An Integrated Approach for Agricultural Ecosystem Management

Lida Xu, *Member, IEEE*, Ning Liang, and Qiong Gao

***Abstract*—Sustainable development and growth of agriculture sector calls for improving its competitiveness through a better understanding of lands, weather and climate, and planting, especially prediction of events with increased accuracy, and systematic integration of observations and prediction into decision-making in agriculture management. In this short paper, a systematic approach based on integrated information systems (IISs) for agricultural ecosystem management is proposed. The approach involves establishing an IIS called agricultural ecosystem enterprise information system (AEEIS) that extracts data on terrain, land use, planting, and others, and integrates them for the purpose of agricultural and ecosystem management. The integration helps in generating managerial/policy alternatives in consultation not only with agricultural and ecological specialists, but also with agriculture and ecosystems management. AEEIS, a platform of enterprise information systems, includes operational database, extract transform and load, data warehouse, data mining, simulation modeling, and knowledge management for generating managerial strategies on land use, planting species/variety, and optimal coverage of plants. AEEIS is part of efforts on integrated agricultural information services that is one of the main applications of China's sustainable agricultural development plan. The short paper concludes that, for effective management of agriculture and ecosystems, a systematic approach is essential in which IISs play a crucial role.**

***Index Terms*—Enterprise information systems (EIS), information infrastructure, service industry, service sector, system integration, systems approach.**

I. Introduction

Monitoring agricultural crop conditions, weather and climate, and ecosystems, and providing decision support for agricultural planning and policy-making are critically important for the development of agriculture to support economic and social development [1]. In China, there has been an urgent need for integrated agricultural data processing and analysis for realizing the so-called digital agriculture as existing agricultural and ecosystems information is stored in many disconnected locations using different formats and systems [2], [3]. This status hinders agricultural management from providing the best and timely decision and puts off agricultural policy makers to develop relevant agricultural policies in time. The infrastructure gap between the existing agricultural and ecological information systems and the expectation on realizing digital agriculture is obvious. To fill the gap, the consensus is that an integrated information system (IIS) be developed to provide systematic information to the decision makers, planners, and government agencies. To respond to such needs, integrated agriculture information services (IAIS) has recently been proposed as one of the main applications of China's sustainable agricultural development plan. The aim of the program is to improve agricultural competitiveness through a better understanding of land, weather and climate, planting, and other important aspects, especially the prediction of events with increased accuracy and the integration of observation and prediction into decision-making in agriculture management [4]. The program requires integrating relevant data into an integrated system such as enterprise information system (EIS) for data exploration and simulation modeling to enhance the quality of agricultural management, as the importance of EIS has been increasing significantly in recent years [5].

To promote the development of agricultural information infrastructures, efforts that have been made underscored the importance of technology implementation in the agricultural sector and addressed the needs of applying integrated information technology to agricultural sector. In 2004, Perini and Susi suggested that a systematic integrated approach is desirable for designing agricultural and ecological system [6]. However, despite more than a decade of research on the agricultural information systems and infrastructure, deficiencies still exist in our capability of establishing an effective agricultural and ecosystems information infrastructure, especially the lack of integration of recent technology into applications. Though IISs are known to be important to agricultural development, there are no comprehensive IISs available that can be employed.

Agricultural consulting service is one of the main components in the service industry [7]. In 2004, the Service Management Special Issue of *Decision Sciences* journal predicted that EIS, enterprise resource planning (ERP), data warehouse, and integrated enterprises would provide exciting new research opportunities in service management [8]. The main purpose of this research is to propose and develop an IIS for agricultural ecosystem management that addresses and incorporates the recent advances in information technology as predicted [8].

In this short paper, we: 1) propose an architectural framework that integrates agricultural and ecosystem information systems; 2) develop a deliverable IIS prototype called agricultural ecosystem enterprise information system (AEEIS) for agricultural and ecosystem management [9]–[13]; and 3) present agricultural and ecosystem management options through the prototype information system described in 2).

The existing literature provides numerous examples of agricultural and ecological information systems. A major drawback of these systems is that their integration capability is limited [6], [14]–[25]. Agricultural and ecological management will be greatly benefited by a highly integrated system to manage, plan, and prioritize agricultural development. This study makes a couple of distinct contributions that include: 1) developing an IIS to replace the existing fragmented and disconnected information systems at individual organizational levels; 2) addressing and demonstrating the use of the new technology as predicted to assist agricultural management in making decisions, as AEEIS includes operational database, extract transform and load (ETL), data warehouse, data mining, simulation modeling, and knowledge management subsystems for agricultural ecosystem management and producing optimal managerial strategies in terms of land use, planting species/variety, and optimal coverage of plants [8]; and 3) representing a novel application in agricultural consulting area, as EIS has traditionally and predominately been developed to handle aspects of manufacturing activities, and its applications in agriculture-related activities are growing [5].

The short paper is structured as follows. Section II provides a review of the existing IISs in agricultural and ecosystem management area, their characteristics and applications, and the motivation for creating a new integrative system. Section III contains a presentation of

Manuscript received February 28, 2007; revised June 14, 2007. This work was supported in part by the Chinese Academy of Science under Grant 2003-2-8 and in part by the K. C. Wong Foundation of Hong Kong under Grant 2007-81. This paper was recommended by Associate Editor R. Subbu.

L. Xu is with the Institute of Computing Technology, Chinese Academy of Sciences, Beijing 100080, China and also with the Department of Information Technology and Decision Sciences, Old Dominion University, Norfolk, VA 23529 USA (e-mail: lxu@odu.edu).

N. Liang is with the Department of Computer Science, University of Central Florida, Orlando, FL 32816 USA (e-mail: chenzz@ns.ibcas.ac.cn).

Q. Gao is with the Institute of Resource Science, Beijing Normal University, Beijing 100875, China (e-mail: gaoq@bun.edu.cn).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSMCC.2007.913894

the integrative system architecture. Section IV provides a description of the data warehousing, data mining, simulation modeling, and knowledge management components with an application example. Section V provides a conclusion with a discussion on the value and managerial implications of the system for agricultural and ecosystem management, the limitation of the current study, and the direction for future research.

II. Literature Review

To promote the development of agricultural information infrastructures, a number of efforts have underscored the importance of the implementation of IISs in the agricultural sector. Developing an integrated information infrastructure has recently attracted a lot of attention. Research indicates that the potential benefits of new technology can be leveraged if stand-alone and disconnected information systems are replaced by IISs. Especially since 2000, there have been increasing efforts and resources devoted to developing IISs for the agricultural industry. Against this background, an increasing amount of literature has been developed on the integrated information architecture in the agricultural industry. Rao *et al.* described the design and development of a prototype Web-Geographical Information System (GIS) decision support system for use in resource management and assessment of environmental quality, aiming at addressing water, soil, and related resource issues in an environmentally sustainable manner [20]. The system is GIS-based and integrates both mapping and modeling components. Nhan *et al.* stressed the importance of the concept of integrated agriculture [25]. In their study, an integrated agriculture–aquaculture (IAA) system was developed to address agricultural diversification and sustainability issues. Saroinsong *et al.* discussed the development and application of a land resource information system for agricultural landscape planning. On the basis of data analysis, agro-ecological land use plan was prepared [24]. Jongschaap introduced an integrated approach for the evaluation of crop and soil management strategies [23]. Bazzani presented an integrated multiscale analysis system for economic environmental assessment of the agricultural activity focusing on irrigation and the system decision support tool for irrigation (DSIRR) for the economic environmental assessment of agricultural activity focusing on irrigation [18], [22]. Cabezas *et al.* presented a model system for studying characteristics of ecological–social systems [19]. Perini and Susi described a decision support system for integrated production in agriculture and stressed the importance of integrating decision support systems and AI systems within a larger information system such as EIS [6]. Pacini *et al.* developed a holistic and integrated economic environmental accounting information system for evaluating the sustainability of integrated farming system [17]. Wagner introduced an IIS that helped to provide solutions to complex industry-level problems and sustain an agricultural production system in a changing environment [15]. Rao introduced a remote-sensing-based integrated approach for sustainable development of land water resources [16].

Although existing studies have all addressed the needs of applying integrated information technology to the agricultural sector, they provide only limited coverage of integrated information architecture; especially, little work has been done on integrating new technology such as EIS, data warehousing, and integrated enterprise information architectures as predicted by the applications [8]. In recent years, both the academic literature and the practitioner publications have emphasized the significant benefits that IISs can bring about [26]. The importance of integrated enterprise systems in the service industry has been stressed by researchers because integrated enterprise systems not only include all important components required, but also offer an ideal platform for improving decision-making in the service sector [8].

