ECOLOGY AND NATURAL RESOURCE MANAGEMENT

Systems Analysis and Simulation

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CHAPTER 3

CONCEPTUAL-MODEL FORMULATION

3.1 INTRODUCTION

The goal of the first phase of systems analysis is to develop a conceptual, or qualitative, model of the system-of-interest (Figure 3.1). Based on a clear statement of the objectives of the modeling project, we abstract from the real system those components that must be considered to address our questions. By including these components within our model and excluding all others, we bound the system-of-interest. Next, we categorize model components depending on their specific roles in describing system structure and identify specific relationships among components that generate system dynamics. We then formally represent the resulting conceptual model, usually as a box-and-arrow diagram indicating points of accumulation of material (boxes), such as individuals, energy, biomass, nutrients, or dollars, and routes by which the material flows within the system (arrows). Finally, we describe expected patterns of model behavior, most often as graphs representing changes in values of important variables within the system over time.

In many respects, conceptual-model formulation is the most intellectually challenging phase of systems analysis. The best basis for the many difficult, and often highly subjective, decisions that must be made regarding choice of model components is a thorough familiarity with the real system. Prior modeling experience also is an asset. There are two general approaches to identifying model components. One makes the initial choice of components as simple as possible and subsequently adds critical components that were overlooked; the other includes initially all components that possibly could have any importance and then deletes superfluous ones. Theoretically, the end prod-

Phase 1: Conceptual-Model Formulation

1. State the model objectives
2. Bound the system-of-interest
3. Categorize the components within the system-of-interest
4. Identify the relationships among the components of interest
5. Represent the conceptual model
6. Describe the expected patterns of model behavior.

Figure 3.1 Steps within Phase 1 of systems analysis: conceptual-model formulation.

uct of either approach should be a conceptual model that is no more complex than is absolutely necessary to address our interests. In practice, it is better to begin with the simplest model possible.

3.2 STATE THE MODEL OBJECTIVES

We begin with a clear statement of our interests in terms of a problem to be solved or a question to be answered. Questions may arise from general observations of a system, as is the usual case in scientific inquiry, or may be imposed by the practical necessity of evaluating proposed management schemes. Because model objectives provide the framework for model development, the standard for model evaluation, and the context within which simulation results will be interpreted, this is arguably the most crucial step in the entire modeling process. Yet, surprisingly, this step often receives far less attention than its importance warrants.

Often, our initial formulation of an objective is too broad to address directly and thus is of little use in guiding model development. For example, recalling the weight fluctuation model of Chapter 2, the objective "to understand the effect of temperature on weight fluctuations of an animal" might be stated more clearly "to determine the effect of temperature-induced changes in respiration on weight fluctuations of an animal." The first form of the objective does not indicate our interest in representing the physiological effect of temperature on respiration and thus provides no guidance in terms of the level of detail to include in the model. As a general rule, objectives that begin with "to understand—" need to be stated more specifically.

3.3 BOUND THE SYSTEM-OF-INTEREST

Bounding the system-of-interest consists of separating those components that should be included within the system-of-interest from those that should be excluded. We do not want an unnecessarily complex model, but likewise we do not want to exclude components that might be critical to the solution of our problem. From the simple simulation model presented in Figure 2.1, the only components included within the system-of-interest were weight of the animal, consumption, consumption rate, respiration, respiration rate, and environmental temperature. Other potential system components such as rainfall, weight of available food, and the number of animals in the population were excluded because they were considered unimportant in predicting fluctuations in weight of the animal.

Obviously, this step in conceptual-model formulation is highly subjective. Often difficult decisions arise regarding the need to include certain components. Our prior modeling experience helps us make such decisions, but ultimately we must base our decisions on the best information available about the system in question. Again returning to the example in Figure 2.1, rainfall clearly may have been irrelevant. But perhaps the decision to exclude the amount of available food and the number of animals in the population was based not on clear evidence that they were unimportant, but rather on the more tenuous assumption that they would have a negligible effect over the range of conditions that we wished to simulate.

