and burned with maize stalks in dry season, before the field is plowed for planting.
B. Zero tillage without a cover crop	No	No	No	230	Fallow vegetation not burned but mulched, maize planted in untilled soil. More labor needed for weeding.
C. Zero tillage with a cover crop	No	No	Yes	275	Same as (B), but perennial legume planted between maize to reduce erosion, suppress weeds and fix nitrogen. More labor required establishing and managing the cover crop.
D. Cover crop plowed under	No	Yes	Yes	298	Same as (C), but cover crop plowed under to improve soil fertility.

Notes: Low cost soil conservation methods assume the same amount of cash costs for all options. Labor use data was based on expert opinions of researchers conducting the field experiments. Scenario B also included the options given in the baseline, and Scenarios C and D also included options in the baseline and in Scenario B.

GRASS (Quantum 1.7.1) and R (version 2.10.0) were used for spatial analysis of the model outputs.

3 RESULTS

Simulations yielded a wealth of outputs, some of them unexpected, for example: Agents decreased fertiliser inputs on low-yielding maize fields, where intensification was expected due to high profitability of maize. Agents' decisions did not consider spatial variability of maize yields to the expected extent. A typical question that arose at the interface between decision-making and biophysical sphere was, whether yield decrease was caused in first instance by decreased fertiliser application or by erosion (which would be concentrated on certain plots, e.g. with steep slopes or on long slopes). Tracking back biophysical causalities became challenging in the coupled model system as land use and fertiliser levels varied between years and scenarios.

One indicator for erosion as primary cause for yield decline would be higher unfertilised maize yields on less eroded plots. Using simple spatial statistics we tried to elucidate this relationship.

Standalone runs of LUCIA under constant land use and allowing only one soil conservation measure per scenario on all maize plots (Fig. 2a) under given fertiliser treatments showed that soil conservation effectively reduced erosion. The most pronounced differences between scenarios, apart from maize, were found in the paddy areas (Fig. 2b). Comparison of topsoil depth showed that these large amounts of sediments stemmed from the entire catchment and were not generated in the paddies.

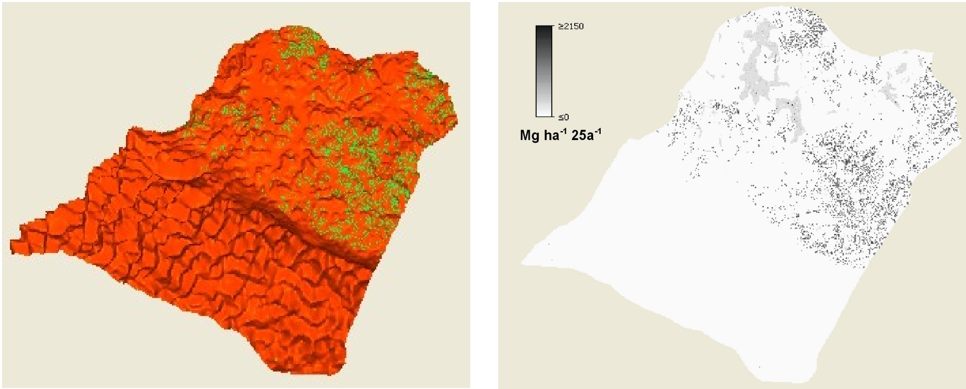

Figure 2 . a) left side: Maize plots (green) in Chieng Khoi. b), right side: Difference in cumulative erosion under legumes (scenario D) minus baseline (A) in a standalone run of the biophysical model after 25 years.

In terms of average numbers, higher levels of maize yield were initially found under soil conservation, but after 5-10 years these successively fell in contrast to baseline levels. Looking at single fertiliser levels showed that this was mainly owed to F1 in the baseline (Figure 3).

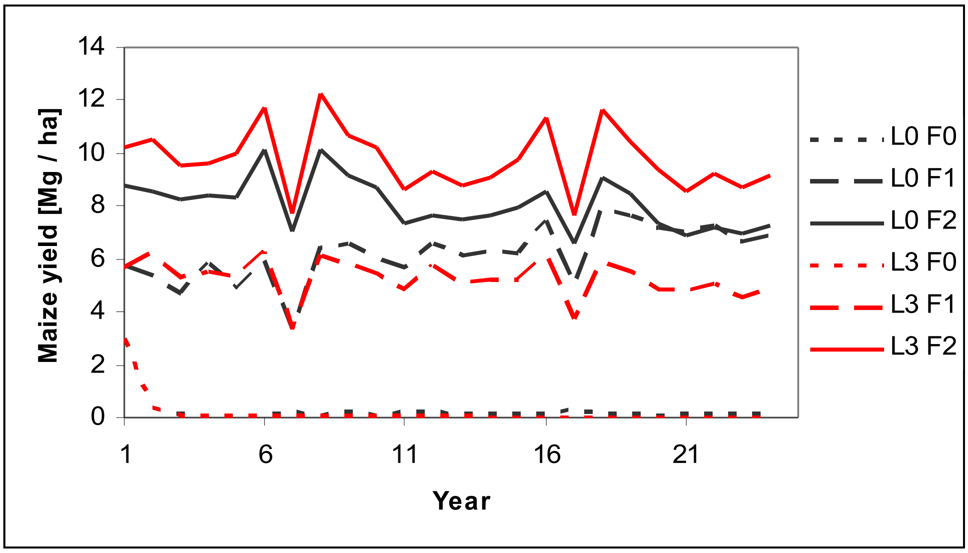

Figure 3 . Maize yields in the standalone run for the baseline (L0)and legume intercropping (L3) under three fertiliser regimes: F0 = unfertilised; F1 = farmers' practice; F2 = high (factory recommendation).

