CHAPTER 4

Conceptual Models

4.1 Introduction

Nine different methods of *conceptualization* are presented in this chapter, along with their advantages and disadvantages. A general recommendation as to which method to use is not given. This is not possible, because, as will become clear from the discussion, the problem, the ecosystem, the application of the model and the habits of the modeller will determine the preference of the conceptualization method.

A conceptual model has a function of its own. If flows and storage are given by numbers, the diagram gives an excellent survey of a steady-state situation. It can be applied to get a picture of the changes in flows and storage if one or more forcing functions are changed and another steady-state situation emerges. If first-order reactions are assumed, it is even easy to compute other steady-state situations that might prevail under other combinations of forcing functions (see also Chapter 5). Two illustrations of this application of conceptual models are included in Section 4.4 to give the reader an idea of these possibilities.

4.2 Application of Conceptual Diagrams

Conceptualization is one of the early steps in the modelling procedure (see Section 2.3), but it can also have a function of its own, as will be illustrated in this chapter.

A conceptual model can not only be considered as a list of state variables and forcing functions of importance to the ecosystem and the problem in focus, but it will also show how these components are connected by processes. It is employed as a tool to create abstractions of reality in ecosystems and to delineate the level of organization that best meets the objectives of the model. A *wide spectrum* of conceptualization approaches is available and will be presented here. Some give only the components and the connections, others imply mathematical descriptions.

It is almost impossible to model without a conceptual diagram to visualize the modeller's concepts and the system. The modeller will usually play with the idea of constructing various models of different complexity at this stage in the modelling procedure, making the first assumptions and selecting the complexity of the initial model or alternative models. It will require intuition to extract the applicable parts of the knowledge about the ecosystem and the problem involved. It is therefore not possible to give general lines on how a conceptual diagram is constructed, except that it is often better at this stage to use a slightly too complex model than a too simple approach. At the later stage of modelling it will easily be possible to exclude redundant components and processes. On the other hand, if a too complex model is used even at this initial stage, the modelling will be too cumbersome.

Generally, good knowledge about the system and the problem will facilitate the conceptualization step and increase the chance of finding close to the right complexity for the initial model. The questions to be answered are:

- What components and processes of the real system are essential to the model and the problem?
- Why?
- How?

In this process a suitable balance is sought between elegant simplicity and realistic detail.

Identifying the level of organization and selecting the correct complexity of the model are not trivial problems. Miller (1978) indicates 19 hierarchical levels of living systems, but to include all of them in an ecological model is of course an impossible task, mainly due to the lack of data and a general understanding of nature. Usually, it is not difficult to select the focal level, where the problem is, or where the components of interest operate. The level one step lower than the focal level is often relevant to a good description of the processes. For instance, *photosynthesis* is determined by the processes going on in the individual plants. The level one step higher than the focal level determines many of the constraints (see the discussion in Section 2.12). These considerations are visualized in Fig. 4.1.

However, it is not necessary, in most cases, to *include more than a few or even only one hierarchical level* to understand a particular behaviour of an ecosystem at a particular level; see Pattee (1973), Weinberg (1975), Miller (1978) and Allen and Star (1982). Figure 4.2 illustrates a model with three hierarchical levels, which might be needed if a multi-goal model is constructed. The first level could, for instance, be a hydrological model, the next level a *eutrophication* model and the third a model of phytoplankton growth, considering the intracellular nutrients concentrations.

Each *submodel* will have its own conceptual diagram; see, e.g., the conceptual diagram of the phosphorus flows in a eutrophication model, Fig. 2.9 and 2.10. In this latter submodel there is a sub-submodel considering the growth of phytoplankton by use of intracellular nutrient concentrations (see Chapter 3C), which is conceptualized in Figs. 3.47 and 4.3. The nutrients are taken up by phytoplankton at a

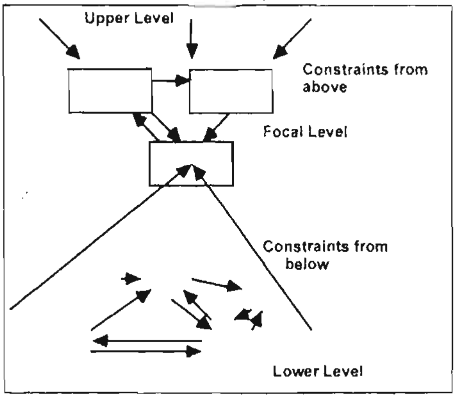


Fig. 4.1. The focal level has constraints from both lower and upper levels. The lower level determines, to a great extent, the processes and the upper level determines many of the constraints on the ecosystem.

