
# Negotiation-support toolkit for learning landscapes

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# 32 | Land-use change impact assessment (LUCIA)

**Carsten Marohn, Georg Cadisch and Betha Lusiana**

The Land-Use Change Impact Assessment (LUCIA) model can be used to assess impacts of land-use changes on soil productivity and fertility, biomass production, watershed functions and environmental services. It operates at high spatial and temporal resolution but can so far only handle small mountainous catchments. It help scientists and land-use planners simulate mid- to-long-term effects of land-use management and changes on environmental degradation and rehabilitation. It is explicit in the consequences of plot-level decision making by farmers and thus operates between the reach of detailed tree–soil–crop interaction models and models that operate at more aggregated watershed scale.

## Introduction

Peoples' decisions with respect to agricultural land use and management have a major impact on natural resource degradation. Soil degradation is largely caused by the activities of land-use decision makers and has substantial feedback effects on both human and environmental systems. Particularly in mountainous areas, degradation is largely due to flow of matter from upstream to downstream areas in the form of water (runoff) that also brings along soil (erosion, deposition) and nutrients. The use of a simulation model such as LUCIA can help land-use planners to assess the impact of landscape management in order to reduce soil degradation.

LUCIA integrates different processes related to soils, water and plants thus allowing a user to assess the benefits and trade-offs of land-use changes and management. These processes are represented in a spatially explicit way so that the effects of positioning of each land use and activity in the catchment are taken into account and can be considered when designing management strategies. Applications of the model encompass the decline and recovery of soil fertility, changes in the water balance, surface runoff, erosion and sedimentation processes, yield levels, as well as food security, biomass and carbon stocks. Scenarios can represent the consequences of local farmers' short-term management decisions (such as fertilization, ploughing or burning), land-use and land-cover changes, or longer-term changes such as climate.

## Objectives

LUCIA was designed to represent processes of water balance, erosion and sedimentation as well as nutrient balance and yield formation in a small catchment responding to plot-level management decisions.

## Steps

LUCIA combines daily time steps for crop growth and hourly sub-time step for infiltration, runoff and erosion. It is a spatially explicit landscape model written in PCRaster, a combination of dynamic modelling language and GIS developed at the University of Utrecht.

LUCIA consists of five main modules: 1) Hydrology/soil water; 2) Soil nutrients; 3) Organic matter and decomposition; 4) Plant growth; and 5) Land-use and management options. The soil water, organic matter and plant modules are built on concepts of established models, namely KINEROS (Woolhiser et al 1990) and SPAW (Saxton and Rawls 2006), CENTURY (Parton et al 1987) and the Crop Growth Monitoring System CGMS (Supit 2003), which is based on the World Food Studies (WOFOST) model.

Input parameters required and outputs produced by LUCIA are provided in the user manual (Hörhold and Marohn 2012) and theoretical background in the documentation (Marohn and Cadisch 2011). An online distance learning course is offered that includes lectures and exercises with the model (https://openilias.uni-hohenheim.de).

The LUCIA model has been successfully coupled with MP-MAS, a model that simulates farm decision making, to explore the impacts of several soil conservation measures on erosion and yields in northern Viet Nam. Currently, LUCIA-Choice is also being developed: a decision-making module, which can be coupled with LUCIA. LUCIA-Choice contains a decision algorithm based on household resources, crop preferences and plot quality. The latter includes top-soil carbon contents and other indicators of soil fertility and it is up to the farmers (as parameterized by the user) how much importance they attribute to these factors. This will allow a reflection of farmers' levels of local knowledge on plot-specific characteristics in terms of their land. A simple tool for building land-cover-change scenarios is the rule-based LUC generator.

## Case study: LUCIA in Viet Nam

Soil degradation is largely caused by the activities of land-use decision makers and has substantial feedback effects on both human and environmental systems. To capture these feedback effects and the resulting human–environment interactions, LUCIA was used to assess the potential impact of low-cost soil conservation methods on maize cultivation in upland areas. The study was carried out in Chieng Khoi in Son La province, Viet Nam, an area which represents the ongoing trend toward intensified maize-based agriculture in parts of northwestern Viet Nam. The combination of heavy rain and mostly steep terrain makes soils highly susceptible to erosion once permanent vegetation cover is removed. With increasing population in the area and stronger market integration, fallow periods have shortened or even disappeared, leading to severe soil degradation.

