Development of a GIS-based decision support system for assessing land use status

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KEY WORDS: EPIC, Land use, Decision support system, International trade model, logit model.

ABSTRACT

The objectives of this study are to assess land suitability and to predict the spatial and temporal changes in land use types (LUTs) by using GIS-based land use management decision support system. A GIS database with data on climate, topography, soil characteristic, irrigation condition, fertilizer application, and special socioeconomic activities has been developed and used for the evaluation of land productivity for different crops by integrating with a crop growth model — Erosion Productivity Impact Calculator (EPIC). International food policy simulation model (IFPSIM) is also embedded into GIS for the predictions of how crop demands and crop market prices will change under alternative policy scenarios. An inference engine (IE) including land use choice model is developed to illustrate land use choice behavior based on logit models, which allows to analyze how diversified factors ranging from climate changes, crop price changes to land management changes can affect the distribution of agricultural land use. A test for integrated simulation is taken in each 0.1° by 0.1° grid cell to predict the change of agricultural land use types at global level. Global land use changes are simulated from 1992 to 2050. Results can be concluded that decision support system described here are useful for assessing and predicting the spatiotemporal probability of land use types, and can be used by policy makers or land use planners to develop effective management strategies.

1. INTRODUCTION

Understanding complex land use change mechanisms and making informed resource management decisions require the integration of scientific data and knowledge across multiple disciplines and diverse landscapes. Agricultural land use patterns and their changes are tightly related with agriculture policy and food security issues under growing food demand, assessment of global climate change impacts on agriculture, environmental issues due to the intensification of agricultural land uses such as water pollution, soil degradation, and recently water scarcity issues. So a sustainable and holistic planning and management of land resources should couple all these related information with efficient tools for assessment and evaluation in order to permit broad, interactive participation in decision-making processes. Successful development of such tools requires integration of spatial, non-spatial, socio-political, economic and expert opinion (Fedra, 1995; Sugumaran, 2002). It seems apparent that no single method or technique can address all of these requirements credibly and satisfactorily (Fedra, 1995). However, modern technologies such as spatial decision support system (SDSS), which are an integration of many sub-systems, including remote sensing, geographic information system (GIS), analytical models, a user interface, data base management, and knowledge based system have the necessary power and flexibility (Densham, 1991; Fedra, 1991).

Integrated system approaches to environmental and resource management problems have been discussed and advocated for a considerable time (Fedra, 1991; Franklin, 1997). This study aims to develop a global Agricultural Land Use Management Decision Support System (ALUMDSS) by integrating process-based crop productivity model—Erosion Productivity Impact Calculator (EPIC) (Williams *et al.*, 1990), International Food Policy Simulation Model (IFPSIM) (Oga and Yanagishima, 1996), and a land use choice model, which allows to analyze how diversified factors ranging from climate changes, crop price changes to land management changes can affect the crop combinations and their geographical extent. ALUMDSS provides not only agricultural land use patterns but also agricultural policy and practices such as fertilizer inputs and irrigation water input, which are indispensable variables to evaluate environmental impacts of agricultural land use changes. The study attempts to accomplish three specific tasks: discussing the architecture and various components of the decision support system; developing a integrated global land use choice model to characterize choice of land use types and the effect on environments; and applying the ALUMDSS to entire study area to map and predict the changes of land use choices with different scenario.

2. ARCHITECTURE OF THE SYSTEM

A key characteristic of SDSSs is that they provide options or scenarios for the decision maker. ALUMDSS is the tool we can used to assess and forecast the impacts of policy strategies and geographically diverse land management

