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An agent-based model for assessing effects of a Chinese PES programme on land-use change along with livelihood dynamics, and land degradation and restoration

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Abstract: Some Payment for Ecosystem Services (PES) programmes are designed to restore ecosystem services degraded by desertification, but evaluation of their effects are not straightforward because of complex human-environment systems (HES) in drylands. A PES system is used across China (the Sloping Land Conversion Programme, SLCP), including desertified regions. Previous research on SLCP indicated the lack of HES approaches to enable the integrated assessment of socio-ecological long-term effects of the programme. In particular, assessment was needed of: (1) multiple benefits, which cannot be positively correlated, including their cost-effectiveness, and (2) the effect of shifts in economic structure, particularly from agriculture to non-agriculture, to ensure socio-ecological sustainability after the programme ends. To address these challenges, a spatial agent-based land-use model was developed, named the Inner Mongolia Land Use Dynamic Simulator (IM-LUDAS). IM-LUDAS was empirically calibrated for a desertified region in northeast China. The model constitutes landscape agents with ecological attributes and sub-models of crop yield, land degradation, and land restoration and household agents having socio-economic attributes and land-use decision sub-models. The agents' interactions are regulated as per external policy settings to assess the complex effects and benefits of SLCP. The effectiveness of SLCP in economic structural changes is evaluated using an adaptive decision-making mechanism. Simulation experiments showed that IM-LUDAS can produce HES properties, such as cross-scale feedback loops, thereby providing new insights into the programme assessment, such as a negative externality of restoration benefits and weak facilitation of economic structural changes.

***Keywords**:* desertification; human-environment system; Inner Mongolia; multi-agent system; Sloping Land Conversion Programme

1 INTRODUCTION

Intensive agricultural land use is a principal cause of desertification; desertification degrades a wide range of ecosystem services such as food provision and soil protection, on which farmers' livelihoods depend. This interaction between farmers and desertification is part of a coupled human-environment system (HES) in drylands. Most desertification estimates have been made either by ecological or by socioeconomic factors on their own, but understanding the complexity of HES is a major challenge in desertification research [Reynolds et al., 2007; Scholz, 2011]. Although Payment for Ecosystem Services (PES) programmes have recently become key policy mechanisms to restore, protect, or enhance ecosystem services, evaluation of their effects are not straightforward because of the inherent complexity of the underlying HES.

In 1999, China launched a PES programme (the Sloping Land Conversion Programme, SLCP), which is one of the world's largest in terms of scale, payment, and duration. This programme is implemented across China including desertified regions. Under SLCP participating households convert their sloping or degraded cropland into tree plantations to restore soil and vegetation conditions, receiving a compensation payment for a maximum of 16 years. While SLCP is considered to have significant socio-ecological impacts, they are poorly understood because of the lack of integrated assessment frameworks [Liu et al., 2008]. This fixed-term PES programme may provide temporary conservation benefits, and subsequent programmes have been little considered [Chen et al., 2009]. Therefore, integrated long-term assessment of SLCP's effects is urgently needed to enable its modification and design of alternative programmes.

The following effects of SLCP are expected, and therefore a need to be assessed: (1) achieving multiple benefits such as the restoration of different ecosystem services and poverty alleviation, which cannot be positively correlated in a cost-effective way [Chen et al., 2010]; (2) facilitating shifts in economic structure, especially from agriculture to non-agriculture, to reduce reliance on vulnerable natural resources [Li et al., 2011], which can be also a proactive measure against future environmental degradation. Liu et al. [2008] indicated that the use of HES perspectives would help in understanding the complexity of impacts of SLCPs. For example, adaptation mechanisms in HES need to be understood to examine potential structural changes in the economy.

This study aimed to construct a spatial agent-based land-use model that represents a complex HES in drylands and enables the integrated long-term assessment of SLCP's effects. We empirically calibrated the model for an agro-pastoral area in northeast China, which is one of the most desertified and poorest regions in Inner Mongolia. In this paper, we describe the model, named Inner Mongolia Land Use Dynamic Simulator (IM-LUDAS), with an overview, design concepts, and details (ODD) protocol [Grimm et al., 2006]. Then, we demonstrate selected results of simulation experiments that show the operational capability of IM-LUDAS for assessing the long-term effects of current and hypothetical SLCP on land use/cover changes and dynamics of households' livelihoods, land degradation, and land restoration.

