Computer simulation models for sustainability

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Abstract *For the broad understanding of sustainable development, items such as seasonal change, timing of restrained harvesting and the rate of regeneration of natural resources, as well as the theories of population growth are crucial. Similarly, in the world of computing as a whole and computing simulation in particular, three important components of models are theory, data and program. A model for global sustainability should include sub-models for different resources and consumers in the ecological system. In this paper, a sample of sub-models relating to areas such as human population growth, water, soil and land, greenhouse gases and* CO_2*, conservation, forests and harvesting are listed, combined with other models such as pollution, waste treatment and ozone levels. The complexity of such simulations and their relevance to the current debate on sustainability are discussed.*

Introduction

As one component of the world's biotope, humans survive by using natural resources and exploring different ecosystems. Individual ecosystems are complex in structure, composition and in the interactions of their components. Exploitation of natural resources without thorough understanding of the resulting effects of such exploitation and out of line with the concept of sustainability, will cause adverse consequences. Through systematic studies, the major components of an ecosystem have been determined and can be identified in each case. What is perhaps not in the general knowledge is that each component's role and functions can be expressed mathematically. Because both biotic and abiotic factors vary from time to time, long-term studies are necessary to explain them mathematically. Each ecosystem has its own components. Unique interactions among components can be expressed mathematically, as the body of data they entail explain items such as relationships and connections. Therefore, whole ecosystems can be considered as a huge data warehouse with networking among them and huge amounts of data stored.

Both understanding and simulation of an ecosystem are complex tasks. Usually, ecological studies can be divided into short-term, small-scale controlled experiments and long-term, large-scale experiments. The short-term, small-scale experiments are generally conducted in laboratories, greenhouses or fields. Such experiments are designed for different treatments and replications. For long-term, large-scale ecosystem studies, there may be only

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one methodology employed, which may take months or years to be fully studied. Long-term, large-scale studies also require huge budgets and are difficult or sometime impossible to be repeated. After costs of more than 200 million US dollars, the most famous ecological experiment, Biosphere 2, was described as "Nearly all the birds and animals and insects that were supposed to thrive inside the greenhouse died, except for cockroaches and 'crazy ants' that now own the place" (Dye, 1998). Biosphere2 was a expensive ecological experiment, but it only included a small portion of the Earth's unique ecosystem.

For some decades now, computer simulations have been attributed as a powerful tool to study complex ecological systems. Compared to the experimental costs, computer simulations are often cheaper, easier to conduct and to some extent, much faster than normal experiments. With the progressive depletion of environmental resources and increase in environmental problems, management strategies for these resources are even more crucial. Since natural resource management and precise predictions depend on sophisticated computer simulation models, this paper will present an overview of the essence, requirements, the scope, use and benefits of computer simulation models for sustainability.

In Figure 1, Mencius (372-289 BC) said: "If you don't interfere with the timing of the farmers, there will be more grain than can be eaten. If fine-mesh nets are kept out of the ponds and lakes, there will be more fish and turtles than you can eat. If loggers are regulated in their woodcutting, there will be more wood than can be used" (translation by Charles Muller, 1999).

Mencius pointed out some major principles of sustainability. The examples in agriculture, forestry and fishery he provided illustrated the significance of human activities and their impact on the environment and on its resources. Proper timing in farming practices, restricted fine netting fishing, and regulated timber harvesting can ensure the continuous supply of resources. According to Mencius philosophy, the modeling of sustainability requires:

- That due account of the seasonal change of the natural resources, i.e. the seasonal change of the carrying capacity of an environment be taken.
- That a balance in the consumption rate of natural resources by human or other organisms is found.
- That theories (especially limits) on population or resource growth and harvesting be considered.