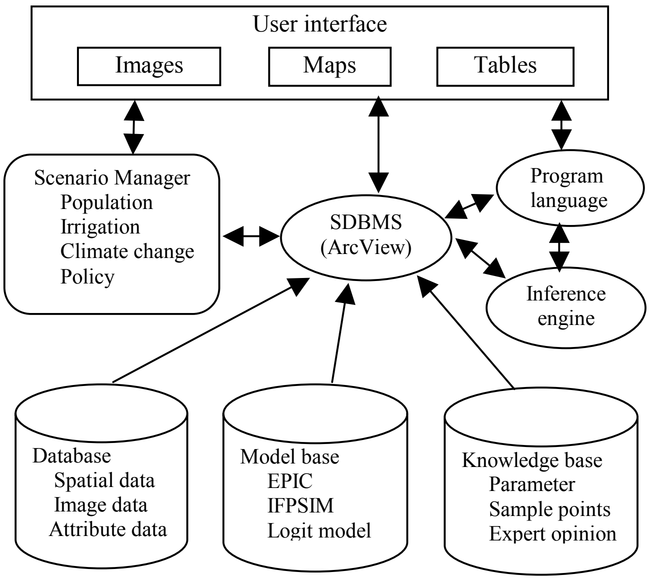

Figure 1. Architecture of the ALUMDSS

strategies on land use types. This section discusses the architecture of the system designed to achieve these objectives. The architecture is schematically shown in Figure 1.

2.1. Inference Model and Knowledge Base

Inference model base contains the models that can be used as methods for evaluating land use attributes. An integrated agricultural land use change model is introduced in ALUMDSS. The models include international trade model, land use choice model, land productivity model and urban expansion model. The integrated structure can be briefly illustrated in Figure 2. In this figure, a GIS-based EPIC is developed to simulate global land productivity with the scenarios of different fertilizer application, different irrigation and climate conditions. Logit land use choice model is a spatial explicit simulation model developed to simulate the agricultural land use change. IFPSIM is a traditional economic model used to simulate the impacts of agricultural trade and policy on food production. The linkage among those models is variables of crop production, harvested area and crop market price. The crop yield and planted area is a result of the output of GIS-based EPIC and land use choice model respectively, while the output of crop prices in IFPSIM are the input variables for land use

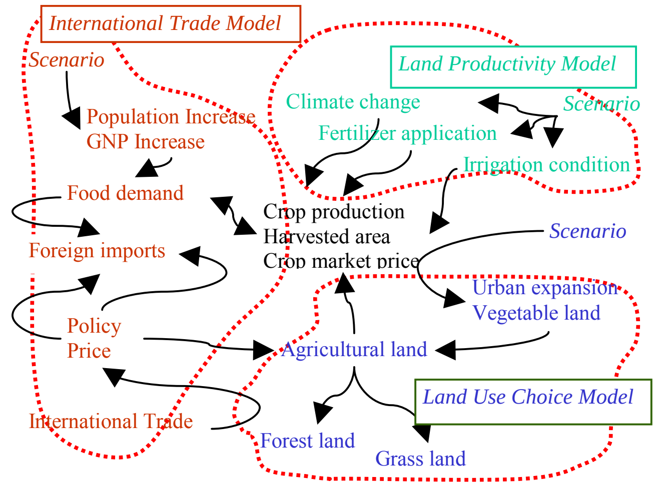

Figure 2. Flowchart of integrated model structure

choice. A more detail about these models will discuss at next section.

Knowledge base includes the knowledge that can be used for land use choice inference, such as model parameters, land use sample points and expert opinions. Model parameters mainly relate to the running of EPIC. They include crop growing parameter, fertilizer parameter, pest parameter, and so on. Land use sample point data indicate the land use types and related factors effecting the decision of land user, which may derived from remote sensing images or site investigation. Expert opinions about crop management, such as the crop planning /harvesting date, crop tillage, fertilizer and irrigation schedule, are also included in knowledge base.

2.2. Database

The data established in the database mainly include topography data, weather data, soil data, and social-economical data. The weather data we use in our study such as monthly maximum air temperature, monthly minimum air temperature, monthly standard deviation maximum air temperature, monthly standard deviation minimum air temperature, monthly precipitation, and monthly standard deviation of daily precipitation, are from WMO with time series of daily maximum and minimum temperature, daily precipitation and elevation for about 6000 available terrestrial stations at global level over the period from 1980 to 1990. Weather data are interpolated by topographically and climatologically informed interpolation method to translate point data into graded data (Tan and Shibasaki, 2002). Future climate change data for monthly maximum and minimum temperature, and precipitation are derived by Intergovernment Panel on Climate Chang (IPCC) from the first version of the Canadian Global Coupled Model (CGCM1) with the standard concentration of CO_2 developed by the Canadian Centre for Climate

Modelling and Analysis (CCCma) (Flato et al., 2000).