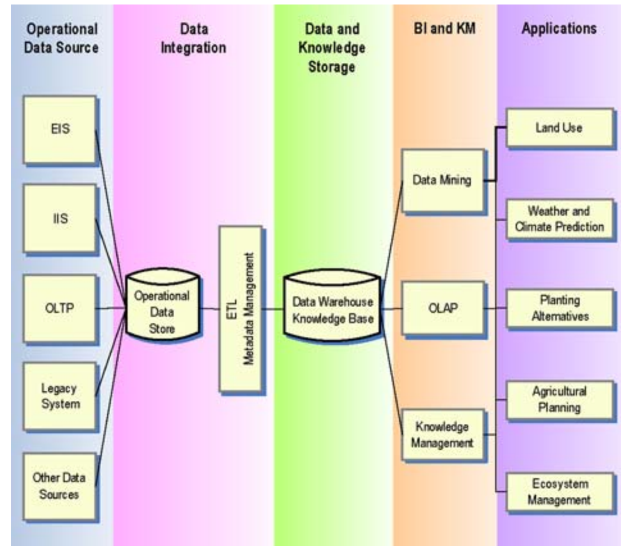

Fig. 1. AEEIS system architecture.

III. System Architecture

In the last decade, many information technology breakthrough efforts have laid the foundation for integrative information architecture. Among them, EIS and business intelligence (BI) have provided a major premise for the creation of IISs. Nevertheless, IISs for agriculture that integrate EIS and BI are almost nonexisting. Therefore, our project aims to develop a prototype system equipped with EIS and BI capabilities to aid agricultural and ecological decision-making. In this and the subsequent section, we present the development of an IIS for agricultural ecosystem management.

The AEEIS system provides a variety of functions including secure and automated exchange of data, data warehousing, data mining, online analytical processing (OLAP), knowledge management, and information dissemination. Fig. 1 shows the structure of AEEIS that consists of an operational database that integrates data from EIS, IISs, online transaction processing system (OLTP), legacy systems and other sources, ETL, data warehouse, data mining, OLAP, and knowledge management components that process the data and information to produce BI and knowledge. It allows integrating disparate data sources into a single coherent framework. The system adopted MSMiner 3.0, described in [27], which is a software system developed in the research project entitled *Integrating Business Intelligence Into Enterprise Information Systems*, participated in by the first author of this short paper. Fig. 2 shows the menu of the software system. It is a full-fledged BI system supporting IISs such as EIS.

The concept of integrated databases is becoming commonplace as agricultural enterprises evolve to engage in digital agriculture that requires the integration of data of diverse sources. The ability to meaningfully integrate existing, yet disconnected, data sources has been included in the database system. In AEEIS, data will not only be integrated, but also be analyzed, explored, and mined for consultation tasks. The operational database in Fig. 1 stores data on characteristics of land uses and plant species or crop varieties as well as their growth conditions. The operational database consists of two layers, with land use database at the top and five vegetation databases at the bottom.

As Fig. 1 shows, the database and data warehouse provide data to the data mining, simulation modeling, and knowledge management subsystems. A number of data mining algorithms and models are

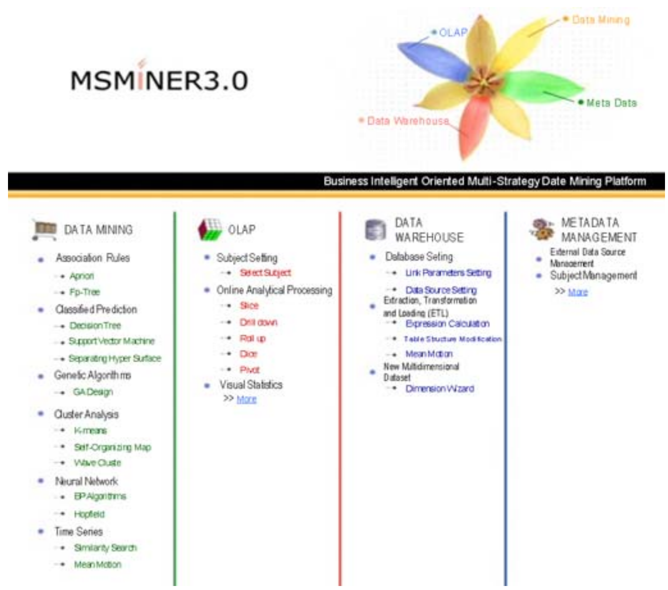

Fig. 2. MSMiner 3.0.

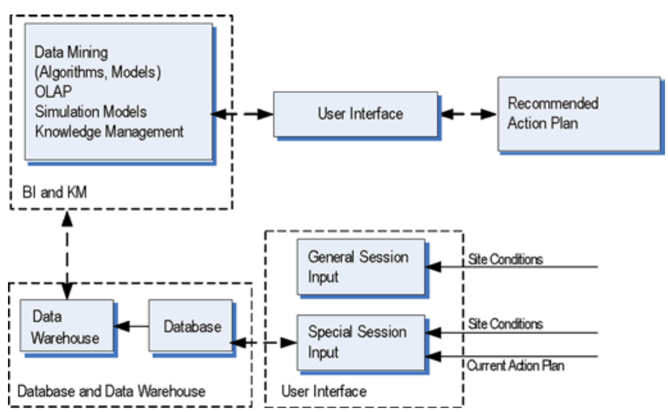

Fig. 3. Partial system flow.

incorporated in the system. For example, assuming the optimal plant coverage based on soil water balance needs to be determined, a relevant model takes into consideration the effect of precipitation, evaporation, and surface runoff and underground seepage due to slope inclination on soil water dynamics. While precipitation is regarded as an independent climatic variable, evaporation is considered to be determined by a number of factors such as temperature, relative humidity, wind velocity, plant species/varieties and their coverage, etc. Runoff and seepage are regarded as functions of slope inclination, vegetation coverage, intensity of precipitation, and saturate soil hydraulic conductivity. The model takes plant coverage as an independent variable and runs for best coverage so that, at equilibrium, yearly average soil water content reaches its maximum. Equipped with a data visualization facility, the output of a typical consulting session includes proposed land use (crop farmland, trees, fruit trees, managed pasture, or seminatural vegetation with little cultivation operation), proposed plant species or crop varieties, and suggested coverage range of vegetation based on soil water balance.

Fig. 3 depicts partial system flow of AEEIS that consists of a database, a data warehouse, a BI and knowledge management component, and a user interface. The database includes land use, crop, tree, fruit tree, managed pasture, and seminatural vegetation data (see Sections III-A and B). The user can input requests to activate the system, which performs interactive process using data, data warehouse, data mining, or knowledge components as appropriate. Relevant data, information, and knowledge are synthesized. Site conditions may include the following: geographical latitude, annual precipitation, annual mean temperature, annual accumulated biological temperature, slope and aspect angels, land cover type, and soil fertility grades. The output of a consultation session includes the recommendations on land use, crop farmland, trees, fruit trees, managed pasture or seminatural vegetation with little cultivation operation, recommended plant species or crop varieties, and recommended coverage range of vegetation based on soil balance. The user can also input site conditions plus accompanying plant proposals into the system for a special session.

A. Operational Data Source: Land Use Database

Land use database covers data on crops, forestry, fruit trees, managed pasture, and seminatural vegetation that are described in terms of the following six attributes.

1) *Topographical Type:* The topography in grassland area is decomposed into four classes: hard hills, soft hills, lower wetlands, and bare sand dunes.
2) *Thickness of Sand Cover:* Each topographical type can be covered with sand of variable thickness.
3) *Slope Angle:* The slope angle of a patch of land is defined as the angle between the land surface and horizontal plane.
4) *Aspect Angle:* The aspect angle is the angle between the projection of the out-normal vector of the land surface on horizontal plane and the due south direction.
5) *Soil Types:* Twenty-one soil types, such as meadow brown soil, chestnut soil, semifixed sandy soil, etc., are used.
6) *Soil Texture:* Soil texture refers to the mechanical property of the soil, such as sandy loam, clay, sands and gravel, etc.

B. Operational Data Source: Vegetation Database

The vegetation database is composed of five independent subdatabases, corresponding to the five land use types. The internal structures of the database is as follows.