Ancient Chinese Wisdom of Sustainability

不違農時，穀不可勝食也；
數罟不入洿池，魚鱉不可勝食也；
斧斤以時入山林，材木不可勝用也。
——— 孟子(**Mencius**) 梁惠王

Figure 1.
Ancient Chinese wisdom of sustainability

Essences of computer simulation models

The three essences for all computer simulation models are theory, data and program. To develop a computer model to simulate the behavior of an ecosystem, detailed knowledge (theory and data) about that ecosystem are fundamental. A given computer program is thus the main tool to express the logic of theory in computer codes. An overview of its three main components follows:

Theory

Before designing a computer model to use with ecological data, you have to tell the computer how to do the calculations by transferring the ecological theory to the logical computer code, i.e. programming. There are different definitions for the word "theory" in the dictionary. In this paper, the word theory is used as a systematic statement of general principle that has been scientifically verified. To establish a useful model, we have to locate, or to develop, the correct theories for the system. For example, when the differences in sex and age are not significant, theories based on total population size can be used. However, when age differences are important, an age-structured population theory is appropriate (Lotka, 1925; Lewis, 1942; Leslie, 1945). Furthermore, if differences exist in both sexes and developmental stages, a sex and stage-structured theory is suitable for the circumstances (Chi, 1988; Caswell, 1989; Manly, 1990).

For example, a logistic model to simulate the population growth in a seasonal changing environment may be the following:

$$\frac{dN}{dt} = r(t)N(t)\left(1 - \frac{N(t)}{K(t)}\right) \tag{1}$$

where

$$r(t) = (r_{max} - r_{min})\sin\left(\frac{2 \cdot 3.41506}{365} \cdot t\right) + \left(\frac{r_{max} + r_{min}}{2}\right) \tag{2}$$

and

$$K(t) = (K_{max} - K_{min})\sin\left(\frac{2 \cdot 3.41506}{365} \cdot t\right) + \left(\frac{K_{max} + K_{min}}{2}\right). \tag{3}$$

This model is presented – even at the risk of confusing the lay-reader – to illustrate the fact that we cannot use logistic growth to simulate the growth of an age-structured population. Therefore, to simulate the growth of the human population, we have to use the age-structured life table theory, such as the Lewis-Leslie matrix (Lewis, 1942; Leslie, 1945). More precisely, we need the age-specific survival rates and fecundity for both sexes. For insect and mite species, if there is significant stage differentiation and sexual dimorphism, an age-stage, two-sex life table theory is appropriate in simulation of the population growth and the change of stage structure (Chi, 1988, 1997, 1999).

Because ecology is a young science and ecosystems are complex, ecologists revealed only a few “theories” about ecosystems. Many ecological observations are still interpreted solely based on statistical analysis and that has a real impact in our ability to fully understand the implications of sustainability. When robust theories are not available, the build up of simulation models based on statistical results or hypothesis require special caution.

Data

To establish an applicable model, we need observed and/or experimental data. The same line of thinking applies to data on sustainability. As the example earlier given illustrates (Equations 1, 2 and 3), the maximal and minimal carrying capacities (K_{max} and K_{min}), the maximal and minimal growth rates (r_{max} and r_{min}) and the initial conditions ($r(0), N(0)$ and $K(0)$) are necessary in simulation processes. To determine what components should be included in the model, it requires thorough and intellectual observation, sampling and analysis of an ecosystem to distinguish the major biotic and abiotic components of an ecosystem from others. When developing an ecological-economic model, we need both ecological and economic data. The decision on what types of data are necessary should be made in close connection with the theoretical background. If an existing theory can properly describe the behavior of an ecosystem in mathematical functions, we can specify the necessary components of a model. If no theory is available, then we may have to use statistical analyses to obtain the required parameters. For the simulation of human population growth, a parameter often referred to in international discussions on sustainability and in carrying capacity, we need life table data such as age-specific survival rates and fecundity for both sexes. Because each geographical region has its own characteristics – a matter which is sometimes ignored or simply overlooked when developed and developing countries discuss what sustainability means for them – regional-specified parameters should be used.

Those involved in teaching natural sciences in higher education institutions will know that, for wildlife conservation, various data, e.g. the phenological data; the life table, the predation rate and population size of the predator, the density of competitors, the dynamics of food resources, etc. are required. Sometimes it may take months or years to collect the necessary information. In many field studies, sensors and data loggers have been widely used to automate the data collection and transfer.