The soil database is obtained from The Global Soil Task cooperated by the International Geosphere—Biosphere Programme (IGBP) with a 5-min resolution. Minimum of EPIC soil parameters with five layers, including percent sand, persent silt, bulk density, PH, percent organic carbon, and percent calcium carbonate, can be generated directly from Spatial Database of Soil Properties. The soil-depth intervals are 0-1mm, 1mm-10cm, 10-30cm, 30-50cm and 50-100cm respectively.

The input variable of maximum annual irrigation water volume in GIS based EPIC is defined as a function of irrigation equipment, water supply and land use coverage. A digital global map of irrigated areas generated by Center for Environmental Systems Research, University of Kassel, (Döll and Siebert, 1999) is used to evaluate the condition of irrigation equipment. Maximum annual fertilizer applied for a crop and other socioeconomic variable data are derived from country-based yearly social-economic statistical database. DEM and slope data are derived from GTOPO30, which was generated from several raster and vector source of topographic information by USGS with a horizontal grid spacing of 30 arc seconds (approximately 1 kilometer).

2.3 Inference Engine

The inference engine controls the execution of methods for evaluating attributes and guards the internal consistency of the inference model. In this context, it is important to note that EPIC is not designed for the application of GIS. In fact, some EPIC parameters such as crop management practice data are very difficult or impossible to derive from GIS directly. Crop management descriptions must specify the timing of individual operations either by the date or by the fraction of growth period. One main objective for inference engine is to determine a part of parameters that EPIC needs such as crop system and planting/harvesting dates for each crop type cell with the climate change at each grid.

2.4. User Interfaces

ARCVIEW GIS can be used as the platform for the design and development of ALUMDSS because it fulfils most of the requirements for the development of an SDSS, such as a data base management system, image processing with the ‘Image analysis ’ extension, simple modeling through the ‘spatial analyst ’, a graphical user interface development through the ‘dialog designer’ extensions, report generator through the ‘report writer ’ extension, and provides different means for communicating with other applications. However, it lacks the capability to handle a knowledge base and powerful modeling capability. So, inference models are developed outside the ARCVIEW GIS using Visual C and Visual Fortran programming language. The link between ARCVIEW and the knowledge-based system can be achieved through the dynamic link library created using the programming language.

The Scenario Manager module allows one to store and manage scenarios. A scenario can be implemented by editing in the table view or by retrieving data from the external database. Using the scenario manager, users can easily return to an old scenario or evaluate new combinations of different scenarios by incorporating forecasts of changes in food demand, climate, fertilizer application, and irrigation water supply.

3. INTEGRATED MODEL METHODOLOGY

The basic concepts for the integrated agricultural land use choice model are based on the following assumptions: (1) land productivity is the major determinant of agricultural land use possibilities, (2) human activity is also the determinate of land use actualities, and (3) globalization of crop trade can affect the food supply and the land use distribution.

3.1 Land Productivity Model: GIS-based EPIC

Land productivity is a crucially important factor for the modeling of agricultural land use pattern and its changes at regional or global level. EPIC is a very popular model to simulate crop yields at field. It integrates the major processes that occur in the soil-crop-atmosphere-management system, including: hydrology, weather, erosion, nutrients, plant growth, soil temperature, tillage, plant environmental control and economics (Williams, 1995). Many test researches about EPIC have been performed using different data and parameters (Roloff *et al.*, 1998). EPIC is well suited for the relative comparisons of influences of soils, crops and management scenarios (Bouzaher *et al.*, 1993). The output of the EPIC not only includes the crop yield, but also economical and ecological by-product such as cost, soil erosion and N-pollution from the application of fertilizer. GIS-based EPIC can apply EPIC efficiently at regional or global level (Tan and Shibasaki, 2001). The aim for integrating GIS with EPIC is to simulate crop yields efficiently at global scale.