2 MODEL DEVELOPMENT

2.1 Study area

The study area was located in the central part of Naiman County, Inner Mongolia, China (42°55′N, 120°42′ E; approximately 360 m above sea level). This region is a temperate zone with a continental semi-arid monsoon climate; the mean annual precipitation is about 366 mm, and the mean annual temperature is about 6.8°C. The major ethnic groups are Han and Mongolian peoples. The study area consists of two Han villages where Han people are the majority of residents, and three Mongolian villages where Mongolian people are the majority of residents. SLCP is expected be implemented in this area from 2002 to 2017.

2.2 Model description with ODD protocol

IM-LUDAS was built using the framework of LUDAS [Le et al., 2008].

2.2.1 Purpose

The primary purpose of IM-LUDAS is to support policy decision-making in desertified regions of northeast China in order to prevent desertification and achieve sustainable livelihoods. The present IM-LUDAS specifically explores the long-term socio-ecological effects of the current and hypothetical SLCP.

2.2.2 State variables and scales

IM-LUDAS consists of landscape agents (grid cells in the study landscape) and human agents (farming households). State variables of the landscape agents are ecological variables (e.g. land use/cover, topography, agricultural productivity, vegetation structure, and soil physiochemical properties), institutional variables (i.e. ownership, village territory, and SLCP protection zone), and land history. State variables of the household agents include socioeconomic attributes (e.g. ethnic group, labour force, educational level, income structure, and land holdings) and involvement in the SLCP. These states are classified into two types: static and dynamic variables. Static variables do not change over time (e.g. topography and village code), whereas the dynamic variables are changed by natural processes (e.g. age and vegetation under succession) or by anthropogenic processes (e.g. income and vegetation under land use). The landscape agents constitute the landholdings of the corresponding household agents; the landholdings and household agents constitute village landscapes and populations, respectively; the whole study area is the highest aggregate level of both agents. The area modelled is represented in a grid of approximately 700 x 1000 cells. Each cell represents 15 x 15 m. A simulation is composed of 30 annual cycles that are from 2009 to 2038.

2.2.3 Process overview and scheduling

IM-LUDAS proceeds in annual time steps. This annual process can be described as eleven steps from initialization to output (Figure 1). The current version of IM-LUDAS is coded with NetLogo 4.1.3 [Wilensky, 1999].

2.2.4 Design concepts

Emergence: All landscape and livelihood changes at every aggregate level emerge from two interrelated agent-based processes: (1) land-use conversion by each household agent; (2) land degradation or restoration occurred in each landscape agent. Macro changes generated by the agents' interactions can create new opportunities or constraints for the agent-based processes, thus forming cross-scale feedback loops.

Adaptation: IM-LUDAS includes landscape and human adaptation mechanisms at two levels. At a primary (reactive and short-term) level, landscape agents adapt to their current land-use, topographic, and ecological conditions by performing corresponding ecological sub-models. Household agents adapt to their current socioeconomic and land (e.g. topographic and ecological) conditions by choosing the best land use in the best location in terms of utility. At a secondary (accumulative and longer-term) level, both landscape and household agents can shift their internal mechanisms in response to qualitative (major) changes in the socio-ecological conditions. If land use/cover types are converted into another type, the landscape agents shift the ecological sub-models accordingly. Following major changes in the pattern of household livelihood assets, the household agents can

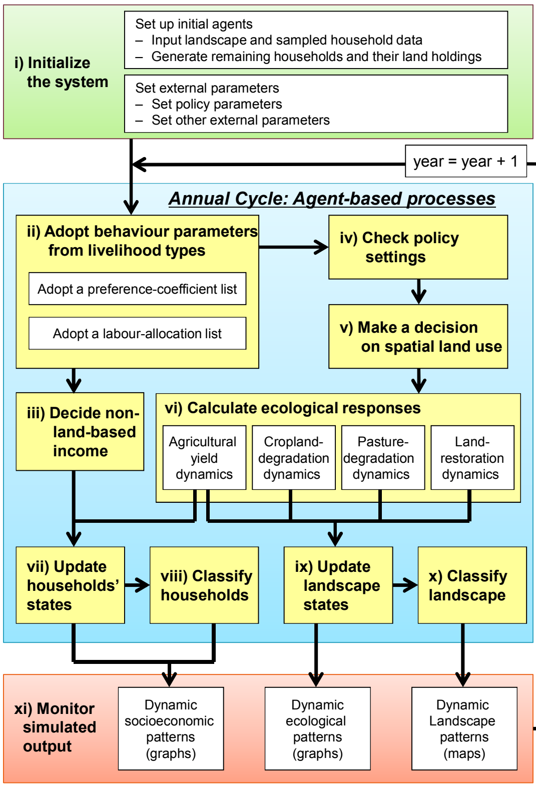

Figure 1. Simulation processes of IM-LUDAS consisting of eleven main steps.

shift their livelihood strategy (i.e. a set of labour-allocation rules and preference coefficients in land-use decision sub-models) on the basis of an imitative learning process [Le et al., 2012].

