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The multiple-scale land use change model LandShift: A scenario analysis of land use change and environmental consequences in Africa

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Abstract: Land use and land cover change are considered as important drivers and targets of global environmental change. In this paper we present the integrated model system LandShift to simulate land use change processes and related consequences for the environment on the global and continental level. LandShift has a modular structure that allows the integration of various functional model components. The first version of the model system includes a newly developed land use change module and modules for crop and grassland productivity, which are based on the ecosystem model DayCent. Furthermore, LandShift is linked to the global hydrological model WaterGAP2 that delivers information on water-availability and water-stress. The use of these dynamic models allows for simulating climate change effects on hydrological and bio-geochemical processes. LandShift operates on a multi-level scale-hierarchy. On country level (macro-level) exogenous model drivers are specified, including demands for agricultural commodities and for services like housing. The land use change module regionalizes these demands to a grid with a spatial resolution of 5 arc-minutes (micro-level). It is structured in three sub-modules dealing with the land use sectors "settlement and industrial" (METRO) and agriculture (AGRO, GRASS). Simulation results are presented from a pre-study for the African continent based on a Millennium Ecosystem Assessment scenario.

Keywords: Land use change modelling, LandShift, Africa study

1. INTRODUCTION

Land use change has been identified as a force of global importance (Foley et al., 2005) since human activities like agriculture and settlement have a substantial impact on the environment. This trend is going to continue in the future due to the increasing food and energy demands of a growing world population.

During the past decade a wide variety of spatially explicit modelling approaches to simulate land use change processes have been developed (Verburg et al., 2004), most of them with a regional focus. In contrast only few models are aiming at a consistent approach for the application on the global scale (Heistermann et al., in press).

This paper describes the concept of the newly developed model system LandShift[1] that aims at simulating and analyzing spatially explicit land use dynamics and related impacts on the environment at global and continental scales. Research questions addressed by LandShift cover aspects like climate change and food production, linkages between land use change and hydrology as well as the impact of the expansion of urban and agricultural land on natural resources in terms of deforestation and loss of natural vegetation.

LandShift integrates model components to account for the interactions of socio-economic drivers and biophysical environment, which both determine land use change processes. Examples include the influence of local crop production on land use decisions and of water-availability on irrigation. Furthermore LandShift is the first large-scale model that puts the emphasis on a detailed representation of the competition for natural resources between the major land use sectors "settlement and industrial", agriculture and (in a later model version) forestry.

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[1] **Land** **S**imulation to **H**armonize and **I**ntegrate **F**reshwater availability and the **T**errestrial environment

First application is a scenario analysis of land use changes in Africa until 2050 conducted as part of the UNEP Global Environmental Outlook (GEO-4) assessment. As GEO-4 is still an ongoing project, we present preliminary simulation results from a pre-study, borrowing scenario drivers from the Millennium Ecosystem Assessment (MEA), to demonstrate the model application.

2. MODEL DESCRIPTION

2.1 Overview

LandShift is an integrated model focusing on global and continental level land use change dynamics. Figure 1 depicts the conceptual model design.

The model input is a set of exogenous drivers, including time series on societal and economic data like population and production of agricultural commodities (crops and livestock). Model output is a time series of raster maps of the changing land use pattern in 5-year time steps, which can be processed by standard GIS software like ArcGIS or IDRISI, or can serve as input for additional models for environmental impact assessment. Moreover, the model generates a set of indicators (like rates of deforestation), documenting the land use change processes in an aggregated form.

The design of LandShift is characterized by a modular structure that allows the integration of functional model components representing different aspects of the land use system. The current model version includes a newly developed module to simulate land use change (LUC-module) and modules to simulate cropland and grassland productivity with the ecosystem model DayCent (Parton et al., 1998). These two modules provide information on net primary production of grasslands and on yield of different crop types for the LUC-module to be utilized by its suitability analysis and land allocation routines. Additionally these routines are using information on water-availability and water-stress, generated by the WaterGAP2 model (Alcamo et al., 2003). As both DayCent and WaterGAP2 are driven by data on current and future climate (changing precipitation and temperature), these data links allow the LUC-module to account for climate change effects on land use change.