1) *Subdatabase for Crop Fields:* Each record in the database for crop fields is headed by two keywords of text values: crop name and variety name, and followed by the attributes associated with specific crop varieties.
2) *Subdatabase for Trees:* Similar to the crop database, the tree database takes the family name and species name as keywords. Attributes associated with a specific tree species are topographical type and slope angle.
3) *Subdatabase for Fruit Trees:* Fruit name and variety name are keywords in fruit tree database. The attributes describing fruit variety recorded in the database are: a) accumulated biological temperature and b) relative location of the site in the area, such as "south," "north," "northeast," etc.
4) *Subdatabase for Managed Pasture:* The managed pasture database adopts keywords such as family name and species name of grass plants, and attributes associated with the grass included: a) topographical type; b) thickness of sand cover; c) slope angle; and d) soil type.
5) *Subdatabase for Seminatural Vegetation:* The land use type of seminatural vegetation recorded the existing plant species of seminatural vegetation and the associated seminatural environmental conditions.

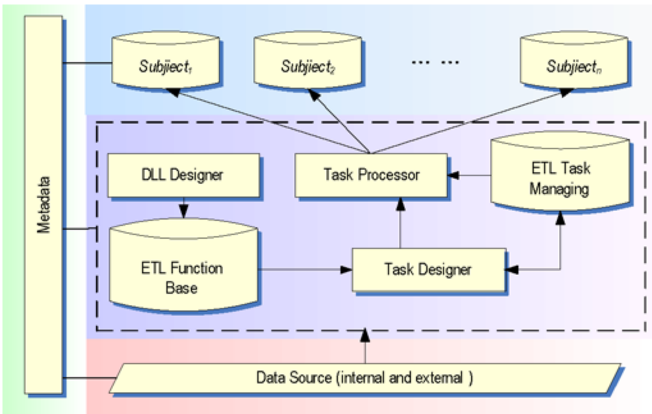

Fig. 4. ETL subsystem.

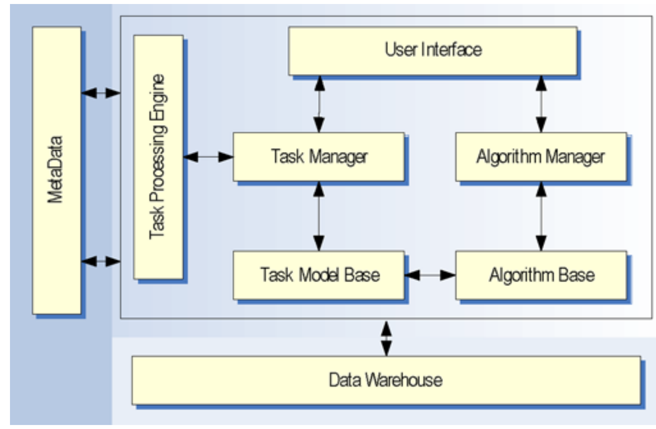

Fig. 5. Data mining subsystem.

IV. Data Warehousing, Data Mining, Simulation Modeling, and Knowledge Management

A. ETL, Data Warehouse, and OLAP

To accommodate *ad hoc* data analysis requests, data must be converted into the same data format and integrated into the data warehouse. In AEEIS, the function of the data warehouse is to provide a general data environment in which agricultural enterprise users can create and maintain their EIS data warehouse for providing data to data mining or OLAP tasks. It is a core for decision support at the managerial or strategic level that separates from operational data.

The data warehouse in AEEIS covers a basic set of the aforementioned important subjects in agricultural ecosystem environment. As the data warehouse is created, users can select subjects according to the application needs, and the system helps users to extract the data for each subject and develop data models including star schema, snow schema, etc. The data warehouse is able to provide multidimensional data to OLAP and help facilitate data visualization.

The main function of ETL is to transform the data from EIS operational data source to analytical data in the data warehouse. The ETL subsystem is to complete the following two main tasks: 1) since data come from disperse sources, ETL is expected to integrate data and 2) ETL is expected to transform the original data structure to subject-oriented structure. The architecture of ETL subsystem is shown in Fig. 4 with main functions as follows.

1) *Integrated ETL function management and ETL task management:* This module handles registering new ETL dynamic link lib (DLL) functions, building new ETL tasks, scheduling and processing ETL tasks.
2) *Uniform metadata management:* All of the metadata related to data source, algorithms, and results are managed by metadata.
3) *User-friendly interface:* Users can perform ETL operations through this interface such as designing ETL tasks, registering new ETL DLL functions, scheduling/executing ETL tasks, and querying the result of ETL tasks.
4) Supporting disperse and various databases such as Oracle, SQL Server, DB2, etc.
5) *Expandable ETL function base:* The main algorithms for ETL functions are realized in terms of DLL with the uniform interface. Users can design an ETL task by choosing the relevant ETL DLLs, developing new ETL DLLs with the uniform interface, and adding them to the ETL function base. In order to improve the efficiency, ETL tasks can be scheduled at designated time and processed concurrently.

Once the data are extracted and transformed to the required format, OLAP is realized through relational OLAP (ROLAP) that is based on a star schema. As OLAP operations are executed in data cube, multidimensional analysis translates requests into SQL statements, making queries to fact tables; the results are shown in the form of multidimensions. The system supports standard OLAP operations, such as slicing, dicing, roll up, drill-down, and pivoting. The results can be displayed in a variety of formats such as cross-tabulation tables, bar charts, pie charts, or other forms of graphical outputs.

B. Data Mining and Simulation Modeling

Data mining and mathematical models are indispensable tools in agricultural/ecological research and consulting. One of the aims is to discover hidden data patterns in the agricultural ecosystems for managing purposes. The data mining subsystem executes data mining tasks with the data obtained from the data warehouse. This component mainly includes mining algorithms, algorithm manager, task manager, and task processing engine. Algorithm manager is in charge of registering algorithms and determining which algorithm will be approved for data mining tasks. The task manager helps select data sources and mining algorithms, and developing corresponding task models through task wizard. The function of task processing engine is to schedule and execute tasks using multithread technology. The architecture of data mining subsystem is shown in Fig. 5.

In the subsystem, the major algorithms are realized in terms of DLL. A set of standard interfaces for the DLLs that embed data mining algorithms is defined. An algorithm as encapsulated with the interface can be integrated conveniently. At present, the subsystem incorporates a number of novel algorithms that are applied to classification, prediction, clustering, and other applications [28]. For end users, the results from data mining may be difficult to understand. The system provides an explainer to help users understand the results. The explainer can explain the mining results in various visual forms.

In addition to models on lands, weather and climate, and planting that are incorporated, the sustainable development of agriculture sector requires a systematic and holistic approach [6], [17], [19], [21], [23], [25]. Therefore, selected models on socioeconomic systems analysis have been developed such as dynamic simulations models in order to integrate both natural and socioeconomic contexts systematically into decision-making in agriculture management [23]. The dynamic simulation model developed by authors is in the process of modification and integration [21]. As agricultural planning prepares from the standpoint of systems approach for sustainable development and growth, it is possible that the plan can be environmentally and ecologically friendly, economically profitably, and socially acceptable.

C. Simulation Modeling: Sample Model for Determining Optimal Plant Coverage

One of the models included in the system is a simulation model for soil water balance for studying the optimal plant coverage in light of different site conditions and plant species/varieties [29]. The model can provide numerical values of yearly average soil water content as a function of plant coverage. The assumptions of the model include the following.

1) Soil water is a key factor for both vegetation development and desertification prevention. Thus, soil water content is used as an important ecological index.
2) Soil water content at a specific site is computed as effective precipitation, defined as actual precipitation minus runoff, transpiration, and soil seepage along the slope.
3) Except precipitation, which is regarded as independent climatic variable, runoff, evapotranspiration, and seepage flow are all affected by surface vegetation types and coverage.
4) Vegetation has mixed effects on soil water dynamics: a) vegetation tends to reduce the effective precipitation by reducing the penetration of water into soil surface as vegetation is present; b) vegetation also tends to increase the transpiration rate, and therefore, the total water loss, as soil surface evaporation is usually small for sandy soil. Root systems of plants can produce organic matter to hold soil water, and thus, to reduce seepage flow.