Computer program

To most people, the first impression about a simulation model is a computer program. The programming languages, e.g. FORTRAN, BASIC and C, were unfriendly and difficult to learn. For many years, programming was tedious for most people, including ecologists. It was also seen as a taboo for specialists on sustainability, since it would require a body of knowledge not often provided in formal academic training, not to mention in the usual professional profile of a practitioner.

In the past, programs were procedural applications and their sizes were very limited (usually 64K on personal computers). To generate a computer graph was often difficult. About 20 years ago, computer simulation models were awkward to most users. From the 1980s, with the prevalence of personal computers, most students learned the basic programming in elementary schools or high schools. In universities, advanced courses were offered in several levels. At the same time, the programming languages, e.g. Visual BASIC and Visual C, become more powerful. Programs became event-driven applications and their sizes are no longer limited by the computer memory. Graphs and charts can be easily generated. The user-friendly computer simulation models became available on Windows operated PCs.

Figure 2 is a Visual BASIC program for the simulation of population growth in a seasonal changing environment (Equations 1, 2 and 3). In 33 lines of

```
SimuTime = Val(txtSimuTime)   'the simulation time
RMax = Val(txtRMax)         'the maximum of r-rate
RMin = Val(txtRMin)         'the minimum of r-rate
KMax = Val(txtKMax)         'the maximum of K
KMin = Val(txtKMin)         'the minimum of K
N(0) = Val(txtN0)           'the initial population size
For i = 0 To SimuTime + 1
   K(i)=(KMax+KMin)/2+Sin(2*3.141592/365*i)*(KMax- KMin)/2
Next i
For i = 0 To SimuTime + 1
   R(i)=(RMax+RMin)/2+Sin(2*3.141592/365*i)*(RMax-RMin)/2
Next i
For i = 1 To SimuTime + 1
   dN(i - 1) = R(i) * N(i - 1) * (1 - N(i - 1) / K(i - 1))
   N(i) = N(i - 1) + dN(i - 1)
Next i
   Graph1.NumPoints = SimuTime + 1
   Graph1.DataReset = 9
Graph1.Visible = True
Graph1.GraphType = 6
Graph1.NumSets = 2
For i = 0 To Graph1.NumPoints - 1
   Graph1.GraphData = N(i)
   Next i
   For i = 0 To Graph1.NumPoints - 1
   Graph1.GraphData = K(i)
Next i
Graph1.BottomTitle = "Time"
Graph1.LeftTitle = "N(t) and K(t)"
Graph1.ColorData = gphLightBlue
Graph1.ColorData = gphLightMagenta
Graph1.YAxisStyle = gphVariableOrigin
Graph1.DrawMode = gphDraw
```

Figure 2.
Visual BASIC program

coding, it can simulate the growth and plot the results in a graph. The old programming languages (Fortran, BASIC, C) did not have the same capability. This program shows that programming can be easily understood and achieved by people with limited programming experience. The complete source codes and forms can be downloaded at

- http://ftp.nchu.edu.tw/nchu/Ecology/Welcome.html and
- http:/nhsbig.inhs.uiuc.edu/wes/chi.html

Because models must be revised and/or modified frequently to cope with the changing ecosystem and computer system, it will be more efficient if the ecologists do the programming themselves. Ecologists, who do the programming by themselves not only save time in communication with computer programmers, but can also be certain that the ecological theory is correctly expressed in computer codes. For those who do not want to learn programming languages, there are also some modeling tools, such as ModelMaker, Stella, etc. available. Although one can build some models using these over the counter modeling software, these software do have their limitations.

Sometimes, a traditional programming language is still used in computer modeling. *The Guideline on Air Quality Models* published by the Environmental Protection Agency (EPA) of the USA, requires that all models submitted to the EPA for evaluation must be in common Fortran language. Because Fortran is no longer a popular and user-friendly language, this limitation needs to be reviewed.

Most ecosystems are unique in their own component structures and system functions, a new computer program is often required for a specific habitat. It is, however, possible to customize and modify an existing program to be used in different habitats (Bugmann and Solomon, 1995).

