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A GIS Based Integrated Land Use/Cover Change Model to Study Agricultural and Urban Land Use Changes

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ABSTRACT: Land use and land cover is an important component in understanding the interactions of the human activities with the environment and thus it is necessary to be able to simulate such changes. The authors have developed a national scale, integrated, dynamic time-series simulation model called the ‘Anthropogenically Engineered Transformations of Land Use and Land Cover’ (AGENT-LUC) Model, which simulates two major land uses that are influenced by humankind – agricultural and urban land uses. The land use transformations are a result of the interaction of the biophysical drivers and human drivers. It applies the concept of the presence of an “agent” as the decision-maker based on the information available to it at a particular point in time and space, in simulating the land use/cover changes. In the process of development of this model, a new spatial model for population growth and changes has also been developed, which has shown that the land use conditions is a major contributing factor in the migratory tendencies. Model outputs are the changes in the cropping pattern of the agricultural land area, the expansion of the agricultural lands, rural-urban migrations and the spread of the urban areas. The model was applied to the Royal Kingdom of Thailand, at a decadal time step and the spatial and temporal results will be presented in the paper. The changes are simulated annually and the entire process is carried out on a grid (1km square) basis.

1. INTRODUCTION

Global change studies are based on a wide variety of information and one of the important components of it is the spatial and temporal distribution of land use and land cover. Data from remote sensing helps us to monitor the current state and changes to the land cover but future estimates of change are hard to tell. To have some reliable information on the land use/cover and an understanding of the changes that occur within them, it is necessary to model these changes to provide for a time-series data of land use/cover. In modelling land use/cover changes realistically, we need to consider the scale of analysis of such changes, as some changes at a particular scale may act as drivers at a different scale. It is recognized that changes in the scale of analysis, changes the results (Alcamo et al., 1994, Robinson, 1994). The model should also take into account the changes in both the biophysical characteristics and socio-economic conditions that propel such actions. At present, the global models and studies of land use changes capture the broad sectoral trends based on the changes in some of the macro variables, like population, quality of life and technology level. The statistical data shows a strong support in concluding that these variables may be the underlying drivers of environmental changes (Bilsborrow et al., 1992). Nevertheless, studies at the local level suggest the existence of other factors too, such as the farmers’ preferences to certain crops, relative desirability aspects, migratory tendencies, topographical conditions and changing local economic structures (Fukui, 1993).

The transformations in the land cover, occurring at on the large scale will lead to large-scale changes in the "global environment". These changes are complex and require analysis to be done at various other scales to put together the big picture. It is good to start at the national scale, as the assumption of uniformity in modelling approach within the national boundaries, does not lead to erroneous conditions vis-à-vis the various variables/parameters used in such a model. The following sections will describe the model structure of AGENT-LUC and its application to simulate the changes to the cropping pattern, rural-urban migrations and expansion of urban areas.

2. AGENT-LUC MODEL

Modelling of land use/cover and its changes depend on the possible causes of change, which can be broadly set into two groups – the biophysical conditions of the land unit and the prevailing economic conditions at a given location and time. But in order to be able to estimate the change mechanisms that may reflect some of the local process, it is necessary to look at the human ability to comprehend this information and then decision that follows from it. The model developed here simulates the land use/cover changes, as a result of the decision made by the “agent” of the land unit. The “agent” is the representative of the grid under consideration. The decision-making process of the agent is autonomous in deciding the next course of action based on the information available to him, from both the worlds of micro and macro-information, at a particular point in time and space. It takes into consideration the prevailing bio-physical characteristics of the land, the economic condition, and the land use history along with the existing social apparatus (demographic pattern) in a given year, for arriving at the choice of the annual land use. As a large amount of datasets is needed to be managed and processed for such a model, GIS was extensively used as the platform for managing and visualizing both the input and output data. The changes are simulated annually and the entire process is carried out on a grid (1km square) basis and is aggregated at the different scales – from the local grid to provincial level and finally at the national level, to analyse and compare the results with the prevailing macro-condition.