For the standalone simulations – hypothetical extreme scenarios of 25 years continuous maize cropping without fallow! – these results imply that the initially positive effects of soil conservation on yields led to higher uptake of resources into plants. Once a turning point was passed, this led to soil mining.

Spatial analysis of the monocropped maize plots in the standalone run showed that correlations between maize yields and the explanatory variables elevation and slope were weak. The positive correlation yields~erosion showed that erosion was not an appropriate measure as high amounts of sediments passing a pixel were also accounted for. The correlation between yields (all fertiliser levels) and topsoil depth, however, proved to be relatively strong (Table 2). A linear regression between yields and topsoil depth and DEM showed an adjusted R square of 0.29. In this case erosion clearly influenced yield levels.

Table 2 . Correlations between maps of maize yield and potential explanatory variables after 25 years in the baseline of the standalone run.

Correlation	Elevation	Slope	Erosion	Topsoil Depth	Yield
Elevation	1	0.64	-0.05	-0.15	-0.12
Slope		1	-0.04	-0.15	-0.08
Erosion			1	0.06	0.11
Topsoil Depth				1	0.54

In the **coupled model**, directly isolating effects of maize treatments was not possible due to the frequent changes in land use. Maize yield response to elevation and slope was more clearly negative than in the standalone model at the end of the simulation (year 25) (Table 3). The negative correlation between topsoil depth and yields The most pronounced effects were expected at the end of the simulation (after 25 years), at an advanced stage of soil degradation.

Table 3 . Correlations between maps of maize yield and potential explanatory variables after 25 years in the baseline of the coupled run.

Correlation	Elevation	Slope	Erosion	Topsoil Depth	Yield
Elevation	1	0.64	-0.04	0.79	-0.32
Slope		1	-0.05	0.62	-0.30
Erosion			1	-0.12	0.07
Topsoil Depth				1	-0.47

Ranking of explanatory power was slightly changed from [topsoil depth > elevation > erosion > slopes] in the standalone runs to [topsoil depth > elevation > slopes > erosion]. The correlation yield~topsoil depth was strongly negative (-0.47) in the coupled run. The counterintuitive negative sign might suggest that previous land use history or generic soil classes had an influence on land use and management decisions (e.g. less fertiliser input or change to other crops on unproductive pixels). Plotting yields against topsoil depth (data not shown) gave an exponential curve with numerous cases of very low yields; this confirms advanced soil degradation. Strong and positive correlations on the maize plots between topsoil depth on one hand and elevation and slopes on the other were also unexpected and suggest that there had been some pre-selection of plots suitable for maize growth. This needs more exploration as decisions on land use are taken at the household level with plots belonging to a farm being randomised.

4 DISCUSSION

Running the biophysical standalone model proved appropriate to explain some processes, but not realistic regarding scenarios as decision making was switched off. The coupled model with dynamic land use prevents such unrealistic scenarios, as in the given case agents facing waning yields would resort to different land uses or fertiliser levels. This, however, implies that single parameters cannot be compared on a plot level between years and scenarios. In future approaches temporal integration at the pixel level would be needed to account for land cover change and crop rotation.

Combining the benefits of both models means that the approach to interpretation of results has to be filtering existing outputs, not changing the scenarios. Further analysis would need to explore whether farmers grow certain crops in particular landscape positions (e.g. maize on less erodible slopes), whether typical crop rotations evolve and how cropping patterns change over the years. Similarly, resource allocation, e.g. of fertiliser, might be concentrated on the most promising plots. At the moment this approach is not feasible, because decisions on plot allocation in the coupled model system at its present stage are taken at the household level. Land use thus reflects the effect of farm resources on decision-making and it is not clear in how far this dominates agents' knowledge on soil fertility. Making the best use of inherent soil fertility, however, is expected to be particularly relevant for those households with limited resources.

5 CONCLUSIONS

Generic tools for post-processing are needed to filter biophysical model outputs correcting for effects of land use and management change and, vice versa, to identify influences of landscape properties (e.g. elevation, exposition) on decision-making. On the other hand, flexibility is required as relevant output parameters and expected causalities differ between case studies. Allocation of activities at the farm level needs to give more priority to soil fertility of the single plot in a future biophysical model with a simplified decision component to make full use of the biophysical model capabilities, but at the same time not inflating model run time.

REFERENCES

Bithell, M.and J. Brasington, Coupling agent-based models of subsistence farming with individual-based forest models and dynamic models of water distribution, *Environmental Modelling and Software,* 24, 173-190, 2009.

Bulatewicz, T., X. Yang, J.M. Peterson, S. Staggenborg, S.M. Welch and D.R. Steward, Accessible integration of agriculture, groundwater, and economic models using the Open Modeling Interface (OpenMI): methodology and initial results, *Hydrology and Earth System Sciences,* 14, 521–534, 2010.

Linstead, C., Typed Data Transfer (TDT) User's Guide, Potsdam Institute for Climate Impact Research (PIK), Potsdam, 2004.

Marohn, C. and G. Cadisch, Documentation and manual of the LUCIA model version 1.2, state Sep 2011, Available at https://lucia.uni-hohenheim.de .

Marohn, C., P. Schreinemachers, D.V. Quang, T. Berger, P. Siripalangkanont, T.T. Nguyen and G. Cadisch, A software coupling approach to assess low-cost soil conservation strategies for highland agriculture in Vietnam, *Environmental Modelling and Software*, in press.

Schreinemachers, P. and T. Berger, An agent-based simulation model of human-environment interactions in agricultural systems, *Environmental Modelling and Software*, 26, 845-859, 2011.

Schreinemachers, P., T. Berger and J.B. Aune, Simulating soil fertility and poverty dynamics in Uganda: A bio-economic multi-agent systems approach, *Ecological Economics, 64*, 387-401, 2007.