Simulation models

Sustainability is an expression of broad meaning in the fields of ecology and economy. The establishment of a universal computer simulation model for sustainability that covers all resources and environments is nearly impossible. Currently, most models were developed for specific resources or habitats/ environments.

The followings are various models dealing with different resources or factors that should be included for sustainability.

Human population growth models

The concern about sustainability increased mainly due to the human impacts on the environment. Therefore, simulation models on human population growth (exploration) are important. There are many simulation models available on the Internet about projection of global and or regional human population. The latest predictions made by the United Nations claim that the human population will reach 60 billion before the year 2050. The author also designed a model for the simulation of population growth in Taiwan, available at the before mentioned Web sites (Chi, 1998). The simulation results of the human population growth are keystones to the models for supply and demand of various resources.

Water models

For thousands of years, the limited supply of water has become one of the most important restriction factors of all organisms and the economic development in many countries. Many models have assisted policy decision makers in planning and managing water resources. The Joint Research Centre (JRC), a service of the European Commission, is working on the SHYLOC project (System for Hydrology using Land Observation for Model Calibration). SHYLOC uses a satellite image to determine the amount of surface water in natural and artificial channels. Furthermore, the JRC is developing a model to control the dimethylsulphide (DMS) pollution in ocean water (http://poplar.sti.jrc.it/public/iain/shyloc/home.html; Shepherd *et al.*, 1998). The Water Resources Research Laboratory (WRRL) of the Bureau of Reclamation (Department of Interior, USA) has used hydraulic modeling to solve water resources and hydraulics problems and to study the dam safety (http://www.usbr.gov/wrrl/index.html). Moore and Negri (1992) analyzed the application of a multicrop production model to water allocation policy of the Bureau of Reclamation. The Everglades Landscape Model (ELM) is an regional ecological model. It simulates the landscape response (vegetation community, biomass, sediment, etc.) to different water management scenarios in the Everglades Protection Area (south Florida, USA) (http://kabir.umd.edu/Glades/ELM.html).

Soil and land models

Land consumption increases globally, especially in developing countries. One of the objectives of the environmental policy of the Federal Republic Germany is to safeguard the state of environment, such that free space is ensured for the development of the future generation (Federal Ministry for the Environment, Germany, 1994). To sustain current agroecosystem development, soil modeling is necessary. Moore and Madison (1985) developed an animal waste-loading model to estimate total phosphorus loading and its loss from the watershed. Young (1991) developed a computer model, SCUAF, to study the maintenance of soil fertility under an agroforesty system.

Greenhouse effect and CO_2 models

The greenhouse effect has been one of the major environmental concerns in the last few decades. Its global influence led the UNFCCC (United Nations Framework Convertion on Climate Change) to organize an international convention in Kyoto in 1997. Kasischke *et al.* (1995) developed a model to study the sensitivity of different carbon stocks and their influence on global warming. In a small greenhouse experiment, Linker *et al.* (1998) developed a neural network greenhouse model to study the optimal CO_2 control. Rosenthal (1998) studied the effects of elevated CO_2 on tropical ecosystems in Biosphere 2 and reported that higher atmospheric CO_2 has increased net photosynthesis in the rain forest. Applying the atmospheric and oceanic CO_2 models, Fan *et al.* (1998) report a large terrestrial carbon sink found in North America. More information is needed to totally understand the global greenhouse effect.

Conservation models

Several simulation models have been published especially for wildlife conservation. Using simulation model and GIS, Liu *et al.* (1995) demonstrated the effects of forest management (harvesting, thinning and burning) on the population dynamics of endangered birds. Combining a population simulation program and GIS, Lindenmayer and Possingham (1995) estimated the probability of extinction of the endangered species, Leadbeater's possum, a small, highly agile, nocturnal marsupial in Australia. Doherty *et al.* (1999) used a population simulation model to study the response of a hypothetical forest bird population to various forest managements. Based on the results of model, they determined the optimal management for balancing conservation and economic gain.

