Interrelations Between Socio-economic Development and Environmental Quality: a Simulation Integrating System Dynamics Models with GIS

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ABSTRACT  System dynamics (SD) theory has long been deployed in modeling complex non-linear interrelationships but, so far it has not been common to do the kind of modeling in support of bringing environmental sustainability policies to practice. This is largely because the challenge of including spatial data has not yet been well met. Potential for adoption of SD and GIS methods in combination is exemplified with the results of a decision-support exercise designed for simulation and prediction of the dynamic inter-relationships between socio-economic development and environmental quality for the “Wen, Pi, Du” county in Sichuan province, southwestern China.

KEYWORDS  system dynamics; GIS; dynamic simulation; eco-economic system; SD model; analytic hierarchy process

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Introduction

Debates about the nature of sustainable economic development have lately included the reference to links between profitability and adoption of environmentally sustainable practice\cite{1,2}. The world’s major stock exchanges maintain sustainability indexes\cite{3,4}, so that stockholders can assess the success of their investment strategies in comparison with the time-series record of such measures. Moreover, private investors, including those who regard themselves as “socially responsible”, “nowresponsible”, now seek to invest in companies that can demonstrate performance in environmental and social terms that is of an outstanding kind\cite{5}. “Financing for sustainability” has found a place on the agenda of major global “peace and world order” organizations\cite{6}. Many public policies are inspired by AGENDA 21\cite{7} and are designed to meet the challenge of bringing sustainability policies to practice\cite{8}. Thus it can be seen that public policies at the national level recognize the importance of achieving and maintaining sustainability in economic development. Practice must involve the development of information systems that can be routinely maintained, usefully queried and deployed for modeling support of decision-making.

For the policy-makers in countries sustaining increased economic growth based upon exploitation of natural resources, much interest attaches to research about developing and diffusing information-age methods for monitoring, and predicting the interactions between socio-economic and environmental systems. In grappling with the system complexities, scholars developed/called for powerful tools. The socio-economic researchers have often favored adoption of SD approaches. At the same time, environmental scientists have begun to work with information-age spatial data handling tools such as GIS\cite{9,12}.

The non-linearity of eco-economic interactions can be simulated by use of systems dynamics ap-
approaches. Which are based on the identification of systemic inner feedback structures defined for modeling by means of a series of differential equations. The SD model simulates the dynamic behavior of a system when the values for key variables are identified and used as data input. Thus, time-series change is simulated but the system spatial factors and situation can’t be described and represented by SD model. The SD approach can be enhanced for those needing spatial feature, but only if the data and information flow paths can be organized to take in outputs from analysis using georeferenced data-viewing tools linked to customizable functions. There is such a tool (Map Objects; MO) that was used in this study.

This article emphasis on combining SD model with GIS component and use data integration based on Analytic Hierarchy Process for simulation and prediction on the dynamic relationship between socio-economic development and environmental quality for the “Wen, Pi, Du” county in Sichuan province.

1 Methods

Our combination of SD with GIS is based on the technology of MO components, DAO (Data Access Object), API (Application Programming Interface) and etc. Programming is in Visual Basic. Thus the interrelations between socio-economic development and environmental quality can be simulated and predicted by the aid of SD model, GIS component and AHP (Fig. 1). System time-series change is simulated by SD model, and data (including attribute and spatial data) are organized and environmental quality evaluation and predicted is carried out based on GIS.

1.1 Site description

The 1922 km² study area (30°37’N to 31°23’N, 103°27’E to 104°06’E) is in southwest China. It ranges in altitude from the mountainous NW to the alluvial plains SE (Fig. 2). The terrain types being are shared by between by Wenjiang, Pi, and Dujiangyan counties. The average forest-cover in the study area is 33%, and it is 45% in Dujiangyan county.

Approximately 1,359,000 people live in the study area. At 703 persons per km², the population density is at the high level of China. Apart from agricultural production (rice, vegetables, eggs, meat and etc.), the main industries include food processing machining, textile manufacture, agric-chemical production, electronics, light industry, and production of building materials. Interest in sustainability mo-
nitoring originates directly from concern about the rapid pace of both urbanization and industrialization. Pressure on both land (which is ever scarcer) and environment (now subject to ever more multiple use) is evident, and the task of keeping harmonious relationships between socio-economic development and environmental sustainability is seen as in need of attention.