The soil water balance model describes the dynamics of water content of approximately 2-m-thick surface soil. The surface soil water content, denoted as *W*, is defined as the volumetric water content integrated over the thickness of the surface soil. A site is considered as having aspect angle A, slope angle α, vegetation coverage C, annual average precipitation $P(t)$, and measured pan evapotranspiration $E_p(t)$, as functions of time t. The potential leaf area index $L_{\mathrm{ai}}(t)$ is defined as leaf area index with vegetation coverage equal to 1.0. The actual leaf area index is $CL_{\mathrm{ai}}(t)$ and the actual transpiration is computed as $E_p(t)CL_{\mathrm{ai}}(t)$. A seepage function $g(C, r, W, \alpha)$ defined in terms of average soil water content $W(t)$ (in centimeters), seepage resisting coefficient *r*, vegetation coverage C, and slope angle α is used to describe the resistive effect of plant root system on slope seepage flow. With all the quantities defined before, the following is the equation for soil water dynamics:

$$\frac{dW}{dt} = P(t)[\lambda_v(\alpha)C + \lambda_s(\alpha)(1-C)] - CL_{\mathrm{ai}}(t)E_p(t)\left[\frac{W-W_L}{W_H-W_L}\right] - g(C,r,W,\alpha). \quad (1)$$

Soil water content W is bounded by maximum water capacity in surface soil W_H and the minimum soil water content W_L. The functions and parameters in (1) are specified as follows.

1) *Precipitation Function* $P(t)$: Assume that $P(t)$ takes the form of $P(t) = P_0\psi(t)$, where P_0 is the mean yearly total precipitation in centimeters and $\psi(t)$represents precipitation distribution profile. It is assumed that yearly precipitation concentrates in June, July, and August, and the maximum value of precipitation appears at the end of July or the beginning of August. A triangular function is used for $\psi(t)$ as follows:

$$\psi(t) = \begin{cases} 0, & t < 0.417 \\ 48(t-0.417), & 0.417 \le t < 0.583 \\ 96(0.667-t), & 0.583 \le t \le 0.667 \\ 0, & t > 0.667. \end{cases} \quad (2)$$

2) *Penetration Coefficients Symbol* λ_v *and Symbol* λ_s: Penetration coefficients are determined by hydraulic conductivity of surface soil and the slope angle. Starting with a flat soil surface with saturated hydraulic conductivity K_{0v} for soil with vegetation and K_{0s} for soil without vegetation, the penetration coefficient for soil with vegetation is

$$\lambda_v(0) = \begin{cases} 1.0, & P(t) < K_{0v} \\ K_{0v}/P(t), & P(t) \ge K_{0v}. \end{cases} \quad (3)$$

It is assumed that soil surfaces with or without vegetation are uniformly meshed and the hydraulic conductivity of the surface with vegetation is always lesser than that of the surface without vegetation, i.e., $K_{0v} < K_{0s}$. As precipitation intensity is somewhere between K_{0v} and K_{0s}, runoff from the surface with vegetation will distribute water into the surface without vegetation, thus increasing the effective precipitation of the surface without vegetation. Considering the mixing effect of vegetation surface and nonvegetation surface, the following is the expression for λ_s:

$$\lambda_s(0) = \begin{cases} 1.0, & P(t) < (1-C)K_{0s} + CK_{0v} \\ K_{0s}/P(t), & P(t) \ge (1-C)K_{0s} + CK_{0v}. \end{cases} \quad (4)$$

The effects of slope on penetration coefficients can then be combined into the expression for penetration coefficients as follows:

$$\begin{cases} \lambda_s(\alpha) = \lambda_s(0)\cos\alpha \\ \lambda_v(\alpha) = \lambda_v(0)\cos\alpha. \end{cases} \quad (5)$$

3) *Vegetation Leaf Area Index* $L_{\mathrm{ai}}(t)$: $L_{\mathrm{ai}}(t)$ is a function of time *t* and vegetation type (plant species). It is supposed to take a form of $L_{\mathrm{ai}}(t) = L_0V(t)$, where L_0 is a coefficient depending on plant species. Specifically, L_0 is the maximum vegetation leaf area index with coverage equals to 1.0. $V(t)$ describes the seasonal profile of plant leaf growth. In particular, $V(t)$ assumes the form

$$V(t) = \begin{cases} 0, & 0.0 < t < t_0 \\ (t-t_0)/(t_1-t_0), & t_0 \le t < t_1 \\ 1.0, & t_1 \le t < t_2 \\ (t_3-t)/(t_3-t_2), & t_2 \le t \le t_3 \\ 0, & t > t_3 \end{cases} \quad (6)$$

where $t_0,\ t_1,\ t_2,\ \mathrm{and}\ t_3$ are time constants specifying initiation, growth, maintenance, and senescence of plant leaves. Observations [29], [30] on plant communities are used to parameterize $L_{\mathrm{ai}}(t)$ to obtain L_0 and these time constants. These values are used as default values for the model.

4) *Potential Transpiration Rate* $E_p(t)$: Measured pan evaporation is used as the potential evapotranspiration rate on a flat surface. Since surface evaporation of sandy soils has been proven to be very small compared to transpiration by plants, we consider that transpiration by plants is approximately the total evapotranspiration. Thus, $E_p(t) = E_0(t) \in (t)$, where E_0 is the measured average yearly total pan evaporation in meteorological station and $\in (t)$ is the distribution profile of E_0. In particular, it is considered to be related to the slope and aspect angles as well as the annual course of solar height, i.e.,

$$\varepsilon(t) = \frac{\max[0, \cosh(t)\sin\,\alpha\,\cos[a(t)-A]+\sinh(t)\cos\,\alpha]}{\int_0^1 \max[0, \cosh(\tau)\sin\,\alpha\,\cos[a(\tau)-A]+\sinh(\tau)\cos\,\alpha]d\tau} \quad (7)$$

where $h(t)$ is the solar height, $\alpha(t)$ is the aspect angle of the Sun ray, and t is time in year. The definition of $h(t)$ and $\alpha(t)$ are listed later

$$\sinh = \sin\,\phi\,\sin\,\delta + \cos\,\phi\,\cos\,\delta\,\cos\,\omega \tag{8}$$

where ϕ is the geographical latitude, δ is the zenith angle with

$$\sin\,\delta = \sin(23.45^\circ)\sin[2\pi(t - 0.227)] \tag{9}$$

and $\omega = 2\pi(365.25t - 0.5)$ is the time angle.

5) *Potential Seepage Function* $g(C, r, W, \alpha)$: Potential seepage is one type of main soil water losses of sandy slopes. The seepage function should meet the conditions such as: a) when soil water content is less than the minimum water content, seepage flux approximately equals zero; b) seepage flux should be bounded by an upper limit with given slope angle and soil properties; c) the function should be able to reflect the water retention by root system of plants. The seepage function is assumed to take the form

$$g(C, r, W, \alpha) = \begin{cases} 0, & W < W_L \\ g_0(1 - rC)(W - W_L)\sin\,\alpha, & \\ & W_L \le W \le W_H \end{cases} \tag{10}$$

where g_0 (per year) is a constant reflecting soil properties, especially soil hydraulic conductivity. For most sandy land soil, it is empirically chosen to be 4.0. The variable *r* is the seepage resisting coefficient of vegetation depending on vegetation type and should be in the range of [0, 1]; *r* = 0 means that plant root has no effect on water retention. On the other hand, *r* = 1 means that the soil seepage will be zero when vegetation coverage is 1.0.

6) *Model Parameterization and Simulation Process*: The model presented before is a simple one with only 11 parameters. Of the 11 parameters, $P_0,\ L_0,\ E_0,\ a,\ A,\ \psi$ can easily be specified by users. Corresponding to 15% maximum and 3% minimum volumetric soil water contents in the 2-m-thick soil, W_H and W_L are set to 30 and 6 cm, respectively. K_{0v} and K_{0s} are set to 70 m per year and 1000 m per year, typical values for sandy soils. g_0 is empirically set to 4.0 per year. A complete sensitivity analysis and justification of the assumptions has been completed [29], [30]. Whenever the system is activated and there is a request to run the model, it will run with parameters defined by users or the default values of parameters and variable plant coverage values from 0.0 to 1.0 at an increment of 0.1. For each value of C, (1) is solved with repeated yearly cycles until a steady-state solution, with value of W at the start of a year equal to the value at the end of the year, is reached. Then, the user is able to decide appropriate plant coverage by inspecting the yearly mean soil water content at steady state as a function of vegetation coverage.

D. Simulation Modeling: Sample Dynamic Model

GEMOD is a model for the purpose of dynamic modeling that is embedded in the system [29], [30]. It has not only the same function as provided by other general dynamic modeling software such as DYNAMO, but also the following features.

