A GIS BASED INTEGRATED LAND USE/COVER CHANGE MODEL TO STUDY HUMAN-LAND INTERACTIONS

K S RAJAN* and Ryosuke SHIBASAKI**
*Institute of Industrial Science, University of Tokyo, Japan
rajan@skl.iis.u-tokyo.ac.jp
** Center for Spatial Information Science, University of Tokyo, Japan
shiba@skl.iis.u-tokyo.ac.jp

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ABSTRACT

Land use and Land cover form an integral part of all modelling initiatives in case of global change studies and hence, there arises a need for time-series data of land use/cover. As such, we need suitable models to explain the changes in the land use patterns and the resulting land cover and also to forecast them. The model proposed here deals with the development and application of a new concept in simulating the land use/cover changes – the presence of an "agent" as the autonomous decision-maker. The biophysical characteristics of the specific lot of land (grid) and its economic potential (based on the macro-economic information) are considered within the existing demographic conditions at a given point in time, in arriving at the choice of the land use. The changes are simulated annually and the entire process is carried out on a grid (1km square) basis. The use of GIS platform and its tools has helped in analysing the micro-information (spatial) within the boundaries of the available macro-level (non-spatial) data. The model was developed and its application was tested to simulate the land use changes, for the period of 1980 to 1990, within the national boundaries of the Royal Kingdom of Thailand. As the model considers the agent behaviour explicitly and at the same time considers the different drivers to landuse, the model can also be used to understand the human responses to the changes in the environment.

1 INTRODUCTION

The spatial and temporal distribution of land use and land cover is very important in understanding a wide variety of global change phenomenon. Data from remote sensing helps us to monitor such changes but future estimates of change are hard to tell. As such, it is necessary to have reliable information on the land use/cover and an understanding of the changes that occur within them. So, there arises a need for time-series data of land use/cover. As such, we need suitable models to explain the changes in the land use patterns and the resulting land cover and also to forecast them. In modeling 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 be able to simulate land use/cover changes in response to changes in both the biophysical characteristics and socio-economic conditions. 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 and changes in land use driven by migrations within the national boundaries (Fukui, 1993).

The transformations in the land cover, occurring on the large scale will lead to large-scale changes in the "global environment". These changes are complex and require different scales of analysis. 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. Also, in order to get a complete picture of the land use changes, we need to account for the drivers based on both the micro-characteristics and the macro-economic scenario that exists.

The model proposed here deals with the development and application of a new concept in simulating the land use/cover changes – the presence of an "agent" as the decision-maker. 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. The biophysical characteristics of the specific lot of land (grid) and its economic potential (based on the macro-economic information) are considered within the existing demographic conditions at a given point in time, in arriving at the choice of the land use. 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. These kind of inter-scale comparison helps to develop a more realistic scenario of the land use changes. The use of GIS platform and its tools has helped in analysing the micro-information (spatial) within the boundaries of the available macro-level (non-spatial) data. The model was developed and its application was tested to simulate the land use changes, for the period of 1980 to 1990, within the national boundaries of the Royal Kingdom of Thailand. As the model considers the agent behaviour explicitly and at the same time considers the different drivers to landuse, the model can also be used to understand the human responses to the changes in the environment

2 AGENT-LUC MODEL

In order to model land use/cover changes under the assumption that it is influenced by both the biophysical conditions of the land unit and the prevailing economic conditions at a given location and time, it is necessary to estimate the change mechanisms that may reflect some of the local process. The human ability to comprehend and anticipate, with a limited risk assessment, needs to be considered in deriving land use/cover changes. The model proposed here deals with the development and application of a new concept, proposed by the authors, in simulating the land use/cover changes – the presence of an "*agent"* as the decision-maker. The agent decides on the next course of action based on the information available to him from both the worlds of macro and micro information. The decision making process 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. (see Figure 1.) 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.