Forest models

Numerous models have been focused on one of the most important natural resources – the forest. The forest is important to water and soil conservation, biodiversity, recreation, education and much more. Krauchi (1995) used a model, FORSUM, to simulate the succession of the forest ecosystem and concluded it can be used to evaluate climate change impacts on the forest ecosystem. Bugmann and Solomon (1995) applied a European forest model in North America to study the ecosystem response to climate change. A complex computer model of forest dynamics (SORTIE) was used to model the forest composition and plant succession (Deutschman *et al.*, 1997).

As a further example of sustainability, the sustainable forest management practiced by the Canadian Model Forest Program deserves special attention (Hall, 1997). Governmental support is especially important and crucial to a successful sustainable development initiative. For example, the Canadian Fund Model Forest (FMF) encompasses approximately 1 million acres of forest. The FMF helps to assess proper management practices and develop indicators of sustainable forest management. It serves not only as a research program, but also as a management and educational initiative. A computer simulation program that integrates all activities in forests, will be beneficial on a global scale.

Harvesting models

Human survival depends on the adequate harvesting of all natural resources. For a sustainable future, it is important to plan all harvesting based on ecological knowledge.

Clark (1976) discussed the economics of harvesting a population based on a logistic model. Authors such as Chi (1994), Carey and Vargas (1988), Chi and Getz (1988), have developed various theories on mass rearing and harvesting.

Models for the timing of management

Sustainability depends on how we manage the available resources. When environmental problems were less serious and sustainability was not an issue of major concern, a farmer would not consider an extra application of pesticide or fertilizer as critical. With the increasing awareness of environmental protection, resource scarcity and sustainable development, it is necessary to avoid any unnecessary management practices. Chi (1990) developed a timing control based on the stage structure of pest population and when combined with corrected degree-day data (e.g. Fettig *et al.*, 1998) it may accurately forecast dates for the application of insecticides.

Pollution models

Pollution is a major adverse factor for sustainability. Pollutants are the sources of health hazards and they worsen resource scarcity. Pollution models can be used to describe the dispersion of pollutant from the source of pollution and/or to estimate the rate of accumulation. Metcalfe and Whyatt (1994) have for example used an atmospheric pollution model, the Harwell Trajectory Model (HTM), to determine the degree or dangers of sulfur deposition. Parson *et al.* (1998) used AGNPS to study the decision-making risk.

Waste models

Because resources are limited, waste treatment and recycling are essential for sustainable development. Waste reduction during the process of production is more valuable than the search for new resources. Nguyen and Saddler (1991) incorporated the production, waste treatment and cost in a process simulation model for ethanol production. Aldrich (1994) constructed a microeconomic model to estimate the long-term liability costs in hazardous waste landfill.

Ozone models

From 1985 to 1989, a European Monitoring and Evaluation Program model for ozone was developed, to calculate the ozone concentration over Europe (Simpson, 1993). Rabl and Eyre (1998) used ozone models to estimate the regional and global O_3 damage in Europe.

Challenges in modeling

The models mentioned above, all associated with sustainability and the environmentally-sound use of natural resources, represent only a small portion of research conducted in computer simulations. Various models indicate the diversity of challenges to maintain sustainable development. Moreover, new problems require new problem-solving skills. For example, with the advancement of biotechnology, we need new models to assess the impact of genetically modified crops on the sustainability of a given ecosystem and on soil fertility. There are many models available on the Internet, some of them are free, whilst others are not. Most models, either academic or commercial, require frequent revision. With new data or new theories available, models can be modified, restructured or discarded. Models may also be revised to complement new computing environments.

Requirements for simulation models for sustainability

In addition to the three essences of computer simulation models: theory, data and computer program, a simulation model for sustainability should include the following.

The fluctuation of resources and the environment

The quantity and quality of resources changes from time to time. Many changes are in coincidence with the seasonal fluctuation; others are mainly due to the continuous exploitation by man. Long-term studies on environmental changes are important. However, due to the large financial requirements for long-term studies, government agencies should be involved. Data collected by satellites in industralised countries should be made available to scientists from around the world. This will enhance researchers' ability to study global sustainability.