1) It provides solutions to mixed systems consisting of differential equations (such as logistic model), difference equations (such as matrix models of population ecology), and general algebraic equations.
2) It fits parameters for the aforementioned systems.
3) It provides modeling capability for studying gray systems.
4) It has a built-in library of special functions including Bessel function, error function, Gamma function, etc.
5) It enables the defining of functions such as rational function, irrational function, transcendental function, piecewise function, even numerical function by users.
6) It produces graphic outputs in many forms.

For small- or medium-sized ecosystems, GEMOD is one of the most powerful tools for dynamic modeling. It can take care of model parameterization. Determining the changes to be made to system variables according to the known parameters and model structure, and estimating model parameters according to the observed values of system variables are two basic features of GEMOD that can be described as

$$1)\ \begin{cases} \dot{x}^1 = f_1(x^1, x^2, \ldots, x^N, P_1^1, P_2^1, \ldots, P_{S_1}^1, t) \\ \dot{x}^2 = f_2(x^1, x^2, \ldots, x^N, P_1^2, P_2^2, \ldots, P_{S_2}^2, t) \\ \vdots \\ \dot{x}^m = f_m(x^1, x^2, \ldots, x^N, P_1^m, P_2^m, \ldots, P_{S_m}^m, t) \\ x^{m+1} = g_1(x^1, x^2, \ldots, x^m, P_1^{m+1}, P_2^{m+1}, \ldots, P_{S_{m+1}}^{m+1}, t) \\ x^{m+2} = g_2(x^1, x^2, \ldots, x^m, P_1^{m+2}, P_2^{m+2}, \ldots, P_{S_{m+2}}^{m+2}, t) \\ \vdots \\ x^N = g_{N-m}(x^1, x^2, \ldots, x^m, P_1^N, P_2^N, \ldots, P_{S_N}^N, t) \end{cases}$$

where $x^1, x^2, \ldots, x^N$ are system variables or state variables, $\dot{x}^i$ is the derivative of the *i*th system variable over time ($i = 1, 2, \ldots, m$), t represents time, $f_1, f_2, \ldots, f_m$ and $g_1, g_2, \ldots, g_{N-m}$ represent total *N* model definition functions, f_i, $i = 1, 2, \ldots, m$, defines the time derivative of $\dot{x}^i$, and g_i, $i = 1, 2, \ldots, N - m$ defines x^{i+m} itself. Expression 1) represents a system consisting of *m* ordinary differential equations and $N - m$ algebra equalities. According to the theory [30], $\dot{x}^i$'s, $i = 1, 2, \ldots, m$, are the *m* slow variables and $\dot{x}^i$'s, $i = m + 1,\ m + 2, \ldots, N$, are fast variables. A system that is consisted of both fast variables and slow variables is called generalized system. Expression 1) may take the following discrete form:

$$2)\ \begin{cases} x_{k+1}^1 = f_1(x_k^1, x_k^2, \ldots, x_k^N, P_1^1, P_2^1, \ldots, P_{s_1}^1, t_k) \\ x_{k+1}^2 = f_2(x_k^1, x_k^2, \ldots, x_k^N, P_1^2, P_2^2, \ldots, P_{s_2}^2, t_k) \\ \vdots \\ x_{k+1}^m = f_m(x_k^1, x_k^2, \ldots, x_k^N, P_1^m, P_2^m, \ldots, P_{s_m}^m, t_k) \\ x_k^{m+1} = g_1(x_k^1, x_k^2, \ldots, x_k^m, P_1^{m+1}, P_2^{m+1}, \ldots, P_{s_{m+1}}^{m+1}, t_k) \\ \vdots \\ x_k^N = g_{N-m}(x_k^1, x_k^2, \ldots, x_k^m, P_1^N, P_2^N, \ldots, P_{S_N}^N, t_k) \end{cases}$$

where x_k^i is the value of variable $\dot{x}^i$ at the moment t_k. According to expression 1) or 2), we can find out that there are total $\sum_{i=1}^{N}\sum_{j=1}^{S_i} P_j^i$ parameters.

For the system represented by expression 1) and expression 2), GEMOD can process in the following two directions.

1) Given parameters P_j^i's, $i = 1, 2, \ldots, N$, $j = 1, 2, \ldots, S_i$, integral interval $[t_0, t_f]$, and initial conditions $x^i(t_0)$, $i = 1, 2, \ldots, m$, by numerical method, GEMOD can obtain $x^i(t_k)$, $i = 1, 2, \ldots, N$, $k = 0, 1, 2, \ldots, n$, and *n* is the number of times by which the interval $[t_0, t_f]$ is divided evenly, i.e., $t_n = t_f$.
2) For $x^i(t_k)$, $i = 1, 2, \ldots, N$, $k = 0, 1, 2, \ldots, n$, observed values of system variables at time serials $t_0, t_1, \ldots, t_n$, GEMOD will take care of parameterization and provide the optimal estimation of P_j^i. The distance between every two of $t_0, t_1, \ldots, t_n$ may not be equidistant. The method used is least squares method. If the forms of f_i and g_i over parameters are linear, then GEMOD will adopt linear least squares method; otherwise, GEMOD will

automatically take nonlinear least squares method to perform iterative fitting. The fitting steps are as follows.

a) Write equations in expression (1) or (2) as the unified representative of discrete time series

$$3) \qquad y_j^i = F^i(\tilde{P}^i, \tilde{x}_j, t_j), \qquad i = 1, 2, \dots, N$$

where $\tilde{x}_j$ is the value of the vector consisting of $x^1, x^2, \dots, x^N$ at moment t_j; $\tilde{P}^i$ is the parameter vector of equation *i* with dimension S_i. The variable y_j^i takes different meanings for different equations: for a differential equation, y_j^i is the value of $\dot{x}^i$, which is the derivative of $\dot{x}^i$ over time at moment t_j; if equation *i* is a difference equation, then $y_j^i = x^i(t_{j+1})$; lastly, if equation *i* is an algebraic equation, then y_j^i is exactly $x^i(t_j)$. For algebraic equations, as $i > m$, the dimensions of $\tilde{x}_j$ equal to that of *m*. For difference and algebraic equations, x_j's are observed values of known system variables, but for differential equation, approximate method is used to provide the following expression:

$$4) \qquad y_j^i = \dot{x}_j^i = \frac{1}{2}\left[\frac{x_j^i - x_{j-1}^i}{t_j - t_{j-1}} + \frac{x_{j+1}^i - x_j^i}{t_{j+1} - t_j}\right], \qquad j = 1, 2, \dots, n-1.$$

F^i in expression 3) equals f_i or g_i.

b) Take the computational value of the right-hand side of expression 3) as $\hat{y}_j^i$, which is the estimate or predictive value of y_j^i, saying $\hat{y}_j^i = F^i(\tilde{P}^i, \tilde{x}_j, t_j)$. Then, we can get nonlinear normalized equation by least squares principle

$$5) \qquad [F_P^i]\left\{\hat{Y}^i\right\}' = [F_P^i]\left\{Y^i\right\}'.$$

The definitions of matrices in expression 5) are as follows.

$\left\{\hat{Y}^i\right\}$ is a column vector with r dimensions (for differential equation, difference equation, and algebraic equation, r takes values of *n* − 2, *n* − 1, and *n*, respectively), whose element is y_j^i, $j = 1, 2, \dots, r$; $\{Y^i\} = \{y_1^i, y_2^i, \dots, y_r^i\}^T$ is a vector of observed values. There are S_i rows and *r* columns in matrix $[F_P^i]$, whose element $F_P^i(j,k)$ is defined as the value of $\partial F^i / \partial P_j^i$ at moment t_k. Expression 5) defines a group of nonlinear algebraic equations about $\tilde{P}^i$, and the formula of iterative method obtained by Gauss–Newton method is

$$6) \qquad \tilde{P}_{I+1}^i = \tilde{P}_I^i + [[F_P^i][F_P^i]^T]^{-1}[F_P][\{Y^i\} - \{\hat{Y}^i\}]$$

where $\tilde{P}_I^i$ and $\tilde{P}_{I+1}^i$ represent the value of vector $\tilde{P}^i$ in the *I*th and $(I+1)$th iterative calculation, respectively. The iterative operation will not stop until convergence is reached. Thus, it can be seen that the premise for fitting calculation is that functions f_i and g_i in model equations must be analytic to $\tilde{P}^i$ and the representatives of f_i, g_i, and $(\partial f_i / \partial_k^i), (\partial g_i / \partial P_k^i)$ are required to be given by users.