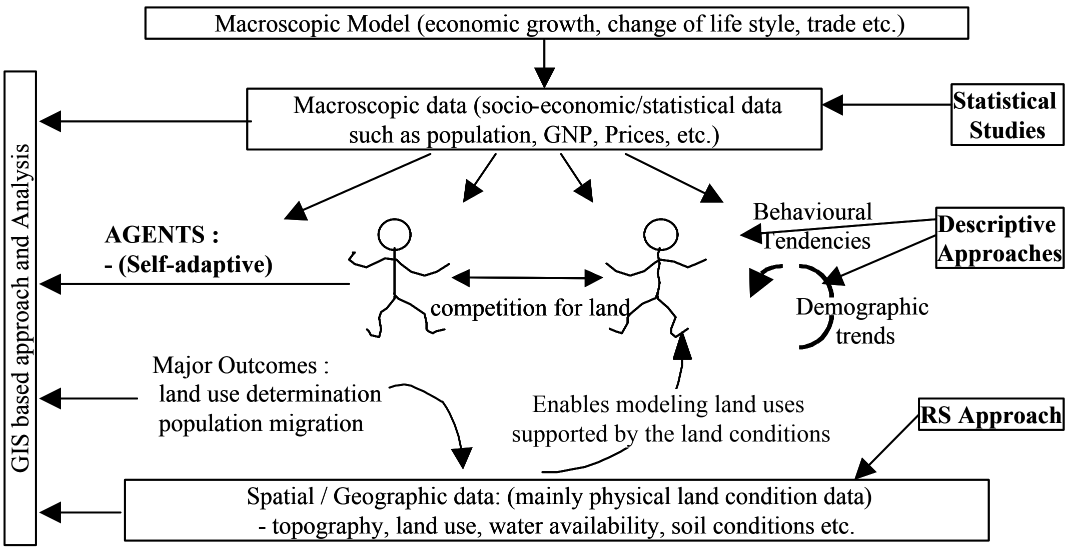


Figure 1. "Digital World of GIS": Agent-based Integration of Macro and Micro Information

2.1 Concept of an Agent.

Here, the term agent refers to an individual or a group of individuals who exist in a given area (referred to as grid) and are capable of making decisions for themselves (or the given area). The agent also acts as an interface in helping to assimilate the broader macro-information into the decision-making process at the grid level, thereby creating an action in response to the natural and economic stimuli.

In this paper, the term 'micro' refers to the data used at the grid level in assessing the supportability of each grid. The crop-specific 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 'world of macro' information refers to the data at the sub-national (regional or provincial) or national level. This data is mainly statistical in nature. It 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.

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.

2.2 Model Description

The overall framework of the model is given below, in Figure 2. 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 sub-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. The model calculations were carried out on a land unit basis, consisting of 1km square grids.

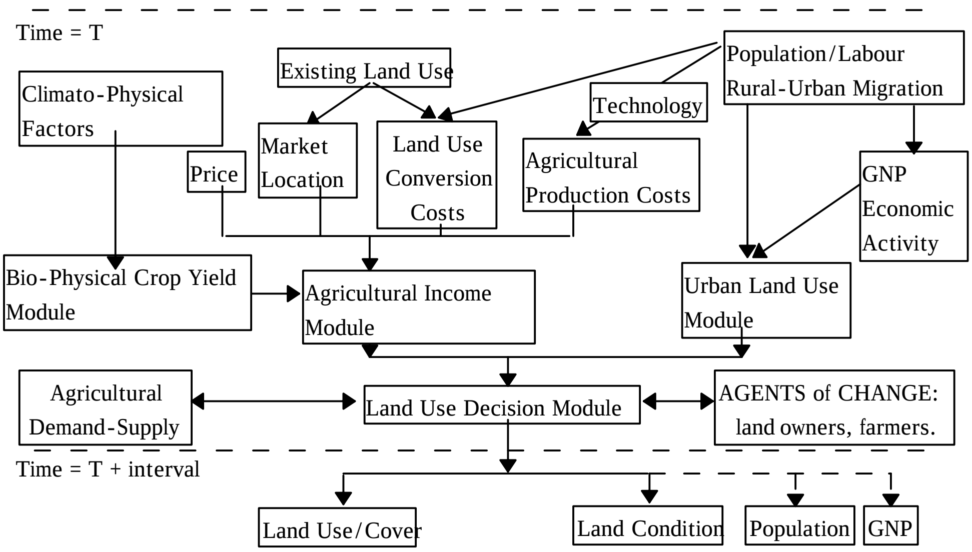


Figure 2. Framework of the AGENT-LUC Model

The bio-physical crop yield model calculates the potential productivity of the land unit for the given conditions of soil, topography, water availability and climatic parameters. The distribution of water availability takes into account the soil conditions, amount of rain-received, and the existence of irrigation facilities. The main assumption of this model is that there is a strong linkage between the climate and crop distributions. (Leemans, et.al., 1993). The crop yield estimates are derived by modifying the approach as described in the EPIC model (Sharpley and Williams, 1990). The central concept of this approach is the growing period and the photosynthetic efficiency of the crops.