The ability to make predictions

Most abiotic environmental factors and biotic factors such as the size of animal and plant populations change from time to time. A deterministic model will not be able to take the randomness or uncertainty into consideration. The uncertainties of models have also been noticed in many reports (Rabl and Eyre, 1998; Krauchi, 1995; Deutschman *et al.*, 1997). For a more realistic simulation result, the simulation model must be able to take the variability of factors and parameters into account.

The economics of management

The urgency for sustainable development is mainly due to the overexploitation of natural resources and damage to the environment by human beings. All types of economic activities have a direct or indirect effect on ecosystems. As Beaton and Maser (1999) suggested, it is time to reunite economy and ecology. Economic value and supplies vs. demand for natural resources are time-variable and crucial to its sustainability.

The balance between regional and global sustainability

No environment is completely isolated from other environments. And no resource can be isolated from its environment. The increasing world trade in natural resources, agriculture and industrial products, make sustainability a global issue. A simulation model for sustainability should cover regional and global ecosystems (Bugmann and Solomon, 1995; Tack and Polk, 1999).

The emphasis on environmental degradation

Agricultural and industrial productions are associated with environmental degradation (e.g. Bhat and Taneja, 1998). For a sustainable development, it is necessary to take the environmental degradation into consideration.

The use of the Internet for speedy communication

For fast and efficient communication, the Internet is an inevitable choice. There is a possibility to provide more up-to-date information on the Internet. A Web site dedicated to computer simulation models for sustainability, administrated by a well-established environmental organization, institute or university, may be helpful. The information provided in the web should nonetheless be carefully screened and selected.

Scale and object of computer simulation models

For administrative purposes, computer simulation models can be designed to cover a country, a city or a community. However, these units usually do not represent the habitats of natural boundary. Ecological habitats, e.g. lake, forest, grassland, etc. are suitable and realistic units for modeling. Simulation models can be designed for the management of specific resources, e.g. water, pine forest, salmon, air, etc. However, these resources do not exist independently from their environments. One cannot model sustainability as a whole, or a specific resource in particular, without taking the respective environment and the other biotic and abiotic factors into consideration. When ecological problems are entangled with political and economic issues, modeling becomes even more challenging.

Conclusions

Just a few decades ago, rapid economic growth was the main objective in many countries. Natural resources (e.g. water, air, soil, forest, fish and animals) were in larger supply than they are today and thus air, water and land were often treated as dumping grounds for all types of pollutants. The increase in environmental problems has changed our ideas about development and development models.

Computer models were once defined as simplifications of the real world. But oversimplified models will never represent real ecosystems. As sustainability models become more complex, interdisciplinary cooperation among ecologists, economists and conservation biologist will be strengthened. Simulation models have played an important role in the past and will play an even more important role in the future. The interactive nature of simulation model is not only an excellent tool for research, but also a great medium of learning and communication. Computer simulation models can be used in research and in teaching on sustainable and, when applied by higher education institutions as part of teaching or research, they can provide a concrete contribution towards increased environmental awareness and towards the goal of sustainable development.

References

Aldrich, J.R. (1994), "Expected value estimates of the long-term liability from landfilling hazardous waste", *Air and Waste*, Vol. 44 No. 6, pp. 800-3.

Beaton, R. and Maser, C. (1999), *Reuniting Economy and Ecology in Sustainable Development*, Lewis, London.

Bhat, P.N. and Taneja, V.K. (1998), "Sustainable animal production systems in India: issues and approaches", *Indian Journal of Animal Sciences*, Vol. 68 No. 8, pp. 701-12.

Bugmann, H.K.M. and Solomon, A.M. (1995), "The use of a European forest model in North America: a study of ecosystem response to climate gradients", *Journal of Biogeography*, Vol. 22 No. 2/3, pp. 477-84.

Carey, J.R. and Vargas, R.I. (1988), "Demographic analysis of insect mass rearing: a case study of three tephritids", *Journal of Economic Entomology*, Vol. 78, pp. 523-7.

Caswell, H. (1989), *Matrix Population Models*, Sinauer, Sunderland.