At the grid-level, the model assesses the potential and real supportability of each grid. For agricultural crops, the productivity is calculated at the grid-level, considering the local bio-physical characteristics. The bio-physical attributes considered here, are the climate (temperature, rain and radiation) and soil properties, along with water and nutrient stresses to agricultural productivity. The non-spatial, statistical data considered in the model at the administrative boundary levels is referred to as macro information. This information helps to build the rural economic structure in the model and is used to compare and adjust the model simulations, to arrive at realistic cause-effect relationships within the model. The macro-data considered are total agricultural demand and supply in a given year, the GNP per capita changes, the contribution of the agricultural and non-agricultural sectors to GNP, and population distributions at the National and sub-national levels. These data are recalculated on an annual basis within some of the sub-models to keep the continuity of the changes taking place, like combining the migration sub-model outputs with the population and education level distributions. In addition to the above data, the experience of different researchers in arriving at qualitative conclusions on the land use practices in the different regions of the study area are also considered in charting out the behavioural patterns of the agents.
The overall framework of the model is given below, in Figure 1. The model consists of four models - the bio-physical crop yield model, the rural income model, the urban land use model and the agent decision model. All these four models interact and have feedback loops, to determine the new course of action by the agent at the next time step. The model structure is sequential and the model calculations are carried out on a land unit basis, at a level of 1km square grids.

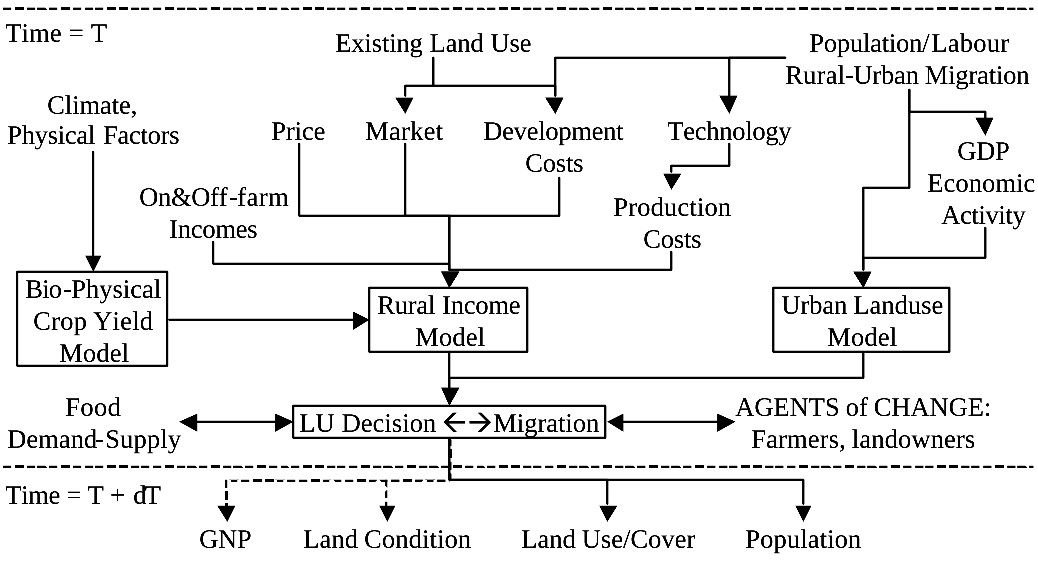


Figure 1. Framework of the AGENT-LUC Model

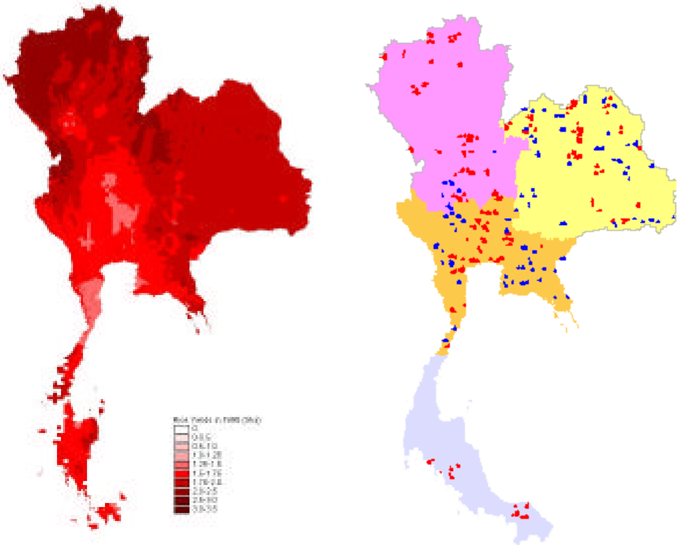
3. AGRICULTURAL LAND USE/COVER

Agricultural land use changes in the model are brought about by the *agent* by considering the economic potential of the agricultural yields and the perceived risk for change with respect to the competing demands from other land uses. The major components that influence the decision are described in this section.