Fitness: Goal-seeking is explicitly modelled in household' land-use decision, in which households calculate utilities (expressed as a probability term) for all land-use and location candidates, and select the candidate with the highest utility. Some household agents, however, may not select the best land-use or location because bounded rational decision-making is made in IM-LUDAS using an ordered choice algorithm [Le et al., 2008].

Sensing: Household agents sense (i.e. detect) and consider land-cover types, which can change with changing vegetation and soil states, topography, and accessibility (i.e. distance between their houses and each plot) in their land-use decision-making.

Stochasticity: IM-LUDAS uses stochasticity to initialize household population and landholdings, and to determine the coefficients of the ecological sub-models and land-use decision sub-models. It is also used to set some state variables not affected by the agent-based processes (all defined by uniform distribution and predefined bounds).

Observation: Outputs include annually updated maps of land-use/cover and graphs which show temporal changes in land-use/cover, income (mean, composition, and equality), cost of SLCP (sum of compensation payments), households' livelihood types (corresponding to distinct livelihood strategies), and ecological properties (plant species compositions and diversity and soil physiochemical properties) at two aggregate levels, i.e. the study area and each village. Such parameters calculated for each livelihood type, or any subsets of landscape and population with user-defined criteria, can be easily gauged.

2.2.5 Initialization

The initial landscape is given by importing GIS raster data, i.e. land-use, topography, and village boundary maps, which were produced by separate spatial analyses. The initialization of the household population consists of the following steps. 1. Data on sampled households (Ns) are imported, and users set the size of the total population (Nt). 2. The total population is generated by the following equation: Nt = Ns × int (Nt / Ns) + mod (Nt / Ns), where int (Nt / Ns) is the integer part of the ratio Nt / Ns and mod (Nt / Ns) is the remainder. Assuming that the samples (Ns) and the total population (Nt) have the same distributions of the state variables, the majority is generated by the equation Ns × int (Nt / Ns). The minority mod (Nt / Ns) is generated by randomly selecting households from the samples (Ns). 3. The creation of landholdings of the newly generated households uses spatially bounded random rules. Given a state variable representing the number of land plots (with explicit land-use types) of the generated households, the corresponding locations of such plots are randomly determined among the pixels bounded by the household's village territory and the corresponding land-use type.

2.2.6 Input

Input for simulations can be classified into two types: data and parameters. The data consists of GIS and sampled household data in the form of text to initialize the landscape and human population. All data were collected and processed by household surveys or remote sensing and GIS analyses in our empirical studies [Miyasaka, 2012]. The parameters can be broken into calibrated and users' defined parameters. Most calibrated parameters are coefficients of sub-models representing the livelihood strategies and ecological dynamics. These parameters were calibrated and validated from field studies [Miyasaka et al., 2011; Miyasaka, 2012]. The input parameters set by users mainly relate to policy, enabling users to test their own questions on SLCP such as its cost-effectiveness; users can set the parameters of an ecological criterion for selecting target plots, an economic criterion for selecting target households, the amount of a payment, implementation periods, and actual enforceability of the programme (a certain amount of tree plantations might be logged or reconverted to cropland).

2.2.7 Sub-models

Main sub-models and procedures are summarized in Table 1. Their details are described in Le et al. [2008] and Miyasaka [2012].

Table 1. Main sub-models and procedures of IM-LUDAS.