Average crop yields were calibrated using a household survey of 490 farms (Quang 2010) and validated based on field data by Schmitter et al (2010) and Rathjen (2010) for paddy rice, maize and cassava, respectively. Pixel size in the Chieng Khoi model was set at 25 by 25 m, which corresponds to the size of an average smallholding plot. Maize fields in Chieng Khoi are slashed and burned between November and March; fields are ploughed at the start of the wet season (April to October) and maize is sown in May. Model scenarios were based on the above data, comparing farmers' practices as a baseline scenario to three alternative scenarios (Table 1). Under these scenarios, the introduction of different soil conservation options in the maize fields was tested.

**Table 32.1.** Scenarios tested for plots under maize cultivation

| Scenario | Management options | | | |
|---|---|---|---|---|
| | Burning | Tillage | Cover crop | Description |
| Baseline: current practice | Yes | Yes | No | Fallow vegetation or crop residues are slashed and burned in the dry season prior to ploughing and sowing |
| B: Zero tillage without cover crop | No | No | No | Fallow vegetation is not burned but mulched; maize is planted in untilled soil |
| C: Zero tillage with cover crop | No | No | Yes | Same as (B), but a perennial legume is inter-planted with maize to reduce erosion; suppress weeds and fix atmo-spheric nitrogen |
| D: Cover crop plowed under | No | Yes | Yes | Same as (C), but the cover crop is ploughed into the soil to improve soil fertility and ease planting |

**Source:** Marohn et al 2013

Three fertilizer levels were implemented for each scenarios: 1) zero fertilizer; 2) farmers' practice which is 75/50/75 kg of N/P/K per hectare; and 3) levels recommended by the fertilizer manufacturer (double the farmers' practice). Fertilizer levels per pixel were not varied between scenarios and years. Legumes were implemented as soil cover not competing with the crop for nutrients.

The objective of the study was to assess 1) whether soil conservation measures under maize were able to directly reduce soil degradation and indirectly reduce it under other land uses on lower slope positions; and if so 2) how far yield levels would be positively affected by soil conservation measures in the long run.

It was found that soil conservation effectively reduced erosion. After the first year, soil conservation on maize plots under no tillage (Scenario B) resulted in 0–7.3 Mg ha$^{-1}$ less sediment loads per pixel as compared to the baseline, while the legume scenarios C and D achieved between 0 and 18.8 Mg ha$^{-1}$ less sediment loads (Figure 32.1). Land uses other than maize showed only minor differences between scenarios. After 25 years, reduced sediment loads on maize plots reached up to 365 Mg ha$^{-1}$ for Scenario B and 1680 Mg ha$^{-1}$ for Scenario C and Scenario D. The most substantial reduction was found in the lowland areas, which receive sediment from the entire catchment. Cumulative reduction ranged from 0 to 780 Mg ha$^{-1}$ for Scenario B and from 0 to 2,150 Mg ha$^{-1}$ for scenarios C and D. Topsoil depth after 25 years was analysed as well. On a few of the pixels (approximately 20% of the entire catchment), topsoil thickness was slightly greater in the baseline as compared to the other scenarios. In all other cases, topsoil was up to 5.3 cm thicker under Scenario B and up to 20 cm under scenarios C and D, as compared to the baseline. Separating these effects between maize and other land covers showed that other land uses were hardly affected, revealing that top-soil loss affected mainly the source cells and that sediments travelled through the lowlands but did not cause a major entrainment of soils under other land-cover types.