3.1 Biophysical Crop Model

The biophysical crop model is a spatial model that calculates the biomass and yield of the crop at each of the land grids. It is based on the approach as enumerated in the EPIC (Erosion/Productivity Impact Calculator) model (Sharpley, et al., 1990) developed at USDA. EPIC is a point-based (a given farm, with no spatial correlation) model.

But as most of our calculations are on a raster/grid system and our main focus is in getting reliable agricultural yields, we adopted only the concepts and mathematical relationships used to simulate the plant growth component. The biomass and yield calculations are carried out on a day-to-day basis and the final yield takes into effect the fluctuations in water and nutrient availability. It has been shown that EPIC performed well in predicting crop yields and runoff in humid regions (Williams, 1985), whereas showed that it was also fairly acceptable in the simulation of the dry land agricultural systems (Steiner et al., 1990). The spatial yield distribution of paddy crop, calculated by the model, in Thailand is shown in Figure.2 (a) and Figure.2 (b) shows the sample village points for which data was collected to verify the model results.



(a) (b)

Figure.2. (a) Spatial yield distribution of paddy crop in Thailand;
and (b) Sample villages for paddy and cassava yields

3.2 Rural Income Model

An income estimation sub-model estimates the income per land unit from various agricultural and non-agricultural sources for people primarily resident in agricultural areas including the yield-related revenue and the cost of production. The model also accounts for the initial cost incurred in land conversion from other uses to agricultural lands. The other incomes are considered in the model as the non-yield-on-farm income like poultry and dairy farming, and the off-farm income consisting of possible incomes during the off-season. These factors influence the decision making process, in case of fluctuating agricultural revenues from a given unit of the land. The model uses the farmgate prices of the crops to calculate the agricultural revenue and is inherent to understanding the effect of the guiding principle. In addition, based on the demand and supply calculations after the model draws up the annual landuse map, the price are simulated within the model. The changes in the price lead to changes in the attractiveness of the concerned crop within the model and are considered as one of the driving forces for the intra-agricultural land use changes to occur.

3.3 Demand for New lands

The demand for new agricultural lands are calculated based on the demand for the seven major agricultural crops, in case of Thailand. Sugarcane and Cassava are used to represent the cash crops, while Paddy, Maize, Sorghum, Soybean and Mungbean are considered as the major crops. The demand also considers the reduction in the land supply due to changes to other land uses.

4. URBAN LAND USE/COVER

A simplified urban land expansion model has been adopted to understand its spread, due to changes in the population – natural growth rate of the population, readjustment in the urban population, and the rural-urban migrations that take place; and economic levels of these areas. The population figures are obtained from the migration sub-model and the changes in population density are used as the main factor in determining the demand for new urban lands. The model calculates the expansion needs of each city individually. The land allocation is done using the neighbourhood and accessibility of the land-unit. The model assumes that all the extra land needed for the urban areas in a given year is fulfilled in the next year. The model provides information on the urban land demand and supply, on a spatial basis.

5. DEMOGRAPHIC CHANGES

Population changes on an annual basis are tracked, to provide information on the demands they generate in the various sectors. The population at any given location can be considered as a sum of its natural growth rate and the migration tendencies. We have adopted the following simple population growth model –

$P_t = P_o\ e^{(\mu/\omega)(e\omega t - 1)}$, where μ is the national or sub-national population growth rate at initial time reference t_0 and ω is the exponential decreasing rate of national or sub-national population growth.

It is assumed that the national population growth rate can be uniformly applied for the entire country in the absence of any detailed information at the individual grid levels. The other changes to the grid population is brought about in the migration sub-model.

6. AGENT DECISION MODEL

This model constitutes the most important part of the entire modelling framework. There are two major decisions that the agent can make – (i) change in the land use; and (ii) changes to population in the grid. It can be described as a rule based model that takes into account the results from all the other models and sub-models, compares it with their preceding values and/or the expected benefits thereof, along with the local conditions and preferences to analyse the information and make a decision on - (i) whether to continue the current land use or undergo a change; or (ii) relocate some of the population and drive land use changes in the subsequent time frame. So, this model compares both the spatial information and their aggregated values to arrive at a decision. The factors considered by the "agent", the decision maker in this model, are the grid-specific economic factor, the demographic condition (age distribution and educational levels) and the land use history. In addition to the land use change decision, the model has a migration sub-model that simulates the changes in the population of each grid as a consequence of the changes in the economic welfare and the demographic distribution that exists in the grid.