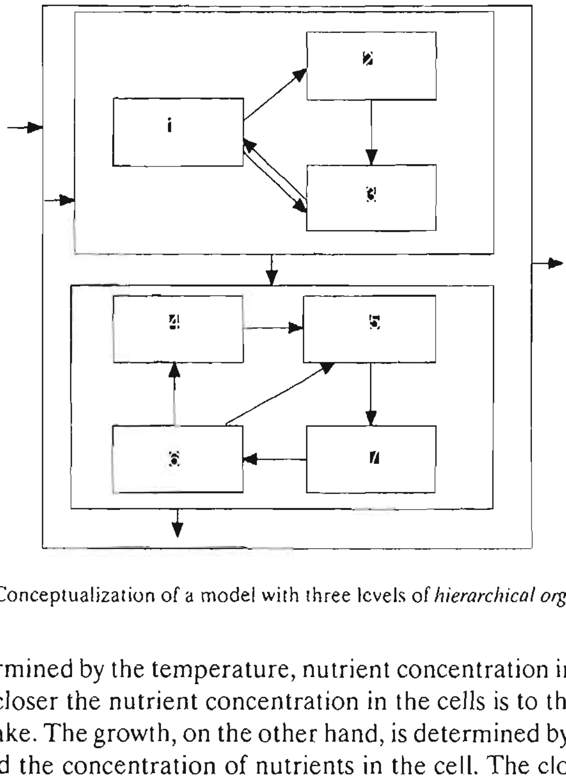


Fig. 4.2. Conceptualization of a model with three levels of *hierarchical organization*.

rate that is determined by the temperature, nutrient concentration in the cells and in the water. The closer the nutrient concentration in the cells is to the minimum, the faster is the uptake. The growth, on the other hand, is determined by solar radiation, temperature and the concentration of nutrients in the cell. The closer the nutrient concentration is to the maximum concentration, the faster is the growth. This description is according to phytoplankton physiology and a *eutrophication model* based on this description of phytoplankton growth (production) is presented in Chapter 7.

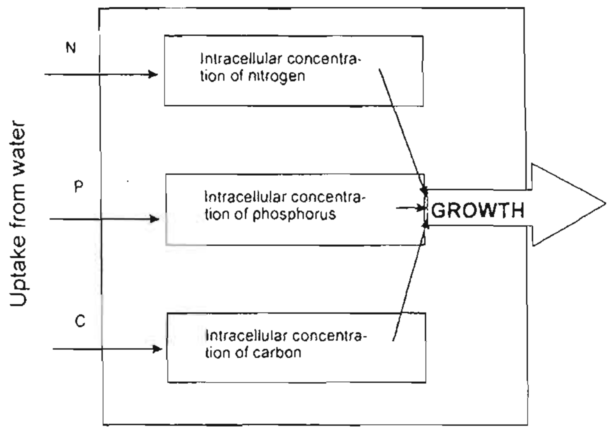


Fig. 4.3. A phytoplankton *growth model* with two hierarchical levels: the cells which determine the uptake of nutrients, and the phytoplankton population, the production (growth) of which is determined by the intracellular nutrient concentrations.

Models that also consider the distribution and effects of toxic substances might often require three *hierarchical levels*: one for the hydrodynamics or aerodynamics to account for the distribution, one for the chemical and biochemical processes of the toxic substances in the environment, and the third for the effect on the organism level.

4.3 Types of Conceptual Diagrams

Nine types of conceptual diagrams are presented and reviewed.

1. *Word models* use a verbal description of model components and structure. Language is the tool of conceptualization in this case. Sentences can be used to describe a model briefly and precisely. However, word models of large complex ecosystems quickly become unwieldy and are therefore only used for very simple models. The saying "One picture is worth a thousand words" explains why the modeller needs to use other types of conceptual diagrams to visualize the model.

2. *Picture models* use components seen in nature and place them within a framework of spatial relationships. Figure 4.4 gives a simple example.