Suppose that after reconsidering the problem of predicting fluctuations in animal weight, we decided that the amount of available food was an important factor affecting animal consumption after all, and that we should represent variability of both the amount of available food and the temperature in the model as functions of season. We then would bound the system differently by including available food as a system component affecting transfer of material from the food source to the animal and by indicating the influence of season on both availability of food and environmental temperature (Figure 3.2). (As we mentioned in Chapter 2, the symbols that we are using to diagrammatically represent conceptual models have specific meanings. We will define them formally in a later section, but figures presented in this section [Figures 3.2 to 3.4] can be interpreted informally without losing meaning for our present purpose.) Further suppose that we could not predict fluctuations in the weight of individual animals without considering the number of animals in the population because population density affected availability of food to individuals. The number of individuals in the population was of course a function of natality and mortality rates, which, let us suppose, were both density-dependent. We would change again our bounding of the system by including the number of individuals in the population as a system component affecting availability of food, and, in turn, affected by density-dependent natality and mortality rates (Figure 3.3).

Another aspect of bounding the system-of-interest involves identifying particular attributes or units of measure of system components that are of interest. In some cases, we may be interested in only a single attribute throughout the entire system. Consider the problem of predicting harvest of a migratory game fish population from specific fishing grounds as fish return from the ocean en route to freshwater spawning grounds. Suppose that for our purposes, we can

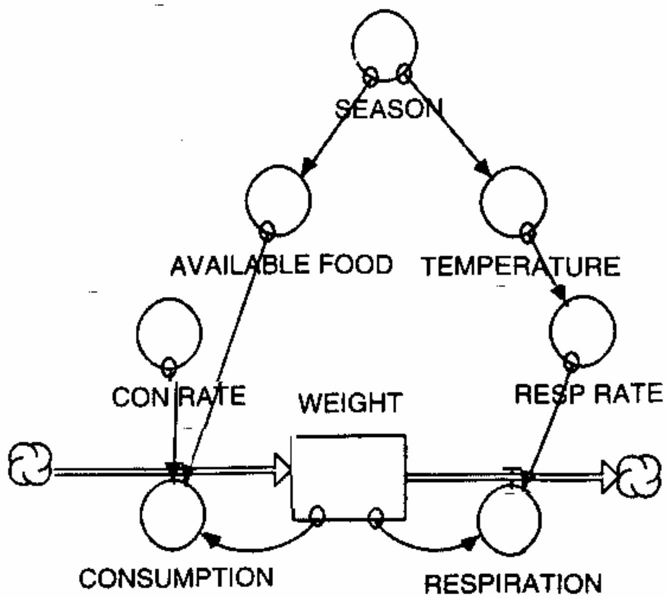

Figure 3.2 The weight fluctuation model (Figure 2.1) modified to represent available food and season as system components affecting weight fluctuations.

assume that fish are all the same size when they pass through the fishing grounds and that natural mortality is zero during the several weeks of their passage. We might bound the system, as indicated in Figure 3.4. We are interested only in the number of fish on the fishing grounds and in the number of fish harvested, perhaps under a variety of management schemes. The rate of recruitment of fish to the fishing grounds is a function of season. The rate of emigration of fish to the spawning grounds is a function of season and the number of fish on the grounds. The rate of fishing mortality is a function of the number of fish on the grounds and restrictions on harvest imposed by management. Thus, our description of the system is univariate: We are interested only in the number of fish passing through the system.

In some cases, we may wish to monitor several attributes of a system simultaneously. For example, we may be interested in population dynamics of a particular species. But we can represent those dynamics in terms of several attributes of the population: numbers of individuals, total biomass, or total energy content. It also is possible that different system components may have different attributes in which we are interested. In Figure 3.2, our interest in the animal component of the model was in terms of number of g, but temperature was monitored in terms of °C. In our later extension of this model to include representation of the number of individuals in the animal population (Figure 3.3), we further increased dimensionality of our description of the system. Thus, system descriptions can be multivariate.