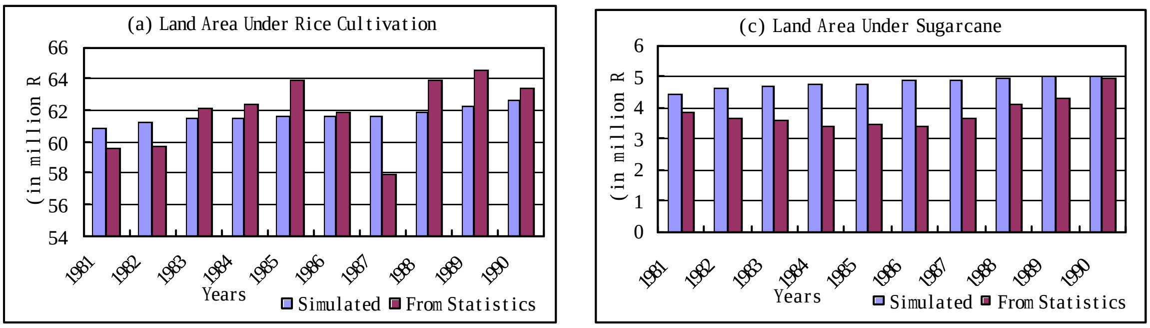
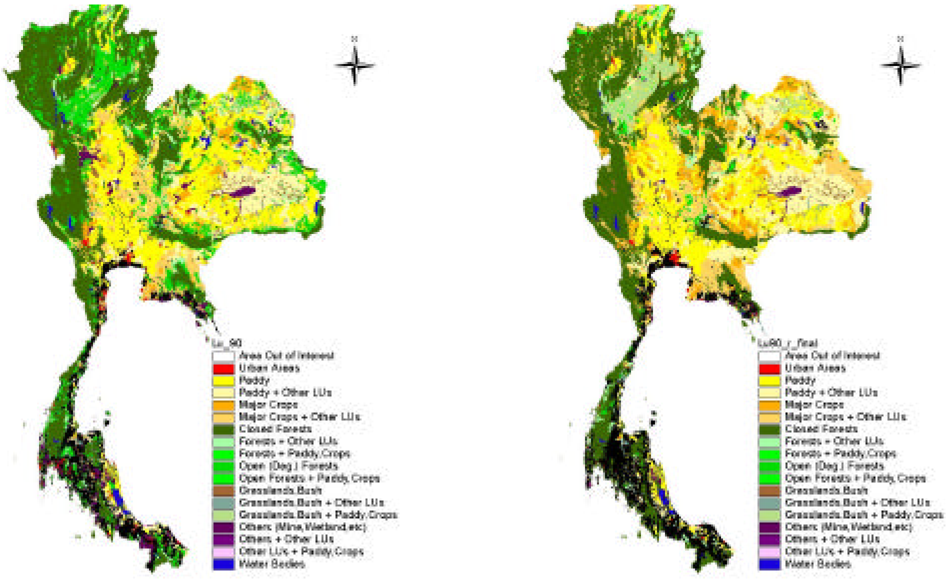


Figure 3. Graphs showing the comparison of the statistical data with the annual Model outputs for the total land Area under Rice; and (b) Sugarcane

6.1 Land Use Change

We use the 'profit maximization' as the guiding principle along with a minimization of risk to help in deciding the land use for a given land unit. As fluctuations in income over a short time frame is quite natural, we prescribe an income range, instead of a single value comparison, to determine the shifts. The age distribution and educational levels of the population in the respective grids are used to derive the behavioural patterns that are liable to influence the decision making process. Also, the model takes into account the external influences that are likely to effect shifts in the agricultural patterns and these are exogenous variables for the model. The model outputs annual changes in the land use, mainly of the seven major crop areas under agricultural land use and changes in the urban landuse. Figure 3 shows the comparison of the statistical data with the annual Model outputs for the total land Area under Rice and Sugarcane. It can be seen, that the model outputs follow the general trend of the changes in the total land area under the different crops. But, is still inadequate in explaining some sudden changes in the land area, as seen from Figure 3(a) for the year 1987. This can be partially explained due to the drop in prices in 1986 for paddy. Similarly in case of sugarcane, a cash crop, it can be possible that the factors for the contraction and expansion of the crop are not very clearly enumerated and hence the mismatch between the two values. This indicates that there is a need to make the decision model a little more broad based to include factors such as irrigation or water availability that might play a major role.

The model outputs a landuse map at the end of each year. This helps the model to keep a record of the land use history and at the same time provide a time series data of landuse changes. Figure 4 shows the simulated land use map and the actual land use map of 1990, for comparison. As the current model doesn't account for changes in the forest land use, other than its conversion to agricultural land use, there seems to be regions of landuse that the model cannot explain at this stage.