2.2 Spatial resolution

LandShift operates on a spatial scale-hierarchy that consists of three different levels: a macro-level (179 countries), an intermediate level (global 30 arc-minutes grid) and a micro-level (global 5 arc-minutes grid).

The exogenous model drivers are specified on the macro-level. Environmental data like land use type, slope, soil type and population density as well as information on zoning regulations such as protected areas are defined on the micro-level. In addition, the intermediate level serves to feed information to the LUC-module that is generated by the productivity modules and the WaterGap2 model. As the scale hierarchy links each micro-level cell to an intermediate level cell, the corresponding information can directly be accessed.

Unlike other large-scale modelling approaches as the IMAGE model (Alcamo et al., 1998), LandShift assigns one dominant land use type to each micro-level grid cell. This approach allows a direct access to land use information, which we regard as a major advantage for further processing the model output with GIS or impact assessment models. The simulated land use types include urban area, cropland and different types of

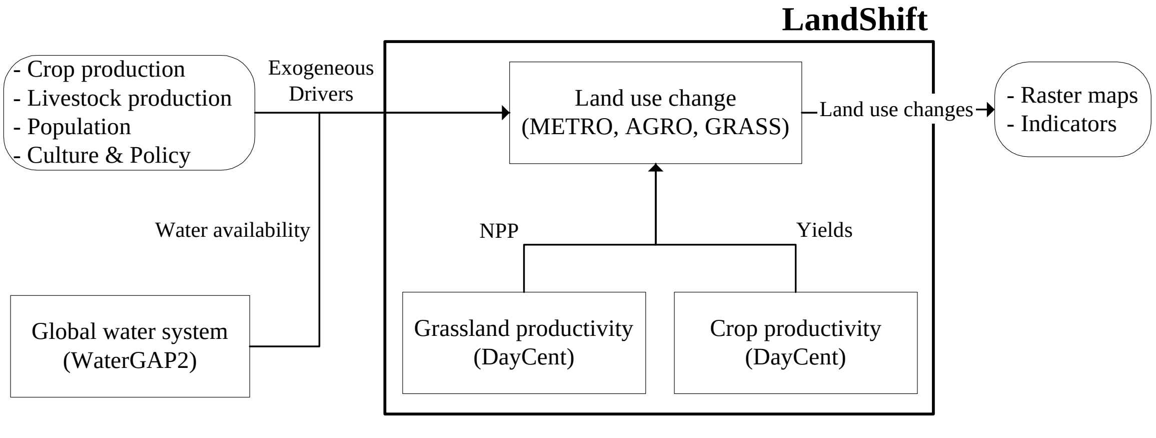

Figure 1. Conceptual model of LandShift

grassland (pasture, rangeland), natural vegetation and forest. The starting conditions are based on the IGBP land-cover classification. Information on the spatial distribution of crop types is generated by a procedure that merges land cover data with sub-national census data, described by Heistermann et al. (submitted).

2.3 Land use change module

The core element of LandShift is the land use change module (LUC-module). The task of this module is to regionalize the country level demands for area intensive commodities and services to the micro-level, i.e. to the grid cells of the particular country. Area intensive goods include various crop types and livestock, while services cover an aggregate of settlement and industrial area.

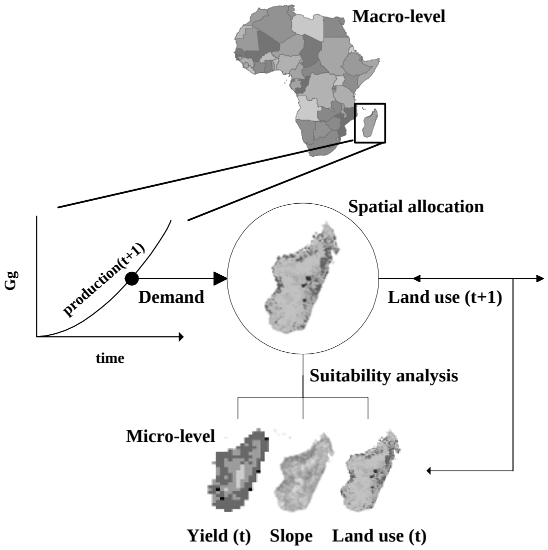

Figure 2. The LUC-module: suitability analysis and spatial allocation of production.