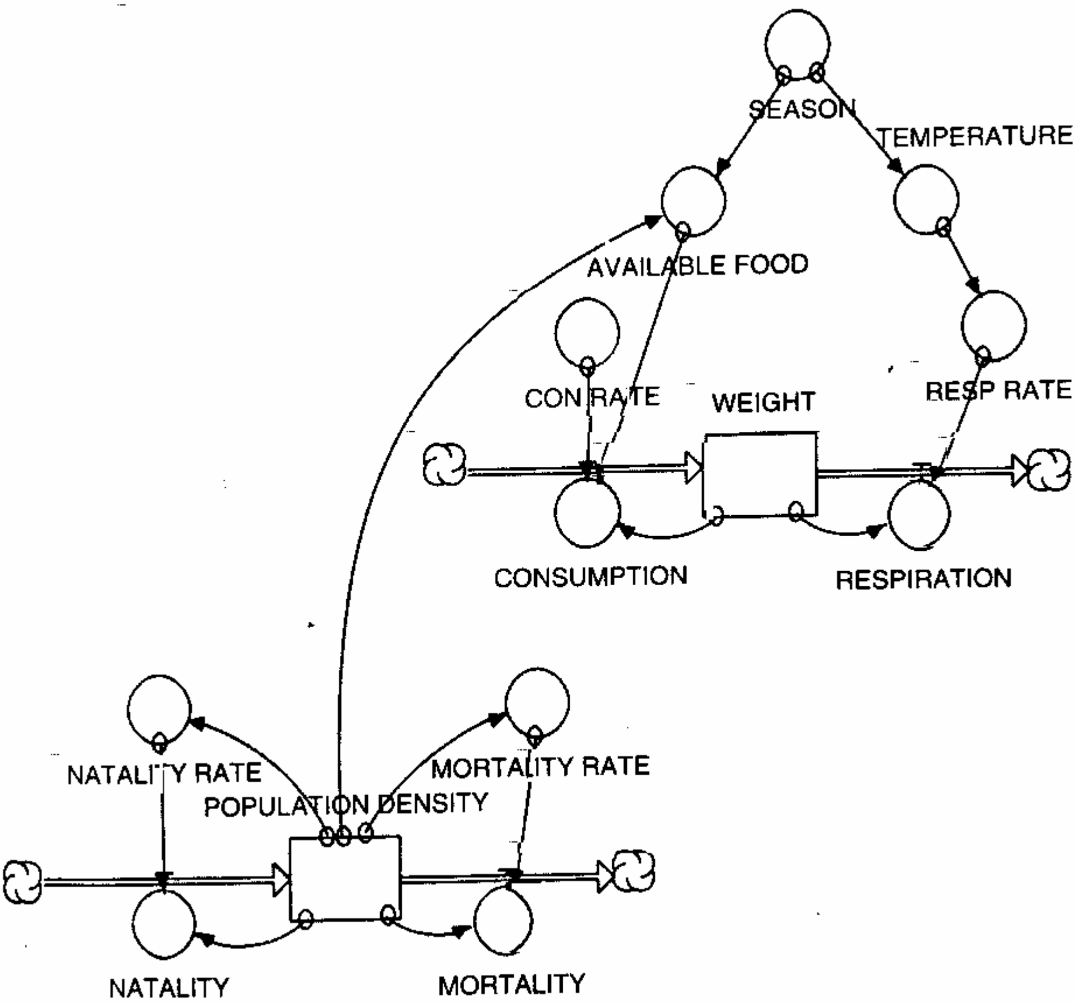

Figure 3.3 The weight fluctuation model (Figure 3.2 and Figure 2.1) modified to represent the number of individuals in the population as a system component affecting the availability of food and affected by density-dependent natality and mortality rates.

3.4 CATEGORIZE THE COMPONENTS WITHIN THE SYSTEM-OF-INTEREST

Once the system-of-interest has been bounded by separating those components that should be included within the system from those that should be excluded and by identifying particular attributes of system components that are of interest, we proceed to step 3 of conceptual-model formulation, categorizing components within the system-of-interest. System components may not all serve the same purpose in a model. Certainly, they all represent important aspects of the system-of-interest, but there may be as many as seven fundamentally different categories of system components: (1) state variables, (2) driving variables, (3) constants, (4) auxiliary variables, (5) material transfers, (6) information transfers, and (7) sources and sinks (Forrester, 1961; Innis, 1979; Grant, 1986).