(a) (b)

Figure 4. (a) Shows the Simulated Land Use Map of Thailand in 1990 based on the model simulation run from 1980-90; and (b) the Existing Land Use Map of Thailand in 1990.

6.2 Migration Sub-Model

The populations are both a cause to population changes and also affected by them. In case of developing new areas for development, they accompany the changes in the land use. But, for increasing populations with limited incomes and due to the limits to the existing land use, they respond by migrating out to already established areas like urban centers. The changes in population are calculated based on the per capita income changes subjected to a maximum population density, along with the data on its current age distribution and the educational levels. This sub-model gives out a migration map at the end of each year, which is then used to calculate the population distribution map.

Urban Migration: The model results for Urban out migration are dependent on the rural to urban migration and the natural population growth rate of the urban area. As there is an increase in population pressure in the existing urban grids, the density readjustment occurs leading to an out migration of the population to the neighbouring grids around the existing urban areas. This out migration is always accompanied by a land use change decision to urban areas.

Rural Migration: The migrations of households to new grids (development) or partially agricultural grids that are accompanied by land use conversion to agricultural lands determine the rural migration.

7. DISCUSSIONS AND CONCLUSIONS

The major feature of the AGENT-LUC model is in characterizing the behavioural aspects of the "agent" in transforming each grid of the land unit. The model integrates both the micro-characteristics of the land unit like the biophysical conditions of the grid and also takes into account the macro features that are characterized at the administrative boundary levels. Figure 5 shows the micro-simulation of the model, the income structure of the rural economy. In Figure 5(a), it is observed that these grids have a substantial part, nearly 50% (in grids growing paddy and maize) to 66%(in grids growing maize), of their incomes coming from off-farm sources of income but grid no.4, growing paddy gets more than 50% of its income from agricultural revenue. This implies that, in spite of the profitability of growing paddy, the issue of availability of sufficient labour may be more predominant here and so, most of the other locations have moved to the maize crop, as a trade-off between keeping their agricultural revenues and the issue of labour availability. In contrast to this, we find from Figure 5(b), the primary source of income is the agricultural revenue and the land use in all these grids are Paddy. The contributions from off-farm income sources are of the order of 20% to 30%.

The detailed structure of the model provides us with various outputs that help in fine-tuning the model to the area of applicability based on the scale of the data that is available. The model structure is modular in nature, allowing for the model to be expanded as and when new knowledge on related systems get available, like a macro-economic trade model to give the export demand and prices of the international market or a forest land cove change model. The model developed here gives due importance to the location specific characteristics in addition to the socio-economic conditions, we hope the model results will be quite reliable to make decent projections on the change phenomenon. The main area of application of this model can be to derive spatially explicit land use and land cover data for use in the environmental models and policy assessments.

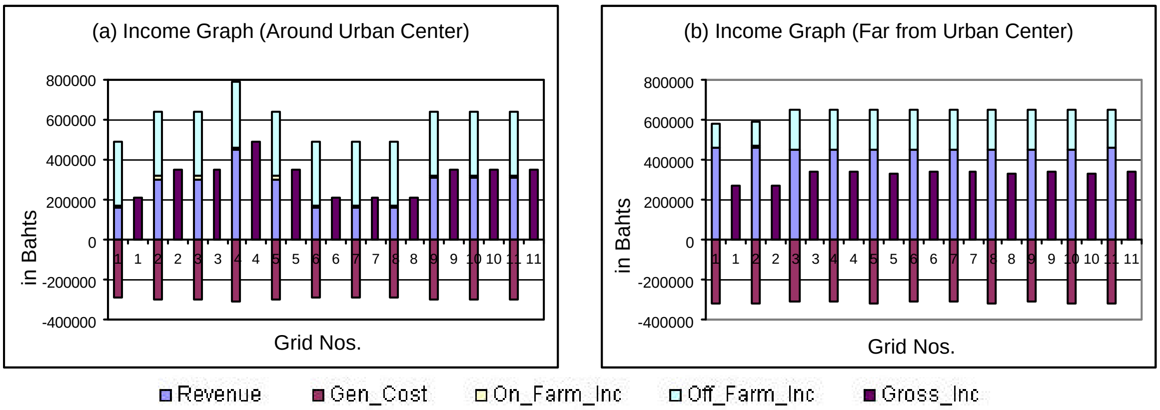


Figure 5. An example of the composition of rural economy in grids
(a) around the urban area; and (b) far from the urban area

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