3. *Box models* are simple and commonly used conceptual designs for ecosystem models. Each box represents a component in the model and arrows between boxes indicate processes. Figures 2.1, 2.9 and 2.10 show examples of this model type. The conceptual diagrams show the nutrient flows (nitrogen and phosphorus) in a lake. The arrows indicate mass flows caused by processes. Figure

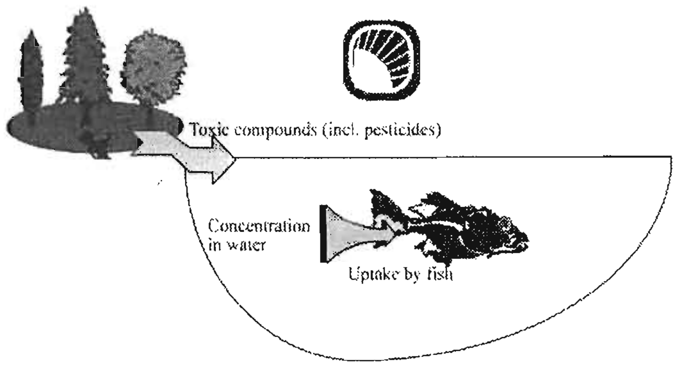


Fig. 4.4. Example of a picture model: pesticides from the littoral zone result in a certain concentration in the water. Fish take up the toxic compounds directly from the water. The model attempts to answer the crucial question: what would be the concentration in the fish of the toxic substance?

4.5 gives a conceptual diagram of a global carbon model, used as the basis for predicting the climatic consequences of increasing concentrations of carbon dioxide in the atmosphere. The numbers in the boxes indicate the amount of carbon on a global basis, while the arrows give information on the amount of carbon transferred from one box to another per annum. Some modellers prefer other geometric shapes, for example, Wheeler et al. (1978) prefer circles to boxes in their conceptualization of a lead model. This results in no principal difference in the construction and use of the diagram.

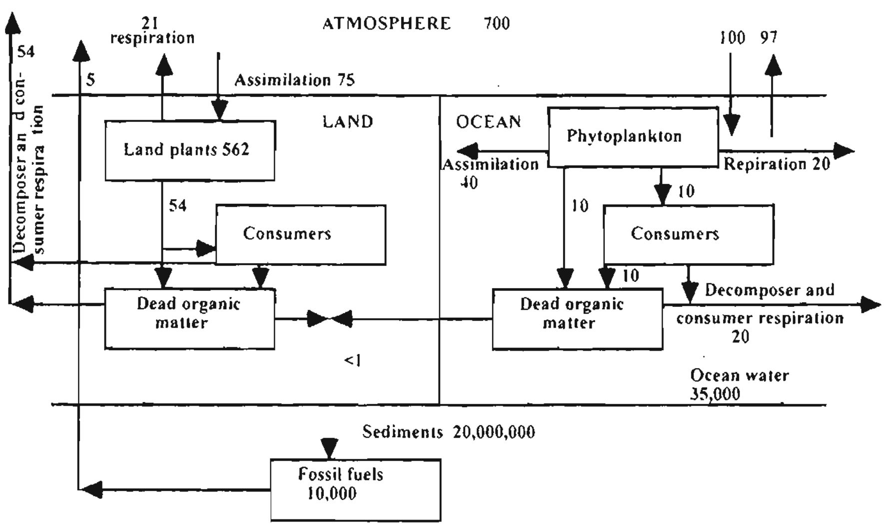


Fig. 4.5. Carbon cycle, global. Values in compartments are in 10^9 tons and in fluxes 10^9 tons/year. All fluxes balance each other with the exception of the transfer of carbon dioxide from fossil fuel to the atmosphere. Fortunately, 60% of this flux is absorbed by the ocean.

A model for predicting carbon dioxide concentration in the atmosphere can easily be developed on the basis of the mass conservation applied in the diagram.

The term *black box models* is used when the equations are set up based on an analysis of input and output relations, for example, by statistical methods. The modeller is not concerned with the causality of these relations. Such a model might be very useful, provided that the input and output data are of sufficient quality. However, the model can only be applied to the case study for which it has been developed. New case studies will require new data, a new analysis of the data and consequently new relations.

White box models are constructed based on causality for all processes. This does not imply that they can be applied to all similar case studies, because, as discussed in Sections 2.3 and 2.5, a model always reflects ecosystem characteristics. In general, however, a white box model will be applicable to other case studies with some modification.