3.2 International Trade Model: IFPSIM

IFPSIM is a multi-commodity, multi-regional and multi-period world agricultural trade and policy simulation model developed and designed on the Oga Model Building System (OMBS). It is an interactive model, in that it allows for the simultaneous determination of supply, demand, trade, stock levels and prices for all the commodities covered. This model also is dynamic in the sense that it allows for the outcome of one year or a sequence of years to influence the outcome of future. In IFPSIM, all commodity prices are determined at the level where world supply is equal to world demand and all variables are simultaneously determined, while world market clearing prices are derived by equating the sum of gross imports and the sum of gross exports. However this model does not identify sources and destinations of trade flows.

IFPSIM includes 8 sections: (1)world market equilibrium equations, which determines crop market prices for each simulation year and for each commodity gross exports and imports for each country/group; (2)gross trade equations, in which gross export and import equations depend upon the country's net trade position; (3)price linkage equations, in which domestic producer and consumer prices are linked to the world market price through constant price transmission elasticity in those countries that are not liberalizing their trade, while changes in bound rates of tariffs and the price effects due to changes in export subsidies determine domestic prices in the liberalizing countries; (4)cereal markets equations, in which crop production is the product of estimated harvested area, yield and a crop condition index; (5)meat markets equations, in which meat production is calculated from number of animals, number of livestock slaughtered; (6)milk market equations, in which milk production is calculated from number of milk cows; (7)oilseed, oils and oil meals, their production is calculated from harvested area and yield; (8)aggregated variables equations, which used to calculate aggregated variables from average feed price, average price of meat, feed requirement of cereals and feed requirement of oil meals.

3.3 Agricultural Land Use Choice: Logit Model

Logit model is a discrete choice model, which is used for modeling a choice from a set of mutually exclusive and exhaustive alternatives. It is assumed that a decision-maker chooses an alternative with the highest utility from the set of alternatives. The utility of an alternative is determined by a utility function, which consists of independent attributes characterizing the alternatives concerned and the relevant parameters. Logistic regression is considered most appropriate for the choice modeling (Ben-Akiva and Lerman, 1985). The results of regression predict the probabilities in each state of dependent variable.

$$U_i = F_i(Y) + S_i(X) + C_i \qquad (i=1,2,\ldots,n) \qquad (1)$$

$$P_i = \exp(U_i) / \sum_{j=1}^{n} \exp(U_j) \qquad (2)$$

where n represents the number of agricultural land use choices; F_i and S_i denote the linear function of basic environment variables Y and main socioeconomic and ecological variables X for choice i respectively; C_i is a constant; P_i is the probability of the choice i at a particular location.

Agriculture land choices can be coded into different options such as rice cropland, maize cropland, wheat cropland, soybean cropland and other land uses. The basic environment variables include natural factors and anthropogenic factors. Natural factors provide basic conditions for crop growth, such as temperature, precipitation, soil physical and chemical properties, and terrain variables. Anthropogenic factors include mainly crop management practices like irrigation and fertilizer applications, and so forth. Basic environment variables are used to determine crop yields—the land productivity from a given land field assigned to a given land use in a particular year, which can be simulated by GIS-based EPIC.

There are several advantages of this approach based on a logit model. One is that the output of logit model is the probabilities of land use types, which can mitigate "artifacts" caused by discrete changes of an entire grid-cell. Another advantage is that it is predictable and relatively easy to incorporate the other factors affecting land uses. For example, assuming the cost of crop production is proportion to gross income, a dynamic land use choice model can be conducted from equation (3) as the following:

$$\begin{aligned}
U_i^T &= A_i \, Profit_i^T + S_i(X^T) + C_i \\
&= A_i \, (Price_i^T Y_i^T - Cost_i^T) + S_i(X^T) + C_i \\
&= A_i^T \, Y_i^T + S_i(X^T) + C_i^T \\
U_i^{T+1} &= A_i^T (Price_i^{T+1} / Price_i^T) Y_i^{T+1} + S_i(X^{T+1}) \\
&\quad + C_i^T - A_i^T / Price_i^T \, \alpha \, (Price_i^{T+1} Y_i^{T+1} - Price_i^T Y_i^T) \\
&= A_i^T \beta_i (1-\alpha) Y_i^{T+1} + S_i(X^{T+1}) + C_i^T + \alpha A_i^T Y_i^T
\end{aligned} \qquad (i=1,2,\ldots,n) \qquad (3)$$