The aforementioned method is the nonlinear square method for general systems with nonlinear parameters. The calculation can reach convergence point only when the initial values of parameters are close enough to their terminal values. If the parameters are linear, GEMOD can automatically test whether the system is linear or nonlinear, then the fitting process is very simple and parameters can be estimated by linear least squares method.

Multiple types of graphical outputs are another feature of GEMOD. Graphical outputs include the display of relation between system variables and time, the display of system variables over system variables (phase plane), and the comparison of theoretical values of system variables with observed values. Fig. 6 shows examples of the model.

In general, model definition is composed of two basic parts. The first part includes the descriptions of variables (VARIABLE), parameters

```
MODEL: GRASS_WATER-BIOMASS (Optimal HarveSting Model)

VARIABLE: T, WATER, MASS, EVAP, GRATE, U, UD =  {[0.0, 1.0],
                                0.643, 3.675, 0.0, 0.2, 0.61, 0.67};
PARAMETER: EQ[1] { P0, SP, ALPHA0, SA, KA} =  { 400.0, 0.5,
                                                0.0001, 0.7, 0.5};
           EQ[2] {F0, SG, A, KD} = { 0.35, 0.3, 0.0001, 0.4};
FUNCTION: ALPHA, PR, F, FW, FT, ALPHAD, QG, Q(t, S), G0, G1, L(t, S);
N_AGO = 0;

BEGIN:
    EQ[1]: WATER.D = PR - EVAP;
    EQ[2]: MASS.D = GRATE - U;
    EQ[3]: U.D = UD;
    EQ[4]: UD.D = - ( UD * ( UD / U + G1 ) + 0.5 * G0 * U);
    EQ[5]: EVAP. = ALPHA * MASS * WATER;
    EQ[6]: GRATE. = MASS * F;
    FW = F0  * (1.0 - 2.0 * WATER * A ) * QG;
    FT = F0 * WATER * (1.0 - A * WATER) * L ( T, SG );
    ALPHA = ALPHA0 * Q ( T, SA ) + KA;
    F =  ......;
    PR = P0 * Q (T, SP);
    ALPHAD = ALPHA0 * L (T, SA);
    G0 = ......;
    G1 = ......;
    QG = Q (T, SG);
    Q ( t, S ) = [ t < S / 2.0 ]         2.0 * ( t / S ) ^ 2,
                 [ t < S ]               1.0 - 2.0 * ( ( S-t ) / S ) ^ 2,
                 [ t < ( 1 + S) / 2.0 ]  1.0 - 2.0 * ( ( t - S ) / ( 1 - S ) ) ^ 2,
                                         2.0 * ( ( 1 - t ) / ( 1 - S ) ) ^ 2;

    L ( t, S ) = [ t < S / 2.0 ]         4.0 *  t / S / S,
                 [ t < S ]               4.0 * ( S - t ) / S / S,
                 [ t < ( 1 + S ) / 2.0 ] - 4.0 * ( t - S ) / ( 1 - S ) ^ 2,
                                         - 4.0 * ( 1 - t ) / ( 1 - S ) ^ 2;
```

```
MODEL: PREDATOR_PRAY  ( NONLINEAR, EXPLICIT );

VARIABLE: T, RABIT, FOX, ST = { [ 0.0, 2.9], 0.4, 0.3, 1.0 };
PARAMETER: EQ [ 1 ] { A31, A32 } = { 0.5, 1.8 };
           EQ [ 2 ] { A11, A12 } = { 3.0, 1.5 };
           EQ [ 3 ] { A21, A22 } = { 2.0, 2.5 };
FUNCTION: AV1, AV2;
N_AGO = 0;

BEGIN:
    EQ [ 1 ]: ST. = A31 * RABIT + A32 * A31 * AV2;
              D_1_1 = RABIT;     D_1_2 = A31 * AV2;

    EQ [ 2 ]: RABIT.D = A11 * RABIT - A12 * A11 * AV1;
              D_2_1 = RABIT;     D_2_2 = - A11 * AV1;

    EQ [ 3 ]: FOX.D = A21 * AV1 - A22 * FOX;
              D_3_1 = AV1;       D_3_2 = - FOX;

    AV1 = RABIT * FOX;
    AV2 = FOX ^ 2;
END;
```

Fig. 6. Model definition examples.

(PARAMETER), and functions (FUNCTION), and the determination of the number of accumulation generating operation (N_AGO). The second part (from BEGIN to END) is the main body of the model. The definitions of system variables, functions defined by users, and the partial derivatives of right representatives in state equations over parameters are included in this part.

To sum up, GEMOD possesses functions of estimating model parameters according to observed data and solving system as well as making dynamic prediction according to model and parameters. It provides a rich library of functions, flexible self-defined functions, simple and convenient model definition, and graphical outputs in multiforms. GEMOD is a powerful tool for simulating middle- and small-sized ecosystems.

E. Knowledge Management

In 2004, Perini and Susi suggested that a systems approach is desirable for designing agricultural and ecological system [6], i.e., a problem should be analyzed in terms of data, information, and knowledge. Research also pointed out that the performance of IISs can be enhanced by knowledge management. In recent years, knowledge management has been emphasized in agriculture as well as ecosystem management as an effective way to make use of empirical knowledge of human experts. The knowledge base in the system stores knowledge acquired from agricultural and ecosystem experts. Different knowledge sources can be integrated including existing literature and expert opinion. The management's involvement in the knowledge acquisition process allows the integration of socioeconomic aspects to assess the multidimensionality of sustainability. The knowledge management component performs logical reasoning and knowledge synthesis, and generates solutions to specific problems [31].

Fig. 7 shows the architecture of the knowledge management subsystem. The system has components such as knowledge acquisition unit, knowledge base, logical inference center, and applications. Users can input site conditions to activate the process such as knowledge management. The knowledge management unit will synthesize the relevant knowledge segments, and finally, providing a recommended planting proposal. The system's knowledge base is integrated with the six operational databases and stores rules and facts about characteristics of land uses and plant species or crop varieties as well as their growth conditions [32]. These rules and facts are derived from databases, data mining results, simulation modeling results, as well as the knowledge directly acquired from agricultural experts and ecologists. The knowledge in

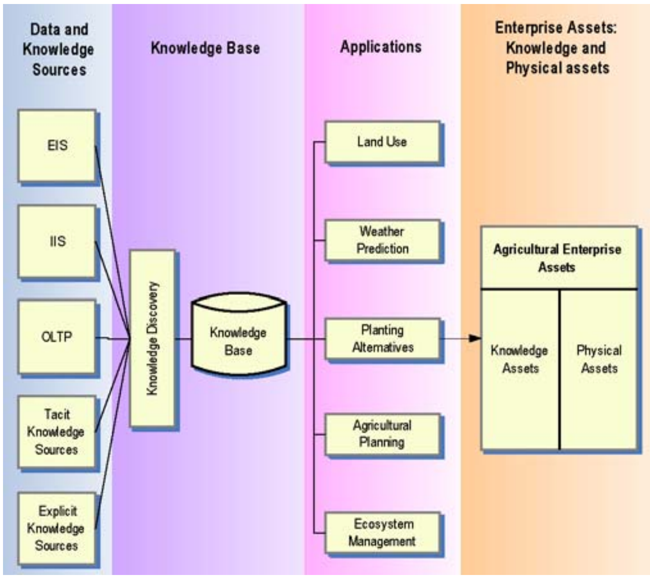

Fig. 7. Knowledge management subsystem.

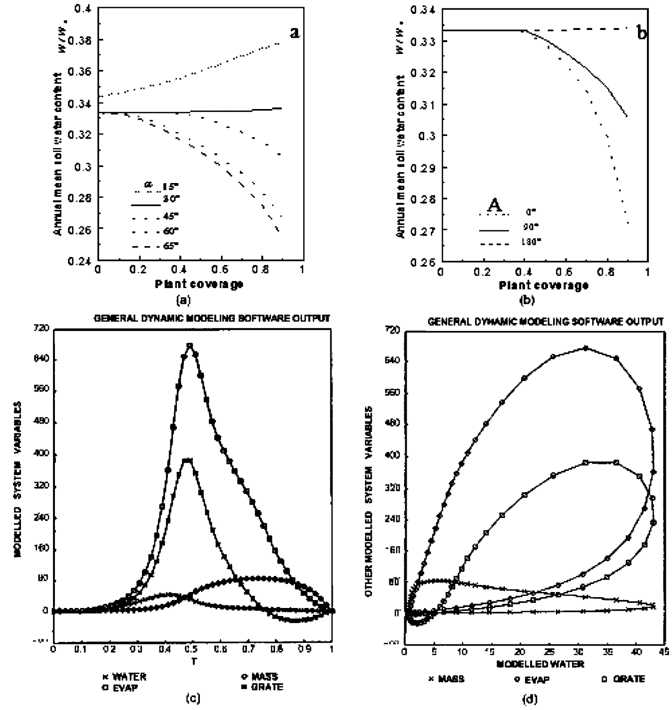

Fig. 8. Sample outputs.

the knowledge bases is represented in terms of multiple formats including IF-THEN rules. The knowledge processor of the system can accept "facts," decompose the facts into individual knowledge segments, and store them appropriately.