The demands are derived from the exogenous model drivers. For example, the demand for new settlement area is computed from population development and assumptions of per capita housing area. In contrast, the demand for a crop type is defined as the production of that particular crop type in the country. This information can be computed with an economic partial-equilibrium model (section 3).

Each commodity and service is linked to a specific land use type, i.e. it can be produced on cells with this land use type. The rationale of the LUC-module is that the production is allocated to the most suitable cells by changing the land use type of as many cells as needed to fulfill the country demand. The amount of a commodity that can be produced in a cell is determined by its local production function. Each cell contains a vector of production functions for any commodity.

The LUC-Module is organized in three sector-specific sub-modules: METRO is responsible for the “settlement and industrial” sector, AGRO for “crop production and irrigation” and GRASS for livestock production. Important sectors like forestry and bio-energy will be integrated in later model versions. Currently processes like deforestation are modeled as an effect of the expansion of other land use types. Competition for land resources between the sectors is modeled by assigning a priority value to each sub-module that reflects assumptions of its’ economic importance. This results in a sequential execution of the sub-modules, starting with METRO, followed by AGRO and GRASS. Competitions between land use types within a sector are handled inside the responsible sub-module (see below).

Each sub-module implements three functional components that are executed subsequently in every time step:

- Demand Processing,
- Suitability Analysis,
- Land Allocation.

Figure 2 shows the basic functioning of a sub-module. The component **Demand Processing** is responsible for deriving country level demands from exogenously provided driver variables.

Suitability Analysis is carried out on the micro-level. A Multi-Criteria-Analysis (MCA) is used to generate suitability values for each land use type the sub-module is associated with, based on a set

$$suit = \sum_{i=1}^{n} w_i p_i \times \prod_{j=1}^{m} c_j \qquad \text{(Eq.1)}$$

of local cell properties (factors).

We adapted and modified the MCA-method developed by Eastman et al. (1995). It consists of two terms (Eq.1). The first term is the sum of weighted factors that contribute to the suitability for a particular land use type. The factor-weight (w) determines the importance of the single factor (p) in the analysis. The sum of the weights equals one. As a pre-requisite, the factors of the first term are standardised by applying value functions (Geneletti, 2004). For this purpose, LandShift provides a wide variety of functional relationships. Figure 3 shows an example of a value function for the factor slope.

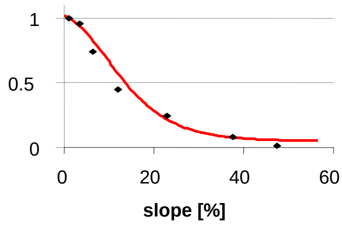

Figure 3. Value function for the factor slope

The set of relevant factors, the types of value functions and the factor weights can be gained either by a data-driven procedure, e.g. by means of geo-statistical analysis or by expert knowledge. Here, tools like the Analytical Hierarchy Process (AHP) can be applied to formalize the process of knowledge acquisition. The second term of Eq.1 represents land use constraints that are connected by multiplication. While the original approach is limited to Boolean values, LandShift permits standard values from 0 to 1. This allows for considering the degree of implementation of a constraint, e.g. the degree of achieved protection of a national park from further settlement activities. Another important constraint is "convertibility" that specifies to which other types a particular land use type can be converted.

All the components of the MCA analysis (factors, weights, constraints) are defined on country level and are implemented as time-dependent variables to represent changing environmental and political boundary conditions during the simulation period. Nevertheless, the simulation experiment presented in section 3 starts with very simplistic uniform assumptions for all African countries. The AGRO sub-module for example regards the three factors local crop yield (generated by the crop production module), slope, and proximity to settlement to compute a cell's suitability for each crop type. The value functions are strictly linear and weights are assumed as equal for each factor. Constraints include convertibility and protected areas.