where U_i^T and U_i^{T+1} represent utility at time T and $T+1$ for choice i respectively; Y_i^T and Y_i^{T+1} are the yield of crop i at time T and $T+1$; α indicates the cost factor proportioning to gross income; $Price_i^T$ and $Price_i^{T+1}$ represent prices of crop i at time T and $T+1$ respectively; and β_i is $Price_i^{T+1}/ Price_i^T$; A_i^T and C_i^T are the coefficients of land productivity variables and constant for crop i at time T respectively.

Market price variables and crop yield variables in equation 3 will be provided by IFPSIM and GIS-based EPIC respectively. IFPSIM provides regional market price data result from clearing prices by equating the sum of gross imports and the sum of gross exports and given scenario such as GNP growth, demographic trend and industrial development. GIS-based EPIC provides spatially explicit land productivity data in different conditions such as climate, soil, fertilizer application, and irrigation.

4. RESULTS AND DISCUSSIONS

A test for simulating land productivity with GIS-based EICP, and agricultural land use pattern with integrated model is taken in each 0.1° by 0.1° grid cell at global level.

4.1 Main Crop Yields

Running GIS-based EPIC model, we can simulate different crops (such as rice, maize, wheat, and soybean) yields in each year. Figure 3 provides one of the geographic details for the simulated rice yields in 2000. In order to analysis the accuracy of simulated results, we calculate the yield per hectare in cultivated fields based on land use pattern data and compare it with FAO statistical data. Comparison shows that the deviations of simulated yield from statistical yield in most countries are not so big,

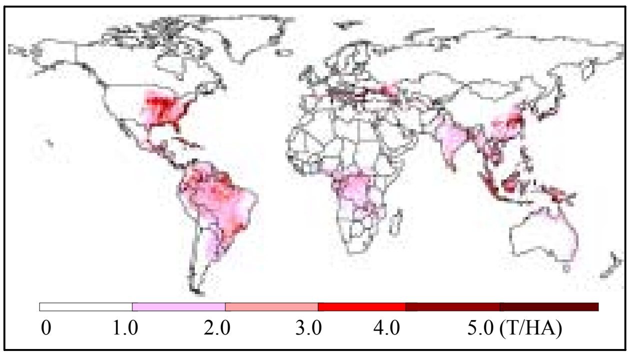

Figure 3. Rice yields in year 2000

The scenario for the impact of fertilizer application from average volume 0Kg/Ha to 400Kg/Ha at an interval of 40Kg/Ha on main crop yields in different countries is simulated to predict the change of crop yields and N-

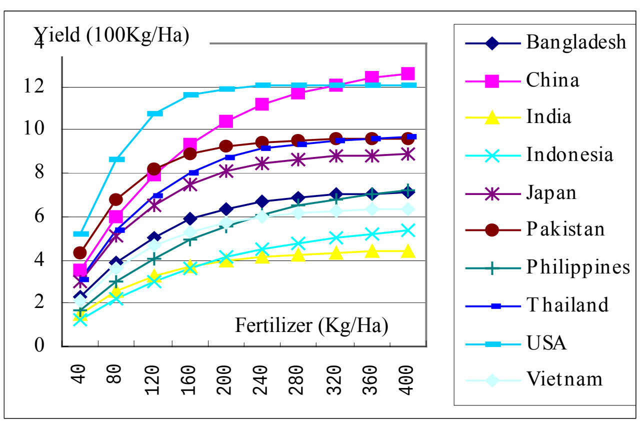

Figure 4. Fertilizer application and increased rice yields

pollution for different scenarios on fertilizer application. Figure 4 shows the relationship between the change of rice crop yields and fertilizer application in ten top countries of rice planted area. These results are not only useful for prediction future crop yields in different scenarios of fertilizer input, but also helpful to make farms more ecologically sound considering the nitrate pollution of fertilizer application.