![Elevation models of "Wen, Pi, Du" counties](image)

**Fig. 2 Elevation models of "Wen, Pi, Du" counties**

### 1.2 System analysis

The study area as comprises an eco-economic system with complete structure and function, and so the spatial boundary of the system is defined by the outer administrative boundary of the three counties: "Wen, Pi, Du". The study lasts through 1992-2010. These temporal bounds were set, realizing that the changes of concern were first noticed widely in the early 1990s, and that simulations of the inter-relationships would be less useful if not extended to the end of the first decade of the new millennium. Four functionally inter-relating sub-systems were defined: economy, society (population), resource and environment.

The aim of the modeling is to simulate the socio-economic outcome of designated economic activity and environmental/resource status change/exploitation.

### 1.3 Model variables

Generally, apart from the deployment of "constants", the variables in the SD model involve four types: state variable, rate variable, secondary variable, and external variable.

1) State variables can represent the function that they describe the system state at some defined time and they are accumulative variables in the system. The main state variables refer to industrial fixed assets (IA), air pollution (AP), water pollution (WP), population level (POPU), and ecological function (EFA) assigned area by area.

2) Rate variable is used to characterize the change of system state over a defined time period. In this paper, rate variables comprise investment of industrial fixed assets (IAI), industrial fixed assets depreciation (IAD), rate of air pollutant increase (RAPI), rate of air pollutant decontamination (RAPD), rate of water pollutant increase (RWPI), rate of water pollutant decontamination (RWPD), rate of population increase (RPI), rate of population decrease (RPD), rate of area increase (RAI), rate of area decrease (RAD), and etc.

3) Secondary variables are the transitional variables in the SD model, and they are used to aid model construction. The main secondary variables refer to agricultural GDP (AG), agricultural output (AO), GDP, investment of fixed capital (AI), industrial GDP (IG), industrial output (IO), arable area (AA), fishery output (FIO), food product (FP), plant output (PO),
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4) External variables constitute externally generated input values. Some external variables, which were used in this study, include industrial output per capital (PPIO), agricultural output per capital (PPAO), difference of water supply and demand (WD), air pollutant emission (APE) and water pollutant emission (PWE).

5) Primary constants set into the adoption of the modeling approach for this study referred to locally accepted values for ecological function (PA), water supply per area (WPA), food output per area (PAFP), water demand for food product per area (WPF), water demand for living per capital (WPP), sewage per capital (PEPP).

1.4 The block and flow diagram of SD model

The system block and flow diagram is the principal basis tool forming SD model equation test. It represents the mathematical relation between variables, each denoted with special symbols in Fig. 3, which is a block and flow diagram of SD model and is designed to provide a high-level overview of the key interrelationships. It is generated through an interactive process based on the causal structural model.

Fig. 3 Stock and flow diagram of SD model
The model was applied using the input values identified from spatial and statistical analysis. Thus, a time-series record of changes in the factors emerges.

2 SD model validation and testing

The validity of the proposed model of the eco-economic system at "Wen, Pi, Du" county is tested by the data of 8 years from 1992 to 1999 (Table 1, Fig. 4 and Fig. 5). According to the testing, it is 98% likely that the relative errors of the variables in model are less than 15%, and it is 92% likely that the relative errors of the variables are less than 10%. The average relative error of variable is 5.01%. The verifying for some variables in model is shown in Fig. 4 and Fig. 5.

3 Model simulation

The SD model runs for the 19-year period 1992-2010. The simulation model performs for assumptions of 10%, 15% and 20% annual increase in GDP during 2005 to 2010. The dynamic change of model variables, which are in modeled with regional studies for which ideal data input may not be available.

4 Environmental quality evaluation

The powerful and flexible decision-making process-analytic hierarchy process (AHP) can be deployed for decision support, for instance, the setting of priorities. By reference to the model, decision support can be informed of the nature of both qualitative and quantitative aspects. It is structured on the assumption that when faced with a complex decision, the natural human reaction is to cluster the elements according to their common characteristics. It involves building a hierarchy (Ranking) of elements and then making comparisons between each possible pair in each cluster (as a matrix). This gives a weight for each element within a cluster (or level of the hierarchy) and also a consistency ratio (useful for checking the consistency of the data)\textsuperscript{115}. The model is readily adaptable for use in “Wen, Pi, Du” county, can be simulated according to the assumptions.