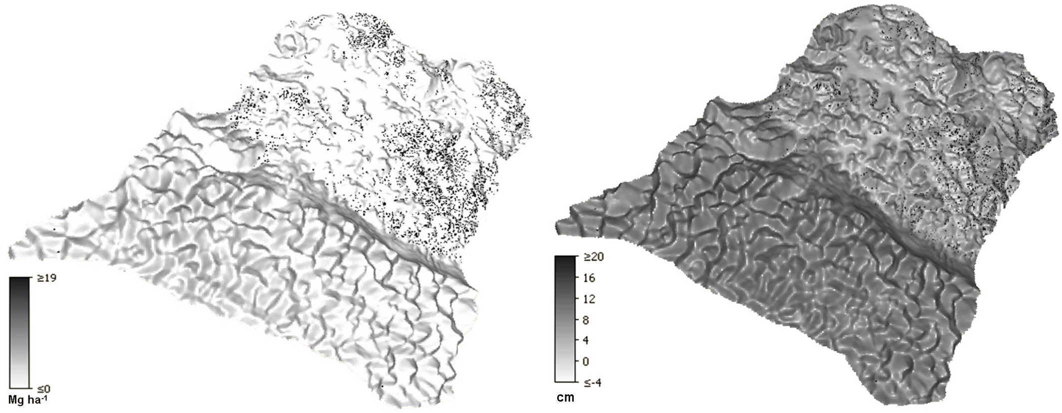


**Figure 32.1.** Difference in sediment loads and topsoil depth

**Note:** Baseline minus scenario D after year 1 (left) and difference in top-soil depth scenario D minus baseline after year 25 (right)

**Source:** Marohn et al 2013

The analysis of yields after 25 years showed that it was mainly maize that was affected by soil conservation measures, as expected (Figure 32.2 ). Owing to landscape-related factors, both maize-derived erosion rates and maize yields showed large spatial variability, as shown in Table 32.2.

**Table 32.2**. Descriptive statistics of yields

| Descriptor | Maize yield F0, year 5 | Erosion, year 1 |
|---|---|---|
| Mean [Mg ha$^{-1}$] | 4.20 | 13.6 |
| St.dev. [Mg ha$^{-1}$] | 2.40 | 30.2 |
| Coeff. Var. [%] | 57 | 222 |

**Note:** On unfertilized (F0) maize pixels for the fifth year of simulation, and erosion across all maize pixels for the first year of simulation, baseline, (n = 3,665)

**Source:** Marohn et al 2013

Clear differences in average maize yields appeared between fertilizer levels, regardless of the soil conservation measures used. Under farmers' practice of continuous fertilizer inputs (F1 treatment in Figure 32.2, left chart) average maize yields started around 6 Mg ha$^{-1}$ and then increased up to 7 Mg ha$^{-1}$ under the baseline and no tillage scenarios, while yields of maize combined with legumes slightly decreased and dropped below the baseline in year 8. As nutrient competition between crop and legume was not modelled, this might have been caused by indirect nutrient insufficiency owing to water stress in the crop (caused by the higher water demand of crop plus legume). Yields under high fertilizer input (F2 treatment; Figure 32.2, right chart) came close to potential yields during years without water stress. Under soil conservation and high fertilizer inputs, yields remained clearly above the baseline at all times, however, during years of extreme weather (for example, 7 and 17) the difference in yields between legume and non-legume treatments shrunk.

Significant effects of ploughing between the two legume treatments were not observed in the simulations.

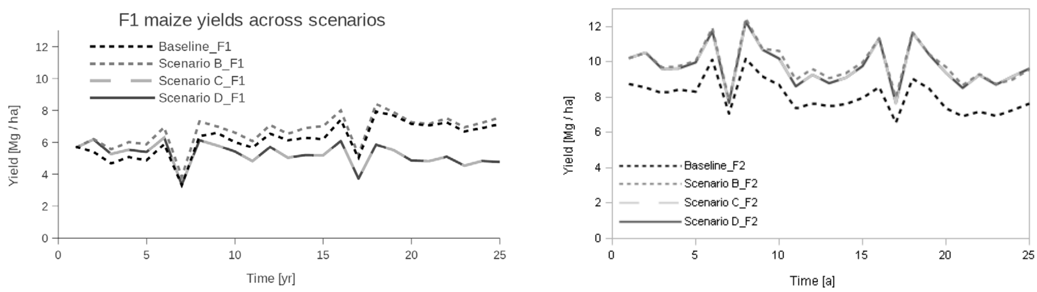


**Figure 32.2.** Average maize yields

**Note**: At farmers' practice (left) and high fertilizer levels (right) under all scenarios over the 25 years of simulation