4.2 Agricultural Land Use Pattern

The significant variables, four main crop (rice, maize, wheat, and soybean) yields, socioeconomic factors such as population density and traffic accessibility, and ecological factors, are entered into the logistic multiple regression to model the land use choice relationship. This model computes the probability of land choice at individual locations. Based on the land use samples selected from land use cover data of USGS (Loveland, *et al*, 2000), the coefficients and constants of utility equations in different regions are determined.

Land use choice probability of the entire study area is assessed by applying the logistic multiple regressions to the GIS coverages corresponding to all independent variables. The output probability values range from 0 to 1, with 0 indicating a 0 probability of the crop choice and 1 indicating a 100 percent probability. The maximum probability among five alternatives implies that this

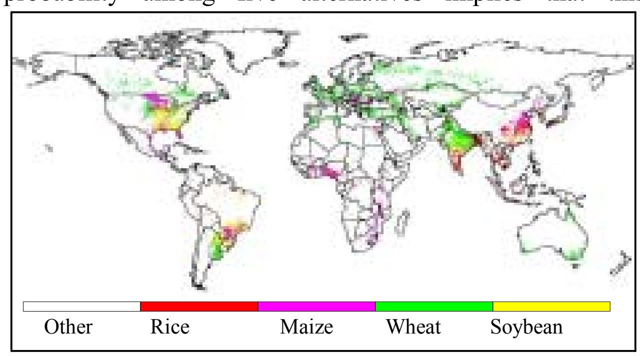

Figure 5. Land use pattern at first growing season in 2000

alternative has the highest probability to be chosen. If the alternative with maximum probability is chosen, Figure 5 shows the distribution of agricultural land use pattern at first crop growing season.

4.3 Predicting Land Use Changes

With the scenarios of IPCC climate change data in the years 2010, 2020, 2030, 2040 and 2050, global crop productivity can be simulated by using the GIS-based EPIC under an adjustment scenario in which planning date is changed by

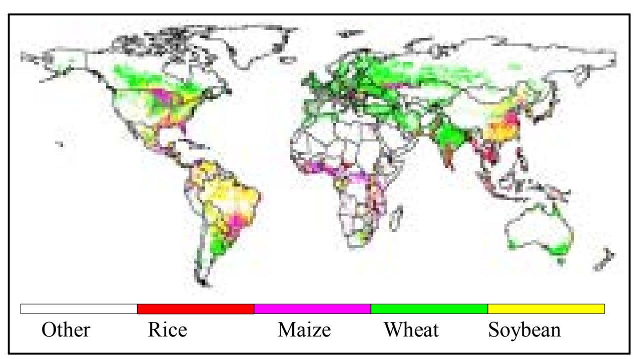

Figure 6. Land use pattern at first growing season in 2040

less than six weeks in response to a change the length of growing season at each grid cell. It shows excluding the soybean crop in Asia, future climate will be harmful for all main crops in all continental areas.

Prediction by IFPSIM is conducted with an increase of gross domestic product, population. Making use of given crop prices, land use choice model can decide or predict the distribution of land use choice or land use conversion related to agricultural management. Figure 6 demonstrates the potential uses of the integrated agricultural land use model to assess the impact of socioeconomic development and ecological change on main agricultural land use in 2040 in the first growing season.

5. CONCLUSIONS

Agricultural land use patterns and their changes are tightly related with agriculture policy, food security issues, global climate change, environmental issues such as soil degradation and recently water scarcity issues. In order to understand and to model the mechanism of agricultural land use change underlain by above issues, an architecture of agricultural land use management decision support system is developed, in which agricultural land use choice model, GIS-based EPIC and International Food Policy Simulation Model are integrated to assess the probability of agricultural land use choice by considering most of important basic, socioeconomic and ecological variables at global level. In this integrated model, the basic environment factors are represented by the different crop yields simulated with GIS-based EPIC at each grid cell, and socioeconomic and ecological variables, including crop price, traffic accessibility, rural population density, cost, soil erosion and N pollution, can further modify the probability of land use choice. Prediction of how international crop market prices will be change under alternative policy and ecology scenarios can rent to the application of IFPSM by an interactive integration with other models to allow for the simultaneous determination of supply, demand, trade, stock levels, and prices.