In practice most models are *grey*, as they contain some *causalities* but also apply empirical expressions to account for some of the processes.

4. *Input/output models* differ only slightly from box models, as they can be considered as box models with indications of inputs and outputs. The global carbon model (see Fig. 4.5) can be considered an input/output model as all inputs and outputs of the boxes are indicated with numbers. Another example is shown in Fig. 4.6: this is an oyster community model, developed by Patten (1985). The same model is illustrated by use of matrix conceptualization (see item 5 below).

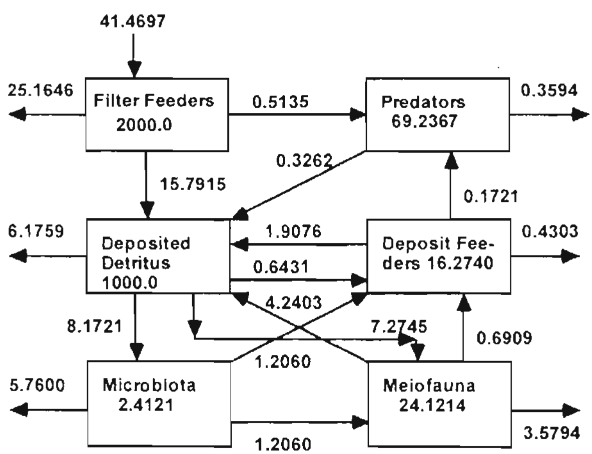


Fig. 4.6. *Input/output model* for energy flow (cal m^{-2} d^{-1}) and storage (kcal m^{-2}) in an oyster reef community, (reproduced from Patten, 1985). In the matrix representation is the sequence: (1) filter feeders; (2) deposited detritus; (3) microbiota; (4) meiofauna; (5) deposit feeders; (6) predators.

COMPARTMENTS

(a)

To \ From	1	2	3	4	5	6	Row Sum
1	1	0	0	0	0	0	1
2	1	1	0	1	1	1	5
3	0	1	1	0	0	0	2
4	0	1	1	1	1	0	3
5	0	1	1	1	1	0	4
6	1	0	0	0	1	1	3
Column Sum	3	4	3	3	3	2	18

(b)

To \ From	1	2	3	4	5	6	Row Sum
1	9.948^{-1}	0	0	0	0	0	9.948^{-1}
2	1.974^{-3}	9.944^{-1}	0	1.395^{-2}	2.930^{-2}	1.178^{-3}	1.071
3	0	2.043^{-3}	1.530^{-1}	0	0	0	1.551^{-1}
4	0	1.818^{-3}	1.250^{-1}	9.121^{-0}	0	0	1.039
5	0	1.608^{-3}	1.250^{-1}	6.850^{-1}	9.614^{-1}	0	1.093
6	6.419^{-5}	0	0	0	2.644^{-3}	8.975^{-1}	1.000
Column Sum	9.969^{-1}	9.985^{-1}	4.030^{-1}	9.629^{-1}	9.934^{-1}	9.987^{-1}	5.353

Fig. 4.7. Oyster reef model first-order matrices (a) A for paths, and (b) P for causality. Example entry in P: $9.948^{-1} = 9.948\times10^{-1}$. See text for explanation of numbers. The time unit applied in the matrix representation is 6 hours, not 24 hours as used in Fig. 4.6.

5. *Matrix conceptualization* is illustrated in Fig. 4.7. The first upper matrix is a so-called *adjacency matrix*, that shows the connectivity of the system. This matrix has $a_{ji} = 1$ if a direct causal flow (or interaction) exists from compartment j (column) to compartment i (row), and $a_{ji} = 0$ otherwise. The lower matrix, called a flow or in/output matrix, represents the direct effects of compartment j on compartment i. The number expresses the probability that a substance in j will be transferred to i in one unit of time. P is a one step transition matrix in Markov chain theory and can be computed readily from storage and flow information. Notice that Fig. 4.6 uses the units cal/m^2 and cal/(m^2 day), while the flow matrix in Fig. 4.7 uses six hours as the time unit. The number for a_{12} is therefore found as $15.7915/(4{\cdot}2000) = 0.1974\times10^{-2}$ indicated in the matrix as 1.974^{-3}.