Chi, H. (1988), Life-table analysis incorporating both sexes and variable development rate among individuals", *Environmental Entomology*, Vol. 17 No. 1, pp. 26-34.

Chi, H. (1990), Timing of control based on the stage structure of pest population: a simulation approach", *Journal of Economic Entomology*, Vol. 83 No. 4, pp. 1143-50.

Chi, H. (1994), "Periodic mass rearing and harvesting based on the theories of both the age-specific life table and the age-stage, two-sex life table", *Environmental Entomology*, Vol. 23 No. 3, pp. 535-42.

Chi, H. (1997), *Computer Program for Two-Sex Life Table Analysis*, National Chung Hsing University (http://ftp.nchu.edu.tw/nchu/Ecology/Welcome.html).

Chi, H. (1998), *Computer Simulation Model for the Growth of Taiwan Population*, National Chung Hsing University (http://ftp.nchu.edu.tw/nchu/Ecology/ Welcome.html).

Chi, H. (1999), *Computer Program for the Timing of Management*, National Chung Hsing University (http://ftp.nchu.edu.tw/nchu/Ecology/Welcome.html).

Chi, H. and Getz, W.M. (1988), "Mass rearing and harvesting based on an age-stage, two-sex life table: a potato tuber worm (*Lepidoptera Gelechiidae*) case study", *Environmental Entomology*, Vol. 17 No. 1, pp. 18-25.

Clark, C.W. (1976), "Bioeconomics", in May, R.M. (Ed.) (1976), *Theoretical Ecology: Principles and Applications*, Blackwell Scientific, Oxford.

Deutschman, D.H., Levin, S.A., Devine, C. and Buttel, L.A. (1997), "Scaling trees to forests: analysis of a complex simulation model", *Science*, Vol. 277 No. 5332, p. 1623.

Doherty, P.F., Jr, Marschall, E.A. and Grubb, T.C., Jr (1999), "Balancing conservation and economic gain: a dynamic programming approach", *Ecological Economics*, Vol. 29 No. 3, pp. 349-58.

Dye, L. (1998), "Biosphere 2 a joke no longer", ABCNEWS.com, 10 June, http://abcnews.go.com/sections/science/DyeHard/dye59.html

Environmental Protection Agency (1999), "Guideline on air quality models", http://www.epa.gov/scram001/main.htm

Fan, S., Gloor, M., Mahlman, J., Pacala, S., Sarmiento, J., Takahashi, T. and Tans, P. (1998), "A large terrestrial carbon sink in North America implied by atmospheric and oceanic CO_2 data and models", *Science*, Vol. 282 No. 5388, pp. 442-6.

Federal Ministry for the Environment (1994), *Environmental Policy in Germany*, Federal Ministry of the Environment.

Fettig, C.J., Berisforn, C.W. and Dalusky, M.J. (1998), "Revision of a timing model for chemical control of the nantucket pine tip moth (*Lepidoptera Tortricidae*) in the southeastern coastal plain", *Journal of Entomological Science*, Vol. 33 No. 4, pp. 336-42.

Hall, J.E. (1997), "Canada's Model Forest Program – bringing community forest values into the development of sustainable forest management in the Canadian context", *Network Paper – Rural Development Forestry Network*, Overseas Development Institute (ODI), London, UK, 1996/1997, No. 20e, pp. 14-22.

Kasischke, E.S., Christensen, N.L., Jr and Stocks, B.J. (1995), "Fire, global warming, and the carbon balance of boreal forests", *Ecological Applications*, Vol. 5 No. 2, pp. 437-51.

Krauchi, N. (1995), "Application of the model FORSUM to the Solling spruce site", *Ecological Modeling*, Vol. 83 No. 1/2, pp. 219-28.

Leslie, P.H. (1945), "On the use of matrices in certain population mathematics", *Biometrika*, Vol. 33, pp. 183-212.

Lewis, E.G. (1942), "On the generation and growth of a population", *Sankhya*, Vol. 6, pp. 93-6.

Lindenmayer, D.B. and Possingham, H.P. (1995), "Modeling the viability of metapopulations of the endangered Leadbeater's possum in southeastern Australia", *Biodiversity and Conservation*, Vol. 4 No. 9, pp. 984-1018.