4.1 Evaluation elements or factors

A hierarchical framework of evaluation elements is built here\textsuperscript{116} (Fig. 6).
4.2 The weight of elements or factors

The matrix was formed through application of the Delphi approach \(^{20,21}\). It involves modification of Eq. (1) in order to meet / ensure that \( \sigma^2 \) is close to minimum. In Eq. (1), \( m \) is the number of experts; \( a_i \) is the mark which is given by \( i \) expert. The eigenvectors can be calculated by sorting, and consistency of matrix was checked. The eigenvectors can characterize the priority of elements in the system, and they are regarded as the weight of elements or factors.

4.3 Evaluation

According to the criterion of evaluation, the marks, by which elements or factors (with different units) are given, are converted into points by the aid of Eq. (2). Then Eqs. (3) and (4) are used to calculate the total points that can represent the environmental quality.

\[
P_i = \frac{20}{\Delta D_i} (x_i - I_m) + P_m \quad (0 \leq P_i \leq 100)
\]

where \( P_i \) is the point of \( i \) element \( j \) factor; \( \Delta D_i \) is the difference between the grades of \( i \) element \( j \) factor; \( x_i \) is the mark of \( i \) element \( j \) factor; \( I_m \) is the standard mark of \( k \) grade of \( i \) element \( j \) factor; \( P_k \) is the point of \( k \) grade of \( i \) element \( j \) factor.

\[
P = \sum_{j=1}^{n} W_j P_j
\]

\[
\sum_{j=1}^{n} W_j = 1
\]

where \( P_i \) is the point of \( i \) element; \( W_i \) is the weight of \( j \) factor; \( m \) is the number of element in system.

5 Results and discussion

The result of environmental quality evaluation is shown in the Table 1. The simulation and prediction on the dynamic relationship between socio-economic development and environmental quality is based on assumptions about designated GDP growth of 10\%, 15\% and 20\% over the 2005 to 2010 period.

| Year | GDP increasing | Wenjiang county | Pi county | Duijiangyan county |
|------|----------------|-----------------|-----------|--------------------|
|      | Economic       | Population      | Resource  | Environment        | Total point | Economic       | Population      | Resource  | Environment        | Total point | Economic       | Population      | Resource  | Environment        | Total point |
| 0.363 | 0.185 | 0.113 | 0.339 | 0.363 | 0.185 | 0.113 | 0.339 | 0.363 | 0.185 | 0.113 | 0.339 |
| 2005  | 92.70 | 78.97 | 85.39 | 81.83 | 85.65 | 81.42 | 66.82 | 76.75 | 87.15 | 78.08 | 89.67 | 90.03 | 92.73 | 83.64 | 88.04 |
| 2006  | 90.45 | 82.05 | 84.87 | 75.49 | 83.19 | 81.95 | 71.99 | 77.27 | 81.03 | 79.26 | 91.52 | 92.75 | 93.32 | 75.32 | 86.46 |
| 2007  | 91.01 | 80.25 | 86.27 | 85.46 | 86.60 | 81.57 | 64.97 | 75.27 | 83.20 | 78.34 | 86.44 | 90.65 | 92.46 | 87.69 | 88.32 |
| 2008  | 92.12 | 84.94 | 85.75 | 84.57 | 87.51 | 81.80 | 67.88 | 72.84 | 73.49 | 75.39 | 91.81 | 94.17 | 93.50 | 86.71 | 90.71 |
| 2009  | 86.87 | 79.33 | 85.06 | 76.31 | 81.69 | 77.61 | 64.58 | 75.36 | 79.51 | 75.59 | 82.37 | 89.49 | 91.28 | 83.29 | 85.01 |
| 2010  | 82.37 | 82.53 | 84.57 | 71.61 | 83.75 | 81.26 | 67.01 | 72.63 | 73.16 | 74.90 | 89.65 | 91.65 | 91.49 | 78.80 | 86.55 |

Increased environmental quality in Wenjiang county and Duijiangyan county is predicted with GDP increase of 10\%, the more so in Duijiangyan county. However, the simulated environmental quality of Pi county declined. With regard to assumed GDP growth of 15\%, the trend of environmental quality change in Wenjiang county and Duijiangyan county still suggest improvement. Indeed, they are predicted by the model, and to have a better outcome than with GDP 10\%. However, and again, the predicted trend of environmental quality in Pi county declined. The prediction is for decline of environmental quality in Wenjiang county and Duijiangyan county if GDP increases up to 20\%. At the same time, the environmental quality of Pi county
would be improved. The relative outcomes are depicted in Fig. 7-Fig. 9.

In summary, the simulated trend of environmental quality in Wenjiang county and Dujiangyan county rises if the growth of GDP is 15\%, but for Pi county, a GDP rise of 20\% is more suitable.

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