**Source:** Marohn et al 2013

At the plot level, the magnitude of soil eroded from maize plots (Table 32.2) was in the range of that found in the reference experiments carried out on similar slopes and soils in Chieng Khoi (Tuan, personal communication). Simulated soil conservation measures on maize plots were effective at reducing soil erosion on these plots and also on other plots downstream. The reduced erosion rates had a positive effect on maize yields in the first years after implementation of the measures.

In combination with the MP-MAS model, LUCIA maize yields led to two different land-use and management strategies by farmers: 1) Intensification, that is, adding more fertiliser when maize yields decreased; and 2) extensification, that is, omitting fertiliser on plots that were not profitable. Consequently, a sensitivity analysis showed that fertiliser prices had a strong impact on soil conservation measures: where fertiliser was cheap, waning yields were compensated by increased fertiliser levels, else soil conservation was practised.

At the landscape level, soil conservation measures in maize fields had limited effects on the sediment loads leaving the entire catchment, as deposition accounted for filtering and delayed delivery. Although absolute quantities of eroded soil at the catchment outflow differed clearly between scenarios, these differences remained small in relative terms, owing to the fact that the large areas under forest and tree plantations that contribute little to erosion remained unchanged between scenarios. Seemingly larger erosion reduction effects in paddies, as compared to maize plots, stemmed from the fact that the model simulated sediment loads and thus did not distinguish between eroded soil originating from a pixel and such passing through a pixel (except for pixels without an inflow, for example, next to a ridge). As sediment from the entire catchment passed the lowland and outflow cells, total amounts were always higher than in the upland source cells.

The LUCIA standalone model captured the spatial variability in erosion and crop yields observed in the field (Lippe et al 2011). The high temporal and spatial resolution of the model allowed identification of erosion hotspots (in terms of reduced topsoil thickness), distribution of sediment loads and patterns of soil fertility (for example, high fertility along previously forested footslopes, outputs not shown) and their development over time. The unchanged land cover and management practices over 25 years, even though not a necessarily realistic scenario, facilitated the tracing back of causal relationships between variables.

## Key references


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The landscape scale is a meeting point for bottom–up local initiatives to secure and improve livelihoods from agriculture, agroforestry and forest management, and top–down concerns and incentives related to planetary boundaries to human resource use.

Sustainable development goals require a substantial change of direction from the past when economic growth was usually accompanied by environmental degradation, with the increase of atmospheric greenhouse gasses as a symptom, but also as an issue that needs to be managed as such.

In landscapes around the world, active learning takes place with experiments that involve changes in technology, farming systems, value chains, livelihoods' strategies and institutions. An overarching hypothesis that is being tested is:

> Investment in institutionalising rewards for the environmental services that are provided by multifunctional landscapes with trees is a cost-effective and fair way to reduce vulnerability of rural livelihoods to climate change and to avoid larger costs of specific 'adaptation' while enhancing carbon stocks in the landscape.

Such changes can't come overnight. A complex process of negotiations among stakeholders is usually needed. The divergence of knowledge and claims to knowledge is a major hurdle in the negotiation process.

The collection of tools—methods, approaches and computer models—presented here was shaped by over a decade of involvement in supporting such negotiations in landscapes where a lot is at stake. The tools are meant to support further learning and effectively sharing experience towards smarter landscape management.

World Agroforestry Centre
ASB Partnership for the Tropical Forest Margins
AARD
Federal Ministry for Economic Cooperation and Development
Norad
IFAD
Enabling poor rural people to overcome poverty
CGIAR
Research Program on Forests, Trees, and Agroforestry