Land Allocation assigns the demand for a commodity or service to the micro-level grid cells with the highest suitability for the associated land use type. For this task, METRO implements a strictly rule-based algorithm (Schaldach and Alcamo, in press) while AGRO formulates a "compromise solution"-problem for handling competition between the different crop types. Here a modified MOLA (Multi Objective Land Allocation) heuristic for the spatial allocation is implemented (Eastman et al., 1995). The MOLA algorithm is modified in two ways. Firstly, instead of a given area, it allocates the country level crop demand. Secondly, conflicts are resolved not only by preferring the land use type with its suitability value closest to the ideal point but also by seeking pattern stability. The productivity P of a grid cell c at time step t for a particular crop type is defined by its production function (Eq.2):

$$P_{tc} = base * tech_t * (Y_{tc} * Area_{tc}) \quad \text{(Eq.2)}$$

Y is the local yield in time step t as generated by the crop productivity module. *Area* is the cell area in km^2 corrected by the share of settlement. The variable *tech* marks the influence of technological change on crop yields. In our Africa study it is provided as a scenario variable. The factor *base* is needed for calibration purposes and serves as a proxy for management intensity. Our current studies aim at a more detailed representation of the crop production by explicitly considering the effect of different levels of management intensity (irrigation, multi-cropping) on cell level yields.

In a similar way, the GRASS sub-module uses data on grassland Net Primary Production (NPP) in the allocation process.

2.4 Productivity modules

The responsibility to generate yield and NPP data lies in the domain of the crop productivity and grassland productivity modules. They compute data for two time slices: climate normal (1961 – 1990) as baseline and future climate, in order to address climate change impacts on crop yields and NPP. Furthermore, crop yield simulations use identical country-level crop management data for both time slices. The impact of technological development on crop yield is considered in the local production functions (see above). The values for each simulation step between these time slices are calculated by linear interpolation.

The core of both productivity modules is a modified version of the agro-ecosystem model DayCent (Parton et al., 1998), which implements a detailed representation of plant phenology, soil water fluxes, soil carbon dynamics and nutrient pool dynamics.

Originally being a site level model, a grid version of DayCent has been developed to compute yield and grassland NPP on the intermediate scale level (Stehfest, 2005). The model has been calibrated against yield data on country-level under climate normal conditions for wheat, maize, rice, soybeans, roots and tubers as well as pulses and cotton. Simulation results indicate that the DayCent model is able to reproduce the major effects of climate, soil and management on crop yields.