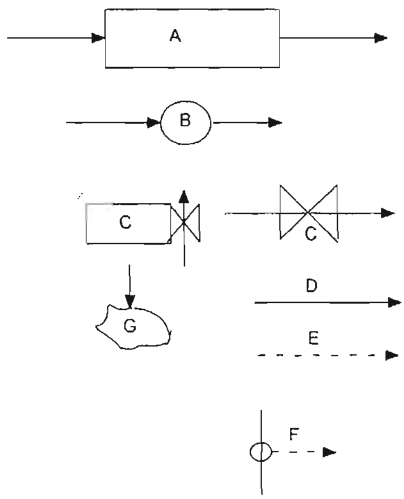


Fig. 4.8. Symbolic language introduced by Forrester (Jeffers, 1978). (A) State variable; (B) auxiliary variable; (C) rate equations; (D) mass flow; (E) information; (F) parameter; (G) sink.

The two matrices provide a survey of the possible interactions and their quantitative role.

6. The *feedback dynamics* diagrams use a symbolic language introduced by Forrester (1961) (see Fig. 4.8). Rectangles represent state variables. Parameters or constants are small circles. Sinks and sources are cloud-like symbols, flows are arrows and rate equations are the pyramids that connect *state variables* to the flows.

   A modification has been developed by Park et al. (1979). It differs from the *Forrester diagrams* mainly by giving more information on the processes.

7. A *computer flow chart* might be used as a conceptual model. The sequence of events shown in the flow chart can be considered a conceptualization of the ordering of important ecological processes. An example is given in Fig. 4.9, which is a swamp model developed by Phipps (1979). The model subjects each of the three species in the swamp to the same sequence of events with specific parameters as a function of species. Trees are born, grow and die off due to old age (KILL), lumbering (CUT) or environmental forces (FLOOD). Birth depends on another process. This type of model is very useful for setting up computer programs, but does not give information on the interactions. For example, it is not possible to read on Fig. 4.9 that GROW is a subroutine, which considers the effects of interactions between the water table and crowding on the individual tree species.

   A subcategory of computer flow charts is analog computer diagrams. Analog symbols are used to represent storage and flows. An amplifier is used to sum

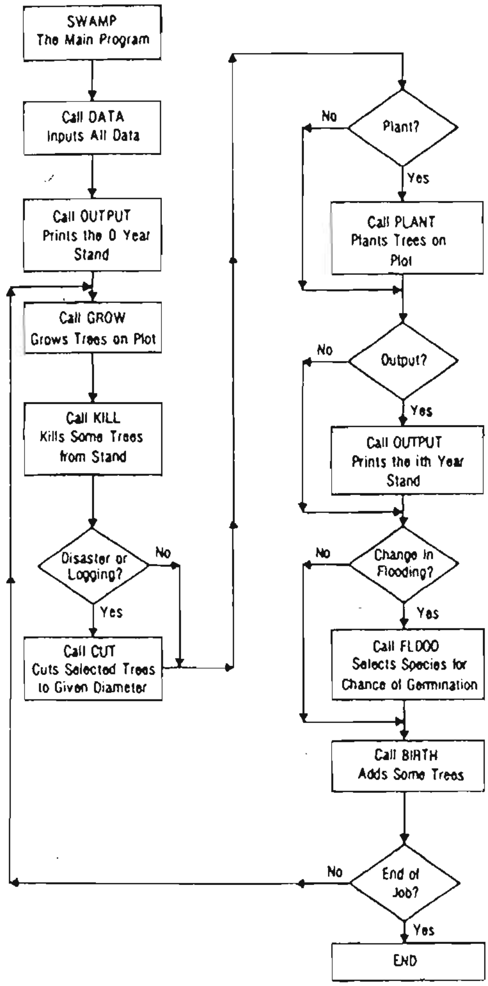
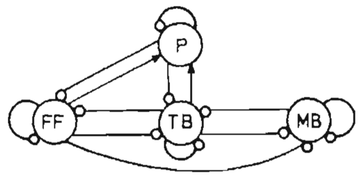


Fig. 4.9. Flow chart of SWAMP (modified from Phipps, 1979).

and invert one or more inputs. By adding a capacitor to an amplifier, we get an integrator. Analog computers have found only a limited use in ecological modelling. For descriptions see Patten (1971–1976).