The agricultural income sub-model calculates the economic potential of the land unit, based on both the agricultural and non-agricultural revenues and expenditures. It also takes into account the accessibility, terrain conditions and current land use in calculating the costs.

Urban land use is the other major land use that is primarily influenced by the activities of the human beings. Here, we estimate the urban land requirements as it competes with the agricultural areas due to increasing population pressures and the rise in the economic levels of the region. The model takes into account the locational value – neighbourhood and accessibility of the land-unit in assessing the new areas that will be urbanized.

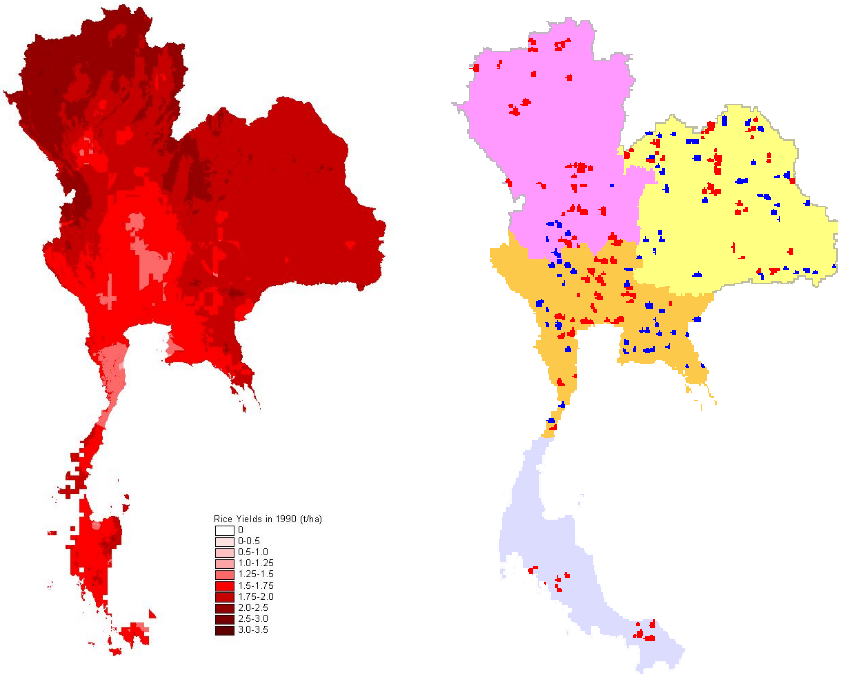
The final step in the simulation is the agent decision model, which uses the estimated income, urban land needs & the existing landuse in the land unit under consideration as its input to predict the land use. The “agent” is the decision maker in this model, where in the agent arrives at a decision taking into account the prevailing conditions in the respective grids. In addition to the economic factor, the demographic condition (age distribution and educational levels) and the land use history are considered to help in arriving at a reasonable estimate for the change in the land use patterns. 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.

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 competing demands from other land uses. The major components that influence the decision are described in this section.

3.1 Biophysical Crop Model (BCM)

Land evaluation and suitability analysis have long used the biophysical factors like climate and soil as its determining factors (FAO, 1978), but the influence of human factors is not so well studied and described. Also, there exists considerable gap between the potential suitability of a given area to its actual productivity. Recent advances in modelling crop-yields based on their phenology have yielded better results, though the majority of them are point/location-specific.



(a) (b)

Figure.3. (a) Spatial yield distribution of paddy crop in Thailand;
(b) Sample villages for paddy and cassava yields

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.3 (a) and Figure.3 (b) shows the sample village points for which data was collected to verify the model results.

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 considered are the non-yield-on-farm income and the off-farm income. These factors influence the decision making process, in case of fluctuating agricultural revenues from a given unit of the land.

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 finds the existing urban areas, ranks them according to their sizes and density of population first; then goes on to calculate the expansion needs of each city individually. The model takes into account the locational value – neighbourhood and accessibility of the land-unit in assessing the new areas that will be urbanized. The model assumes that all the extra land needed for the urban areas in a given year is fulfilled in the next year. This also for some realistic calculations on the changes in the areal extent and locating such changes. The model provides information on the urban land demand and supply, on a spatial basis. In case of Nan province, in the North of Thailand, between the year 1980 and 1990 the model simulated a rise of urban grids from one grid to five grids, whereas the existing land use map of 1990 showed the existence of four grids.