F. Application Example

The system developed in this research has been tested and applied in a number of grassland sites including Maowusu sandy grassland. Maowusu sandy grassland is located in the middle and southern part of Ertos plateau (east longitude: $106^\circ27'$–$111^\circ28'$; northern latitude: $37^\circ38'$–$40^\circ52'$). This area has typical continental semiarid climatic conditions. Annual precipitation of the area ranges from 401.6 mm in the southeast to 162.4 mm in the northwest, with more than 60% of precipitation concentrate in two summer months. Measured annual pan evaporation in the area varies from 2047 to 3085 mm. The annual mean temperature is about 6 °C, with monthly mean temperature of 22 °C in July and -11 °C in January. It is not difficult to postulate a severe hydrological limitation for vegetation development and to realize the importance of water budgeting for local agricultural management.

The problem of insufficient water supply is further complicated by sandy soil, which has poor water retention capability and large hydraulic conductivity, and the diversity of hilly landscapes reflecting great spatial heterogeneity. The geographical area is meshed with basically four types of landscape components: hard hills resulting from erosion and aging of bedrock, soft hills consisting of sediments accumulated during the quaternary period, lower wetlands resulting from cuffing on the quaternary sediments by rivers and stream, and bare sand dunes. The first three types of landscape components can be covered with sands of variable thickness.

Past inappropriate agricultural management has caused much degradation of the sandy grassland, with decreased biomass production, vegetation coverage, and increased coverage of bare sand dunes. Agricultural management has begun to realize the importance of applying ecological principles to management and policy-making, so a number of research projects have been implemented to investigate the ecosystem dynamics of the hilly sandy grasslands [29], [30].

While observational studies on soil water dynamics in the geographical area are intensively carried out for various particular situations, investigation on seasonal dynamics of the biological aspects of the sandy grassland ecosystems is much weaker. The empirical knowledge of local agricultural experts is still one of the main sources to utilize in grassland management. The complicated site conditions of four different landscapes and the lack of quantitative understanding of adaptability of plants to a specific site make it appropriate to use knowledge management for local agricultural management. As a result, the knowledge management subsystem that synthesizes the empirical knowledge of agricultural experts is employed. The knowledge management subsystem, in conjunction with other components in the system, is designed to help solve managerial problems involving land use, plant species/varieties selection for a specific site, and optimal coverage of plants for a specific site, etc. To achieve such a goal, the knowledge management subsystem emulates the problem-solving processes of human experts by incorporating the results of studies on soil water dynamics with the empirical knowledge of agricultural experts.

The system has been tested with a number of sample runs. The site conditions used in sample runs are soft hill at 38° north latitude, the annual precipitation is 360 mm, pan evaporation is 2200 mm, mean air temperature is 6.4 °C, and soil fertility grade is 1. The system has been consulted for variable slope and aspect angles. The sample results are as follows.

The first step of the process provided the information that the site was suitable for seminatural vegetation, then the system started with the seminatural vegetation data/knowledge base. It provided a list of plant species suitable for the site. Then, *Artemisia ordosica* was selected, a dominant plant for the geographical area, and supplied the system with maximum leaf area index $L_0 = 1.95$. Default values for other parameters in the model were used. The model of optimal coverage was then activated.

The effect of variable slope angles on the relation between soil water content and plant coverage was shown in Fig. 8(a). The aspect angle was set to 0 (south slope). For small plant coverage from 0.0 to 0.2, soil water content was relatively invariant for all slope angle values. For a slope angle smaller than 15°, the yearly mean soil water increases with plant coverage. However, for larger slope angles, yearly mean soil water decreases with plant coverage. An explanation was that when a slope angle was small enough, gravitational drainage was not as profound as water retention by plant roots, hence resulting in the increase in soil water with plant coverage. On the other hand, when slope angle was large enough, gravitational draining became dominant over the water retention by plant roots; thus, soil water decreased with plant coverage.

Fig. 8(a) also indicates that, to keep soil water content close to its maximum in order to prevent soil erosion or desertification, plant coverage should be adjusted or controlled for different slope angles. In general, a larger slope angle should have less plant coverage. For slope angle smaller or equal to 45°, plant coverage can go as high as 0.5; however, with a slope angle larger than 55°, plant coverage should be within 0.3.

Fig. 8(b) shows the effect of aspect angle on the relation between annual mean soil water and plant coverage, with slope angle fixed to 45°. For all aspect angle values, soil water content was largely invariant for small and moderate plant coverage value ($C < 0.4$), and decreased with coverage for larger C values. North slope ($A = 180°$) has better soil water condition than that of south slope ($A = 0°$), because of the shading attenuation of radiation by slope that leads to less evapotranspiration. The outputs of the system are consistent with the theoretical models and practices. Fig. 8(c) shows the example of GEMOD graphical output of the model illustrated in Fig. 5(a), and its phase relation is shown in Fig. 8(d).

V. Conclusion

This short paper was motivated by the need to address the gap in the application of information technology to agricultural and ecosystem management. This research presents an initial effort to propose and develop an IIS that has the potential to provide agricultural management and planners with data, information, and knowledge for agricultural decision-making. The proposed integrative framework and system is illustrated with a prototype that combines operational database, data warehouse, data mining, simulation modeling, and knowledge management for agricultural and ecosystem management with an application example of hilly sandy grasslands in north China, in order to achieve the goal of optimal management based on ecological principles. The prototype system has demonstrated the value of using IISs for analyzing agricultural and ecological data. The agricultural management is greatly benefited by such a system in their decision-making and planning activities. For example, alternate management scenarios can be studied and evaluated by altering model input parameters. In addition to agricultural and ecological models, socioeconomic models could be integrated into the system, thereby providing more comprehensive and effective decision support for management and policy-making.

Our study shows that the effectiveness of decision-making in agriculture can be improved by using IIS, especially the provision of data and knowledge and their effective integration, retrieval, analysis, and utilization for agricultural management consulting and decision-making. The study, which is a part of IAIS, opens the door for future research on a large-scale comprehensive nation-wide agriculture information infrastructure, as we are in the midst of a transition where dramatic transformations in integrated information technology offer us unprecedented opportunities to create an integrated agriculture information infrastructure. The contribution of this study includes developing a prototype IIS for agricultural and ecosystems management and enhancing the feasibility of creating a full-fledged integrated agricultural information infrastructure, as the framework could serve as a building block for the inclusion of additional integrations geared toward a full-fledged system.

There are several factors that limit our approach, and therefore, need to be discussed. We are still faced with a number of challenges before a full-fledged IIS can be fully implemented. Data standards, information system compatibility, and well-trained staff are a few significant issues. When information systems do exist at individual organizations, data formats and standards vary. These limitations present noticeable challenges to creating a national IIS. Both researchers and practitioners are currently identifying data needs and evaluating mechanisms and costs for improving data and filling the gap of an IIS. We do not target this issue directly in this short paper but work on overcoming this difficulty in related research projects.

As the agricultural and ecological information processing has evolved from stand-alone databases, to integrated information architecture, the significance of IISs is growing. One of the benefits of the prototype lies in its ability to guide future research. The results of the prototype system hold promise that we will be able to integrate more features into the system. A few suggestions for future research are proposed including standardizing and transforming a broader range of data that are stored in different formats to ensure that existing databases at various sources are integrated, and expanding knowledge management to include all the major management practices adopted in the knowledge base. As every agricultural system is a complex system of interacting components residing in a natural and socioeconomic environment [25], one of the future objectives of the IIS is to provide decision support for planning and decision-making within the complex socioeconomic environment in addition to the provision of scientific information and its effective acquisition, retrieval, analysis, and utilization for agricultural managerial decision-making. Although a number of modeling simulation models have been developed and are ready to be integrated into the system such as systems dynamics models [21], another area for research could incorporate more socioeconomic features into this single platform that integrates broader ecological, economic, and social dimensions going beyond the current level. The goal is to help agriculture management apply the IIS to the effective management of the agricultural system within the context of both natural and socioeconomic environments, and obtain insights into the long-term interactions involved in the ecological agricultural development.