8. *Signed digraph models* extend the adjacency concept. Plus and minus signs are used to denote positive and negative interactions between the system components in the matrix and the same information is given in a box diagram; see Fig. 4.10 which shows a general benthic model (Puccia, 1983). Lines connecting the components represent the causal effects. Positive effects are indicated by arrows; lines with a small circle head show a negative effect.



MODEL 4

Parameter input to	Change in equilibrium FF	TB	MB	P
FF	+	-	+	-
TB	-	+	-	-
MB	+	-	+	+
P	+	+	+	+

Fig. 4.10. A *general signed digraph model* for the east coast (USA). Benthic organisms from a sandy environment (from Puccia, 1983).

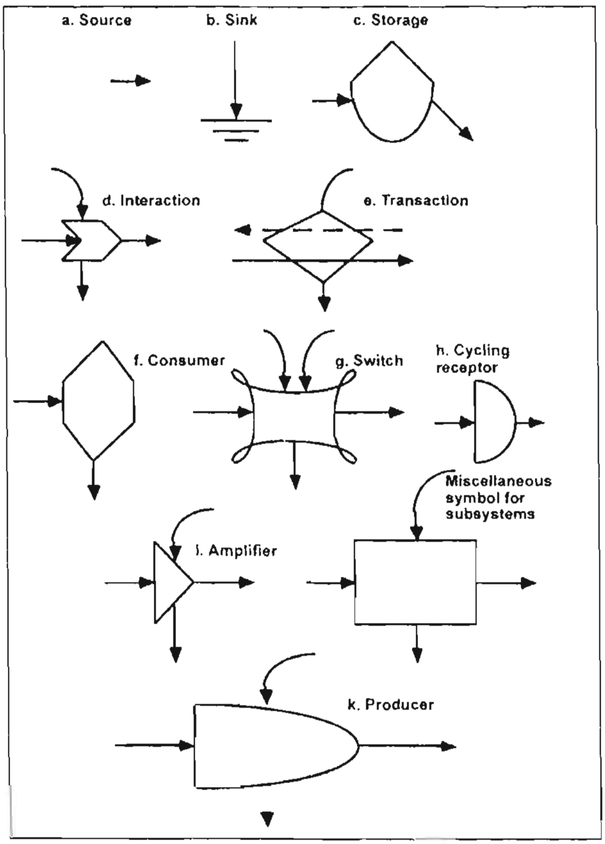


Fig. 4.11. Diagrammatic *energy circuit language* of Odum (1983) developed for ecological conceptualization and simulation applications.

9. *Energy circuit diagrams*, developed by Odum (see Odum 1983), are designed to give information on thermodynamic constraints, feedback mechanisms and energy flows. The most commonly used symbols in this language are shown Fig. 4.11. As the symbols have an implicit mathematical meaning, much information is given about the mathematics of the model. It is, furthermore, rich in conceptual information and hierarchical levels can easily be displayed. Numerous other examples can be found in the literature; see, for example, Odum (1983). A review of these examples will reveal that energy circuit diagrams are very informative, but they are difficult to read and survey, when the models are a little more complicated. On the other hand, it is easy to set up energy models from energy circuit diagrams. Sometimes it is even sufficient to use the energy circuit diagrams directly as energy models. These diagrams have found a wide application in the development of ecological/economic models, where the energy is used as the translation from economy to ecology and *vice versa*. In this context, H.T. Odum has used the approach for developing models for entire countries. As mass carries energy, it is possible to use the energy circuit diagram for *biogeochemical models*, too, although it is sometimes more cumbersome and causes unnecessary complications.

4.4. The Conceptual Diagram as Modelling Tool

The *word models*, *picture models* and *box models* all give a description of the relationship between the problem and the ecosystem. They are very useful as a first step in modelling, but their application as a modelling tool on their own is limited. Additional information is needed to answer even semi-quantitative questions. This is, however, possible using many of the other conceptual approaches demonstrated in this section.