5 DEMOGRAPHIC CHANGE

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,

$$P_t = P_o\, e^{(\mu/\omega)(e\omega t\ -\ 1)} \tag{1}$$

where, μ is the national population growth rate at initial time reference t_0 and ω is the exponential decreasing rate of 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 agent decision model calculates the migratory population from or to the respective grid cell.

6 AGENT DECISION MODEL

The most important part of the entire modelling framework, is this model. 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 Rural economy usually consists mainly of the agricultural income. But, in addition to it, the farmers and their households also undertake various other part-time occupations during the off-season, or are continuously deriving some form of an additional income by engaging in other occupations like poultry and dairy farming and so on. To account for these additional incomes as a means of cross-subsidizing their main agricultural income, it is essential to include such factors in understanding the rural economic structure. A look at the Figure 4., would help the reader better understand the income structure of the rural economy. Figure 4(a) refers to the income structure of the grids that are located around the Urban area – 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. The only grid that gets more than 50% of its income coming from the agricultural revenue is the grid no.4, where the land use is Paddy. This implies that, in spite of the profitability on 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 crop maize, as a trade-off between keeping their agricultural revenues and the issue of labour availability. In contrast to this, we find from Figure 4(b), in case of grids located far away from the Urban areas, the primary source of income is the agricultural revenue and the land use in all

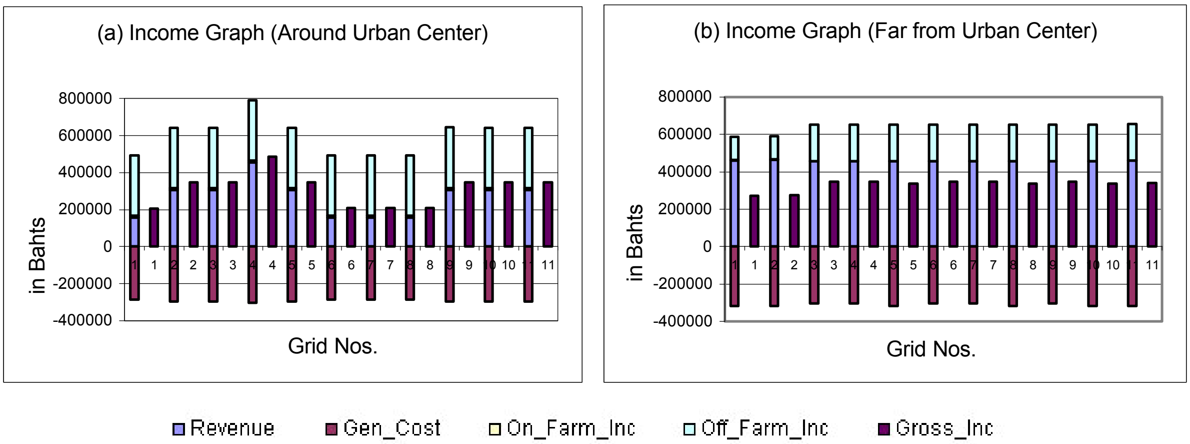
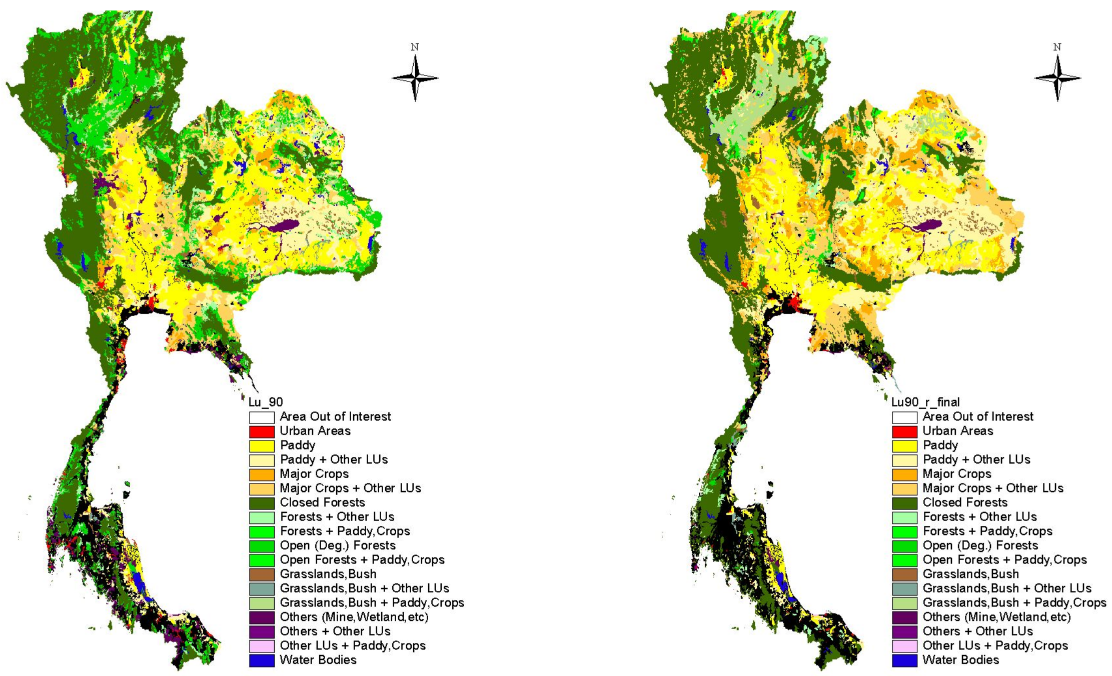