Finally, it should be emphasized that this scientific effort to integrate state-of-the-art techniques for developing an integrated approach to agriculture ecosystem management is, by no means, limited to the application areas introduced in this study. This effort's main aim is not only to provide IISs that agriculture management in developing countries such as China can adopt, but also serve as a useful extending point to integrated ecosystems management in general, in order to effectively deal with the ecosystem deterioration issue in both developing and industrialized countries as a global issue. We believe that developing and applying an integrated systems approach to global ecosystem management, from interdisciplinary research, stand-alone systems such as decision support systems, to highly integrated systems such as EIS, is an emerging research area of increasing interest that may result in more effective approach to ecosystems management in years to come [5], [33]–[35].

Acknowledgment

The authors thank all research team members for their wholehearted participation during the study. They are also grateful to three anonymous referees and two anonymous associate editors for their insightful comments and thoughtful suggestions on the manuscript, which has led to improvements in the short paper.

REFERENCES

[1] S. Chaudhary, V. Sorathia, and Z. Laliwala, "Architecture of sensor based agricultural information system for effective planning of farm activities," in *Proc. 2004 IEEE Int. Conf. Services Comput.*, 2008, pp. 1–8.

[2] B. Qiu, "Digital agriculture under the framework of digital province," in *Proc. IEEE Geosci. Remote Sens. Symp.*, 2005, pp. 862–865.

[3] G. Zhu, K. Wang, and Z. Shi, "Design and technical realization of network-based management information system for modern agricultural demonstration areas," *J. Zhejiang Univ.*, vol. 31, no. 1, pp. 7–11, 2005.

[4] C. Fraisse *et al.*, "AgClimate: A climate forecast information system for agricultural risk management in the southeastern USA," *Comput. Electron. Agric.*, vol. 53, no. 1, pp. 13–27, 2006.

[5] Agricultural Software Solutions. (2008). [Online]. Available: http://www.tgiltd.com/agricultural_software_solution.html.

[6] A. Perini and A. Susi, "Developing a decision support system for integrated production in agriculture," *Environ. Model. Softw.*, vol. 19, pp. 821–829, 2004.

[7] (2007). [Online]. Available: http://www.census.gov/epcd/naics02/def/ND541690. HTM.

[8] K. Bretthauer, "Service management," *Decis. Sci.*, vol. 35, pp. 325–329, 2004.

[9] Z. Laliwala, V. Sorathia, and S. Chaudhary, "Semantic and rule based event-driven services-oriented agricultural recommendation system," in *Proc. 26th IEEE Int. Conf. Distrib. Comput. Syst. Workshops*, 2006, pp. 24–29.

[10] S. Barrington, P. Nieuwenhof, C. Vigeneault, D. Choiniere, and S. Clarke, "A computer program to size agricultural standby power units and electrical service entrances," *Comput. Electron. Agric.*, vol. 36, pp. 79–86, 2002.

[11] T. Sullivan, M. Saunders, K. Tonnessen, B. Nash, and B. Miller, "Application of a regionalized knowledge-based model for classifying the impacts of nitrogen, sulfur, and organic acids on lakewater chemistry," *Knowl.-Based Syst.*, vol. 18, pp. 55–68, 2005.

[12] J. Sell, T. Koellner, O. Weber, L. Pedroni, and R. Scholz, "Decision criteria of European and Latin American market actors for tropical forestry projects providing environmental services," *Ecol. Econ.*, vol. 58, pp. 17–36, 2006.

[13] H. Gomann, P. Kreins, R. Kunkel, and F. Wendland, "Model based impact analysis of policy options aiming at reducing diffuse pollution by agriculture—A case study for the river Ems and a sub-catchment of the Rhine," *Environ. Model. Softw.*, vol. 20, pp. 261–271, 2005.

[14] N. Lorentzos, A. Sideridis, C. Yialouris, and V. Kollias, "An integrated spatiotemporal system," *Comput. Electron. Agric.*, vol. 22, pp. 233–242, 1999.

[15] W. Wagner, "Sustainable agriculture: How to sustain a production system in a changing environment," *Int. J. Parasitol.*, vol. 29, pp. 1–5, 1999.

[16] D. Rao, "A remote sensing-based integrated approach for sustainable development of land water resources," *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 31, no. 2, pp. 207–215, May 2001.

[17] C. Pacini, A. Wossink, G. Giesen, C. Vazzana, and R. Huirne, "Evaluation of sustainability of organic, integrated and conventional farming systems: A farm and field-scale analysis," *Agric., Ecosyst. Environ.*, vol. 95, pp. 273–288, 2003.

[18] G. Bazzani, "An integrated decision support system for irrigation and water policy design: DSIRR," *Environ. Model. Softw.*, vol. 20, pp. 153–163, 2005.

[19] H. Cabezas, C. Pawlowski, A. Mayer, and N. Hoagland, "Sustainable systems theory: Ecological and other aspects," *J. Cleaner Prod.*, vol. 13, pp. 455–467, 2005.

[20] M. Rao, G. Fan, J. Thomas, G. Cherian, V. Chudiwale, and M. Awawdeh, "A web-based GIS decision support system for managing and planning USDA's conservation reserve program," *Environ. Model. Softw.*, vol. 22, pp. 1270–1280, 2007.

[21] T. Shi and R. Gill, "Developing effective policies for the sustainable development of ecological agriculture in China: The case of Jinshan County with a systems dynamics model," *Ecol. Econ.*, vol. 53, pp. 223–246, 2005.

[22] G. Bazzani, "A decision support for an integrated multi-scale analysis of irrigation: DSIRR," *J. Environ. Manage.*, vol. 77, pp. 301–314, 2005.

[23] R. Jongschaap, "Run-time calibration of simulation models by integrating remote sensing estimates of leaf area index and canopy nitrogen," *Eur. J. Agron.*, vol. 24, pp. 316–324, 2006.

[24] F. Saroinsong, K. Harashina, H. Arifin, K. Gandasasmita, and K. Sakamoto, "Practical application of a land resources information system for agricultural landscape planning," *Landsc. Urban Plan.*, vol. 79, pp. 38–52, 2007.

[25] D. Nhan, L. Phong, M. Verdegem, L. Duong, R. Bosma, and D. Little, "Integrated freshwater aquaculture, crop and livestock production in the Mekong delta, Vietnam: Determinants and the role of the pond," *Agric. Syst.*, vol. 94, pp. 445–458, 2007.

[26] R. Kishore, H. Zhang, and R. Ramesh, "Enterprise integration using the agent paradigm: Foundations of multi-agent-based integrative business information systems," *Decis. Support Syst.*, vol. 42, pp. 48–78, 2006.

[27] Z. Shi, L. Zeng, L. Xu, MSMiner 3.0, Inst. Comput. Technol., Chin. Acad. Sci., Beijing, China, Tech. Rep., 2007.

[28] L. Duan, L. Xu, F. Guo, J. Lee, and B. Yan, "A local-density based spatial clustering algorithm with noise," *Inf. Syst.*, vol. 32, pp. 978–986, 2007.

[29] N. Liang, *A Planning Advisory System of Maowusu Sandy Grassland, Inner Mongolia, China, Based on Soil Water Balance*. Beijing, China: Inst. of Botany, Chin. Acad. of Sci., 2005.

[30] Q. Gao, N. Liang, and X. Dong, "A modeling analysis on dynamics of hilly sandy grassland landscapes using spatial simulation," *Ecol. Model.*, vol. 98, pp. 163–172, 1997.

[31] E. Awad and H. Ghaziri, *Knowledge Management*. Englewood Cliffs, NJ: Prentice-Hall, 2003.

[32] M. Shaffer and M. Brodahl, "Rule-based management for simulation in agricultural decision support systems," *Comput. Electron. Agric.*, vol. 21, no. 2, pp. 135–152, 1998.

[33] J. Warfield, "Systems science serves enterprise integration: a tutorial," *Enterprise Inform. Syst.*, vol. 1, pp. 235–254, 2007.

[34] H. Hou, S. Xu, and H. Wang, "A study on X party material flow: the theory and applications," *Enterprise Inform. Syst.*, vol. 1, pp. 287–299, 2007.

[35] S. Xu, "A new discipline in the era of knowledge economy: material flow science and technology," *Syst. Res. Behav. Sci.*, vol. 23, pp. 251–257, 2006.