Name	Brief description	Agent
Initialization	Import GIS and sampled household data, generate the remaining households and their landholdings, and create household-pixel links	Landscape Household
SetLabourBudget	Annually define the labour allocation of each household	Household
DefineNewProtectionZone	Annually define participants and plots of Sloping Land Conversion Programme	Landscape Household
LandUseChoice	Annually perform bounded-rational land-use choices	Landscape Household
AgriculturalYieldDynamics	Annually calculate yields of cropland in response to different cropland types and topography	Landscape
CroplandDegradationDynamics	Annually calculate vegetation and soil properties in response to different cropland types and topography	Landscape
CalculateGrazingPressure	Annually calculate grazing pressure in response to the area of pastureland and the number of livestock	Landscape Household
PastureDegradationDynamics	Annually calculate vegetation and soil properties in response to grazing pressure and topography	Landscape
LandRestorationDynamics	Annually calculate vegetation and soil properties in response to different restoration measures and topography	Landscape
GenerateSubsidy	Annually calculate compensation payment that participants receive	Landscape Household
GenerateOtherIncome	Annually calculate non-land-based income	Household
UpdateHouseholdState	Annually update household profiles	Landscape Household
AgentCategorizer	Annually categorize households into the most similar livelihood types	Household

2.3 Model validation

We tested IM-LUDAS using a multi-criteria approach with reference to Le et al. (2010, 2012): (1) rational evaluation of model structure by expert opinions (construct validity), (2) empirical validation of sub-models by inferential statistics (internal validity), and (3) behavioural test of model output by sensitivity/uncertainty analyses (output robustness).

3 SIMULATION RESULTS

3.1 Socio-ecological long-term effects of SLCP in the study area

Figure 2a shows temporal changes in the area of shifting sand dunes under the status quo SLCP scenario (S0) and an altered SLCP scenario in which massive cropland conversion was facilitated (S1). A time lag is shown in Figure 2a: the area of shifting sand dunes under S1 gradually became higher than that under S0 over time. Since shifting sand dunes are formed with vegetation and soil degradation, and cannot be used for any production activities, their expansion indicates the loss of ecosystem services. This result would reflect the following process: a continuous increase of tree plantations facilitated by the intensive SLCP (S1) can gradually decrease pastureland area and increase grazing pressure around the plantations. Figure 2b illustrates this process spatially. Although vegetation and soil properties within the tree plantations were ameliorated, this intensive SLCP can also have the negative externality outside the target plots.

Figure 3b shows changes in the household number of each livelihood type. While economic structural changes hardly occurred in S0, the number of households who changed their livelihood strategies in S1 was also low (about 20 households), considering about 200 households eventually participated in the programme during a simulation. Households' income dropped eight years after starting the simulation, i.e. when SLCP ended, only in S1 (Figure 3a). These results showed that most of the participants did not find alternative income sources, tended not to re-cultivate because of a logging ban, and that their income then decreased after the compensation stopped. The livelihood strategies are determined by households' multiple attributes in IM-LUDAS as in reality, but SLCP cannot directly affect possibly key attributes such as ethnicity and education levels. This implies that implementing only SLCP cannot be enough to facilitate economic structural changes; other policies, such as educational programmes, could be effective.

3.2 Socio-ecological long-term effects of SLCP in single villages

The expansion of shifting sand dunes occurred in a Mongolian village, where all pastureland was distributed to each household, but not in a Han village, where all pastureland was communally used (Figure 4). This result indicated that grazing pressure increased only in the landholdings of the participants in the Mongolian village,

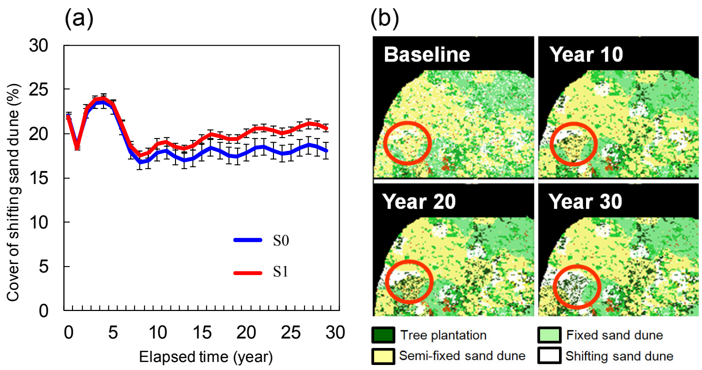

Figure 2. Changes in the area of shifting sand dunes in the study area under scenarios 0 (S0) and 1 (S1) (a) and subset images of their spatial patterns under S1 (b). Vertical bars indicate the confidence intervals of the mean values (95%, n = 9), and red circles highlight the land-use process described in Section 3.1.