Linker, R., Seginer, I. and Gutman, P.O. (1998), Optimal CO_2 control in a greenhouse modeled with neural networks", *Computers & Electronics in Agriculture,* Vol. 19 No. 3, pp. 289-310.

Liu, J.G., Dunning, J.B., Jr and Pulliam, H.R. (1995), "Potential effects of a forest management plan on Bachman's sparrows (*Aimophila aestivalis*): linking a spatially explicit model with GIS", *Conservation Biology*, Vol. 9 No. 1, pp. 65-72.

Lotka, A.J. (1925), *Elements of Physical Biology*, Williams and Watkins, Baltimore, MD (reprinted and revised as *Elements of Mathematical Biology*, 1956, Dover Publications, New York, NY.)

Manly, B.F.J. (1990), *Stage-Structured Populations: Sampling, Analysis and Simulation*, Chapman & Hall, London.

Metcalfe, S.E. and Wyatt, J.D. (1994), "Modelling future acid deposition: a critical loads approach", *Global Environmental Change – Human & Policy Dimensions*, Vol. 4 No. 2, pp. 125-39.

Moore, I.C. and Madison, F.W. (1985), "Description and application of an animal waste phosphorus loading model", *Journal of Environmental Quality*, Vol. 14 No. 3, pp. 364-9.

Moore, M.R. and Negri, D.H. (1992), "A multicrop production model of irrigated agriculture, applied to water allocation policy of the Bureau of Reclamation", *Journal of Agricultural & Resource Economics*, Vol. 17 No. 1, pp. 29-43.

Muller, C. (1999), 'Mencius", (English translation), Web site: http://www.human.toyogakuen-u.ac.jp/~acmuller/contao/mencius.htm

Nguyen, Q.A. and Saddler, J.N. (1991), "An integrated model for the technical and economic evaluation of an enzymatic biomass conversion process", *Bioresource Technology*, Vol. 35 No. 3, pp. 275-82.

Parson, S.C., Hamlett, J.M., Robillard, P.D. and Foster, M.A. (1998), "Determining the decision-making risk from AGNPS simulations", *Transactions of the ASAE*, Vol. 41 No. 6, pp. 1679-88.

Pool, R. (1992), "The third branch of science debuts", *Science*, Vol. 256 No. 5053, pp. 44-7.

Rabl, A. and Eyre, N. (1998), "An estimate of regional and global O_3 damage from precursor Nox and VOC emissions", *Environment International*, Vol. 24 No. 8, pp. 835-50.

Rosenthal, Y. (1998), "Variations of ecosystem gas exchange in the rain forest mesocosm at biosphere 2 in response to elevated CO_2", *Global Change Biology*, Vol. 4 No. 5, pp. 539-47.

Shepherd, I.M., Al-Khudhairy, D., Kaiser, C., Thompson, J.R., Zalidis, G., Hadjiakiannakis, S. and Refsgaard, A. (1998), "SHYLOC: system for hydrology using land observation for model calibration", in Babovic, V. and Larsen, L.C. (Eds) (1998), *Hydroinformatics '98.*

Proceedings of the Third International Conference on Hydroinformatics, Copenhagen, Denmark, 24-26 August 1998, Vol. 1, Balkema, Rotterdam, The Netherlands.

Simpson, D. (1993), "Photochemical model calculations over Europe for two extended summer periods: 1985 and 1989. Model results and comparison with observations", *Atmospheric Environment*, Part A, General Topics, Vol. 27 No. 6, pp. 921-43.

Tack, J. and Polk, P. (1999), "The influence of tropical catchments upon the coastal zone: modelling the links between groundwater and mangrove losses in Kenya, India/Bangladesh and Florida", in Harper, D. and Brown, T. (Eds) (1999), *The Sustainable Management of Tropical Catchments*, John Wiley & Sons, Chichester.

Young, A. (1991), "Maintenance of soil fertility for sustainable production of trees and crops through agroforestry systems", *Tropical Agriculture Research Series*, No. 24, pp. 197-206.