REFERENCE

Ben Akiva M., Lerman S.R., 1985, Discrete choice analysis: theory and application to travel, Demand. MIT Press, Cambridge, Massachusetts.

Bouzaher, A., Shogren, J.F. et al. 1993. Agricultural policies and soil degradation in western Canada: An ago-ecological economic assessment (Report 2: The environmental modeling system). Technical Report 5/93. Agriculture Canada, Policy Branch, Ottawa, ON. 110pp.

Densham, P.J., 1991. Spatial decision support system, geographical information system. In: Maguire, D.J., Goodchild, M.S., Rhind, D.W. (Eds.), Principle and Applications. Longman, London, pp. 403- 412.

Döll, P. and Siebert, S., 1999, A digital global map of irrigated areas, *Kassel World Water Ser. 1*, Center for Environ. Syst. Res. Univ. of Kassel, Germany.

Fedra, K., 1991. A computer-based approach to environmental impact assessment. In: Proceedings of the Indicators and Indices for Environmental Impact Assessment and Risk Analysis. Joint Research Centre, Ispra, Italy, pp. 11-40.

Fedra, K., 1995. Decision support for natural resources management: models, GIS and expert systems. AI Applications 9, 3 / 19.

Flato GM, Boer GJ, Lee WG, McFarlane NA, Ramsden D, Reader MC, Weaver AJ, 2000, The Canadian Centre for Climate Modelling and Analysis global coupled model and its climate. CLIMATE DYNAMICS, 16: (6) 451-467.

Franklin, J.F., 1997. In: Boyce, M.S., Haney, A. (Eds.), Ecosystem Management, Natural Resource. Management, an Overview. Springer, Berlin, pp. 233- 245.

Loveland, T.R., Reed, B.C., Brown, J.F., Ohlen, D.O., Zhu, J, Yang, L., and Merchant, J.W., 2000, Development of a Global Land Cover Characteristics Database and IGBP DISCover from 1-km AVHRR Data: *Int. J. Remote Sensing*, **21**, pp1303-1330.

Mertens, B., Lambin, E., 1997. Spatial modeling of deforestation in southern Cameroon. Appl. Geogr. 17, 143–162.

Nelson, G., Hellerstein, D., 1997. Do roads cause deforestation? Using satellite images in econometric analysis of land use. Am. J. Agr. Econ. 79, 80–88.

Oga, K. and Yanagishima, K., 1996, JIRCAS Working Report No.1: international food and agricultural policy simulation model. Japan International Research Center for Agricultural Sciences (JIRCAS) Ministry of Agriculture, Forestry and Fisheris. pp.121.

Roloff, G., de Jong, R., et al., 1998, EPIC estimates of soil water, nitrogen and carbon under semiarid temperature conditions. Journal Info Canadian journal of soil science. AUG 01 1998 v 78 n 3, pp.551-562.

Sugumaran, R., 2002. Development of an integrated range management decision support system, Computers and Electronics in Agriculture, 37, 199- 205.

Tan, G. and Shibasaki, R., 2001, A study on the integration of GIS and EPIC: methodology and application, Journal of the Japan Society of Photogrammetry & Remote Sensing, Vol. 40, No. 3, pp4-13.

Tan, G. and Shibasaki, R., 2002, Monthly climatologically aided global interpolation of weekly air temperature and precipitation, Theory and Application of GIS, Japan, Vol. 9, No.1.

Williams, J.R. 1995. The EPIC. Pages 909-1000 in V.P. Singh, ed. Computer models of watershed hydrology. Chapter 25. Water Resources Publications, Littleton, CO.

Williams, J.R. et al. 1990. EPIC-Erosion/ Productivity Impact Calculator. United State Department of Agriculture, Agricultural Research Service. Technical Bulletin Number 1768, Springfield, VA, USA.