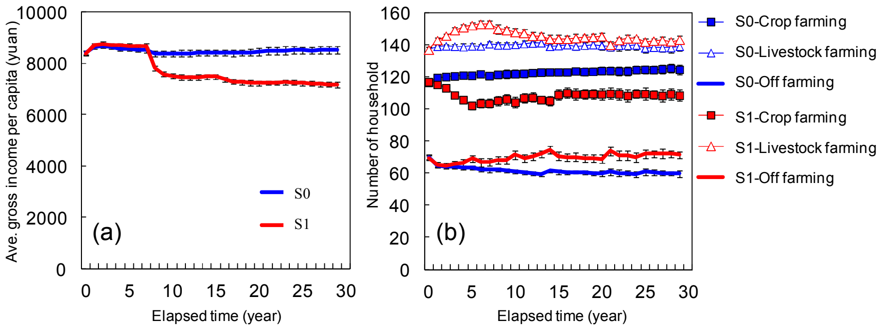

Figure 3. Changes in average gross income under scenarios 0 (S0) and 1 (S1) (a) and the household number of each livelihood type (b) in the whole study area. Vertical bars indicate the confidence intervals of the mean values (95%, n = 9).

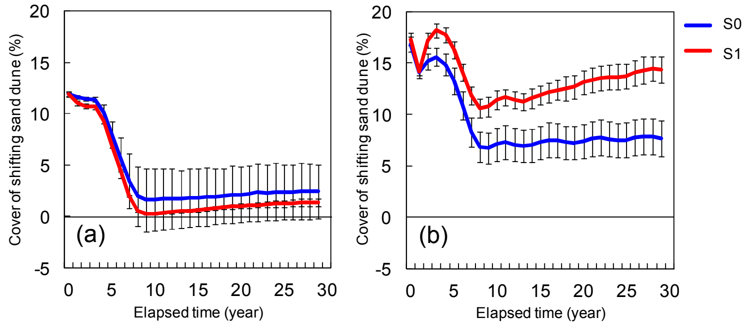

Figure 4. Changes in the area of shifting sand dunes in a Han village (a) and in a Mongolian village (b), under scenarios 0 (S0) and 1 (S1). Vertical bars indicate the confidence intervals of the mean values (95%, n = 9).

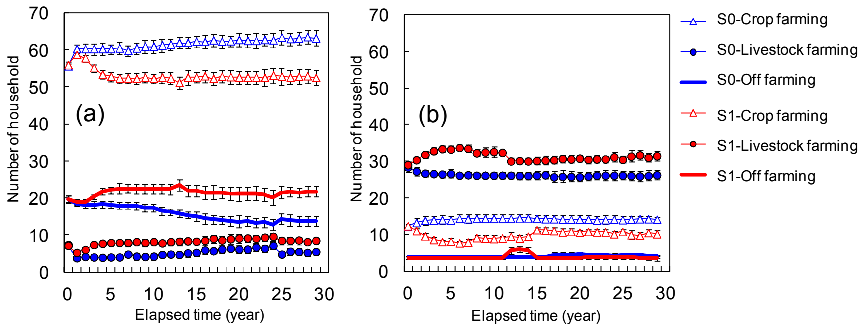

Figure 5. Changes in the household number of each livelihood type in a Han village (a) and in a Mongolian village (b), under scenarios 0 (S0) and 1 (S1). Vertical bars indicate the confidence intervals of the mean values (95%, n = 9).

whereas the increased pressure dispersed across the whole communal pastureland in the Han village, which was an effect of cross-scale feedback loops.

Figure 5 shows that patterns of change in households' livelihood strategy differed between the Han and Mongolian villages. Han people mainly shifted from crop-farming to off-farming, whereas Mongolian people tended to shift from crop-farming to livestock-farming. This indicates that ethnicity is an important factor in deciding economic structure and also supports the abovementioned result that multiple factors should be considered to change economic structure.

4 CONCLUSION

IM-LUDAS is one of the first spatially-explicit models that represent a complex HES in drylands. The simulation results indicates that the model can produce key properties of HES, such as a time lag and cross-scale feedback loop, and thereby provide information to interpret and assess the effects of SLCP's, such as a negative externality and weak facilitation of economic structural changes. Although this paper shows only selected results, IM-LUDAS can assess various scenarios on SLCP as a decision-support system, e.g. cost-effective targeting scenarios based on heterogeneity of landscape and households. IM-LUDAS was empirically built on the basis of our socio-ecological studies, but empirical studies focusing on many factors consisting of the actual HES are still lacking. IM-LUDAS could be used as a base model to integrate the future empirical research with its agent-based structure having a built-in flexibility for upgrading and modifications.

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