Figure 4. The composition of rural economy in grids (a) around the urban area; and (b) far from the urban area

these grids are Paddy. The contribution from off-farm income sources are of the order of 20% to 30% in these grids, with the lower side being in grids with a comparatively lower population density.

6.1 Land Use Change

We use the 'profit maximization' as the guiding principle along with a comparative ranking system ('risk aversion') 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.



(a) (b)

Figure 5. (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.

Also, the model takes into account the external influences that are likely to effect shifts in the agricultural patterns. The main factor considered here is that the external demand generated from export policies of specific crops, like cassava in Thailand, lead to large-scale shifts from conventional agricultural practices. As of now, these external influences are exogenous variables and are not calculated within the model. Figure 5. (a) shows the simulated land use map of Thailand in 1990 based on the model simulation run from 1980-90; and (b) the actual 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 change the land use. But, for increasing populations with limited incomes 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.

6.2.1 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.

6.2.2 Rural Migration: The migration of households to new grids (development) or partially agricultural grids that are accompanied by land use conversion to agricultural lands determine the rural migration. Figure 6. shows the result of the total in and out-migration from the individual grids, in the Nan province during the simulation period of 1980-90.

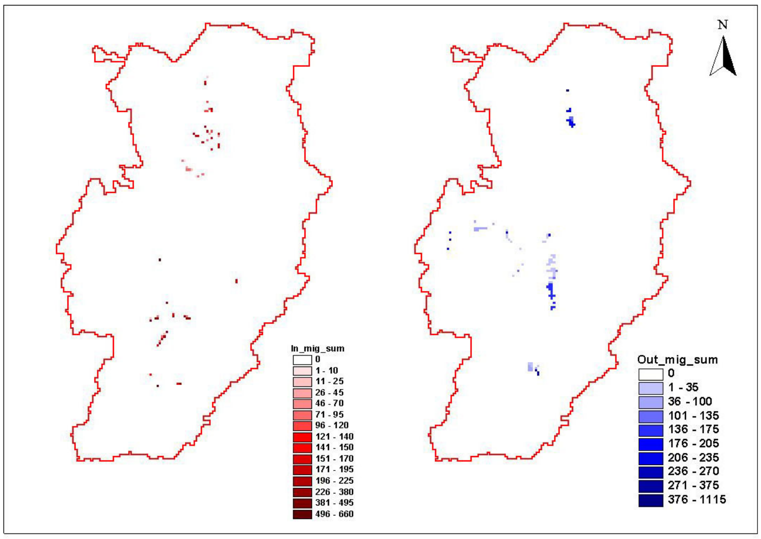


Figure 6. Shows the result of the total in and out-migration from the individual grids, in the Nan province during the simulation period of 1980-90.

7 DISCUSSION 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. 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 scale and resolution of the data available vary rather widely for different regions. It is of utmost importance to develop a model framework that can be easily ported across the various scales and can be implemented. As the basic framework of this model is dependent on mostly global datasets and can derive most of its information for the national level datasets, it can be readily applied to areas where these data can be made available. If a particular region or country is able to provide the model with more accurate and finer datasets, then the agent decision model may have to be tuned to the local conditions, without there being a need to alter the model structure.

The model developed here has the potential for use in not only trying to understand the mechanism of land use and land cover changes in the areas of application, but also provides a way to explore the human-land interactions. As it 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.

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