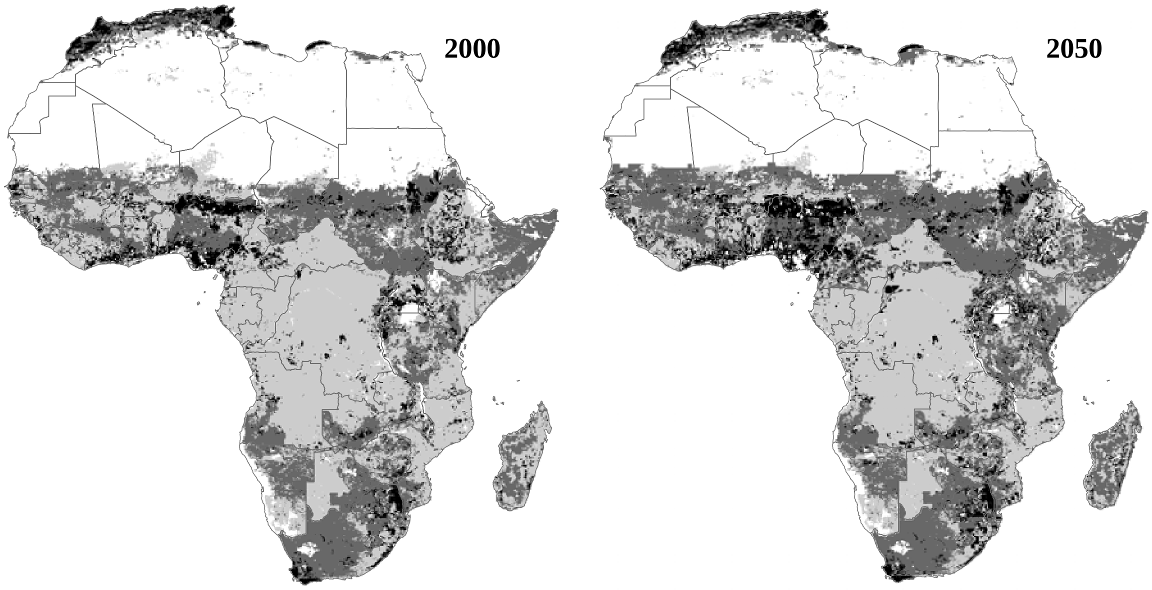

Figure 4. LandShift model output: agricultural area (black), pasture (dark gray) and natural/semi-natural land (light gray)

3. SIMULATION EXPERIMENT

3.1 Study Set-up

The first application of LandShift is on continental scale for Africa in the context of the UNEP Global Environmental Outlook 4 (GEO-4). In the presented pre-study, we use scenario data from the Millennium Ecosystem Assessment to perform first simulation experiments. According to the aims of the GEO-4 exercise the scenario horizon of the study is the year 2050 while the base year is 2000.

We chose the MEA “Order from Strength” scenario that represents “a regionalized approach, in which our emphasis is on security and economic growth, again reacting to ecosystem problems only as they arise“ (MEA, 2005). The scenario assumes a population growth in Africa from about 800 million people in 2000 to more than 1.9 billion in 2050. This leads to a large increase of crop and livestock production where part of the increasing crop production is achieved by intensification.

Country level scenario drivers cover the settlement (population) and agricultural sector. Data of crop production and livestock products as well as assumptions on crop yield increase due to advances in the agricultural management practice are derived from model output, generated by the agro-economic model IMPACT (Rosegrant et al., 2002). The demands of spatial data to perform DayCent simulations are described in detail by Stehfest (2005). Climate data for the decade 2041 – 2050 has been derived from GCM simulation runs performed for the MEA.

The most important input data for the LUC-module cover a land use map (Heistermann et al., submitted) as well as information on population density (CIESIN, 2004) and slope (USDA, 1998) and protected areas (WDPA, 2004). These data describe the state during the mid of the 1990ies. Base year information for 2000 is computed from LandShift in a spin-up simulation step. Moreover, a strict conservation policy is assumed, i.e. land use in protected areas does not change.

3.2 Simulation Results

Figure 4 shows the simulation results. For visualization purposes land use types are aggregated to 3 classes. Crops are aggregated to the class agriculture. The second class includes pasture and grassland to provide livestock production while the third class is an aggregate of different types of natural vegetation including savannah and forests. The left map depicts the base year 2000, the right map the end point of the simulation 2050.

Although the results are of a very preliminary character, the generated maps indicate three main directions of development. (1) Despite the assumed efforts of intensification, the cropping area as well as the area that is designated to pasture has to expand to fulfill the given demands.

(2) This process of expansion occurs at the cost of the extent of natural vegetation leading to an area decrease of almost 20%. (3) In the Sub-Saharan countries, the pressure of growing livestock population leads to an expansion of pasture further northwards, into regions with even higher risks of draughts.

4. CONCLUSIONS

Result of our ongoing work is the prototype of LandShift. In a first simulation experiment for Africa we could demonstrate how it can be applied as a tool to analyse lands use change and its impacts on the environment on continental level.

A major improvement of LandShift compared to other global models is the leap forward to a finer spatial resolution both of the micro-level (5 arc-minutes) and on the macro-level (countries). This allows a more detailed analysis of the temporal development of land use pattern and thus opens new directions for environmental impact assessments, being conducted based on the generated maps. Beyond, the modular structure of LandShift and the scientifically well established methods for suitability assessment (MCA) and allocation (MOLA) improve the transparency of the simulation studies, as they support the communication of the internal functioning of the model to potential users.

Our further research focuses on three fields of action. First is the refinement of the methodological aspects of LandShift. Here a major issue is the inclusion of irrigation and a closer coupling to the WaterGap2 model. The second field covers questions of model testing while the third field aims at extending the ability for environmental impact assessment (e.g. soil erosion and biodiversity) by integrating additional models into the LandShift framework.

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