Illustration 4.1

In Fig. 4.5 the *global C-cycle* is shown. It is seen that the input of carbon dioxide due to the use of fossil fuels increases the atmospheric carbon dioxide concentration by (5/700) per annum or (5/7%). If the amount of carbon dioxide dissolved in the sea is deducted, the increase will only amount to (2/7%). As the carbon dioxide concentration in 1970 was 0.032% on a volume–volume basis, it is easy to see that at the present rate of fossil fuel combustion, the concentration will reach 0.040% in 2003–04. It is, of course, also possible to compute the concentration at year *x*, when a certain trend in the use of fossil fuels is given, or the time it will take with a certain global energy policy to reach a given threshold concentration. These computations assume that the percentage of carbon dioxide transferred to the sea is constant or at least given as function of time. A far more complex computation is, of course, required to find the carbon dioxide concentration in the atmosphere if we want to incorporate the actual mechanisms for these transfer processes from the atmosphere to the sea, but as seen by this illustration it is possible to get some first approximations by using a conceptual diagram with indication of storage, input and output flows.

Illustration 4.2

Patten (1991) uses the *matrix representation* directly to compute what he calls the indirect effects. If the adjacency matrix is multiplied by itself, the product A^2 indicates the number of indirect paths of the length 2 from one compartment to another. In general the product of the matrix A^n will represent the number of length n paths from compartment j to compartment i. Figure 4.12a shows the tenth-order matrix of the model. As can be seen, the number of paths of length 10 is incredibly

COMPARTMENTS

(a)

From / To	1	2	3	4	5	6	Row Sum
1	1	0	0	0	0	0	1
2	23696	34729	23697	27201	23696	16168	149187
3	11033	16168	11032	12664	11033	7528	69458
4	16169	23696	16168	18560	16169	11033	101795
5	23695	34729	23696	27201	23696	16169	149186
6	11032	16]69	11033	12664	11032	7527	69457
Column Sum	85626	125491	85626	98290	85626	58425	539084

(b)

From / To	1	2	3	4	5	6	Row Sum
1	9.491–1	0	0	0	0	0	4.494–1
2	1.883–2	9.494–1	7.290–2	<u>2.988–1</u>	2.410–1	1.137–2	1.592
3	4.029–5	<u>2.303–3</u>	1.581–4	6.662–4	5.254–4	2.430–5	3.718–3
4	1.416–4	1.396–2	<u>6.616–2</u>	4.011–1	1.915–3	8.512–5	4.833–1
5	3.353–5	4.009–3	1.089–1	3.899–2	6.753–1	2.014–5	8.282–1
6	6.203–4	4.520–5	3.003–2	5.831–4	2.203–2	9.755–1	1.002
Column Sum	9.690–1	9.697–1	2.521–1	7.401–1	9.408–1	9.870–1	4.859

Fig. 4.12. Oyster reef model tenth-order matrices. (a) A^{10} for paths, and (b) P^{10} for influences. Smaller values than corresponding non-diagonal entries in P^3 are underlined. Note: 1.883–2 is shorthand for 1.883×10^{-2}.

high. There are more than 500 000 length 10 paths in the model. The reason is that the length of a cyclic path is infinite. Matter, energy and information may pass around such a path until it either dissipates from or leaves the cycle.

The P^{10} for influences is shown in Fig. 4.12b. Smaller values than corresponding non-diagonal entries in P^3 are underlined. Thus indirect effects are generally still tending to grow at the 10th order level due to the enormous number of paths. Patten demonstrates, by this simple analysis, the importance of indirect effects. These aspects will be discussed further in Section 5.3.

PROBLEMS

1. Draw a Forrester and energy circuit diagram for Fig. 2.8.
2. Set up a matrix representation of the model in Fig. 2.5.
3. Set up a matrix representation of the global carbon cycle Fig. 4.5.
4. Make a STELLA diagram of the picture model in Fig. 4.4. Set up an adjacency matrix for the model.
5. What will the probable carbon dioxide concentration in the atmosphere be in year 2025? It is presumed that 0.00032 volume/volume % increase will cause a temperature increase of 0.02°C. Which temperature increase relatively to 1900 (the concentration was 0.028 volume/volume %) and 1970 should be expected in the year 2004 and year 2025?
6. Set up an adjacency for the model of Illustration 5.1.

Developments in Environmental Modelling, 21

Fundamentals of Ecological Modelling

Third Edition

by

S.E. Jørgensen

DFH, Miljokemi, Universiteitsparken 2, 2100 Kobenhaven, Denmark

and

G. Bendoricchio

Università di Padova, Dipartimento di Processi Chimici dell'Ingegneria, Via Marzolo 9, 35131 Padova, Italy

2001

2001
ELSEVIER
Amsterdam — London — New York — Oxford — Paris — Shannon — Tokyo