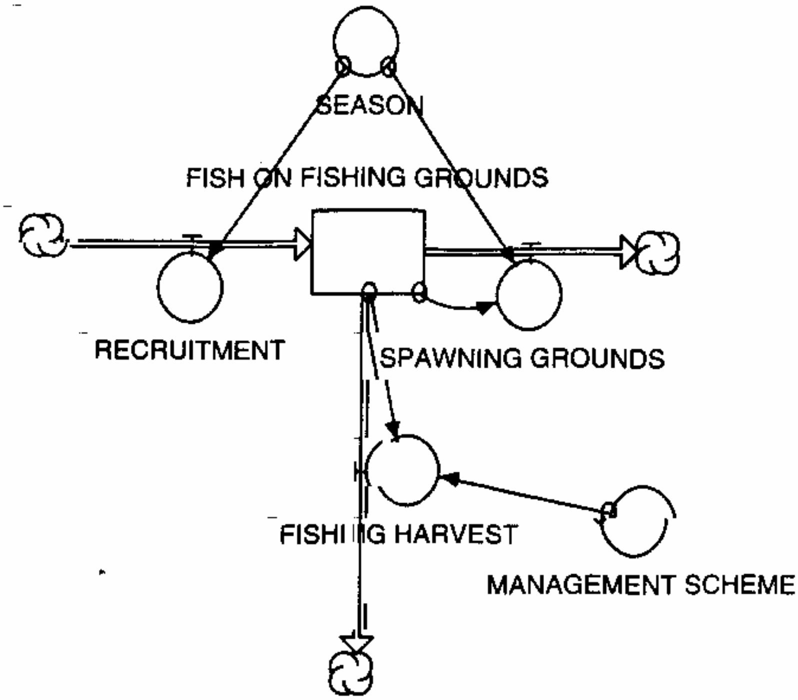

Figure 3.4 A model predicting harvest of migratory game fish from a specific fishing grounds under different management schemes.

3.4.1 State Variables

State variables (Figure 3.5) represent points of accumulation of material within the system. If we are interested in energy flow through an ecosystem, energy contained in plants, energy contained in herbivores, and energy contained in carnivores might be three state variables in the model (Figure 3.6). In the version of our weight fluctuation model described in Figure 3.2, the weight of the animal (measured as number of g) is a state variable. We later expanded this model to include population density of animals (measured as number of individuals/ha) (Figure 3.3), which also is a state variable. In our model predicting the harvest of migratory game fish (Figure 3.4), the number of fish on the fishing grounds is the only state variable, representing the single point of accumulation of "material" in the system.

3.4.2 Driving Variables

Driving variables (Figure 3.5) affect but are not affected by the rest of the system. For example, we may wish to represent the transfer of energy from the sun to plants as a function of the amount of rainfall (Figure 3.6). But, of course, the amount of rainfall is not affected by plants or by another system component. The season is a driving variable in both our weight fluctuation model (Figures 3.2 and 3.3) and our migratory fish model (Figure 3.4). In the fish model, season affects rates of recruitment to and emigration from the

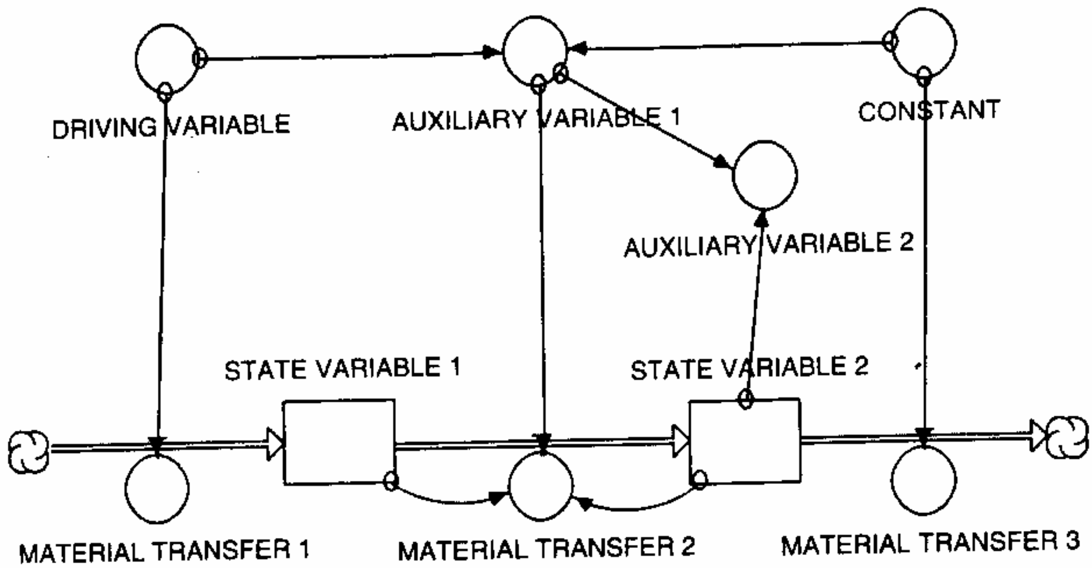

Figure 3.5 Symbols used to construct conceptual-model diagrams indicating all permissible connections (High Performance Systems, Inc., 1994).

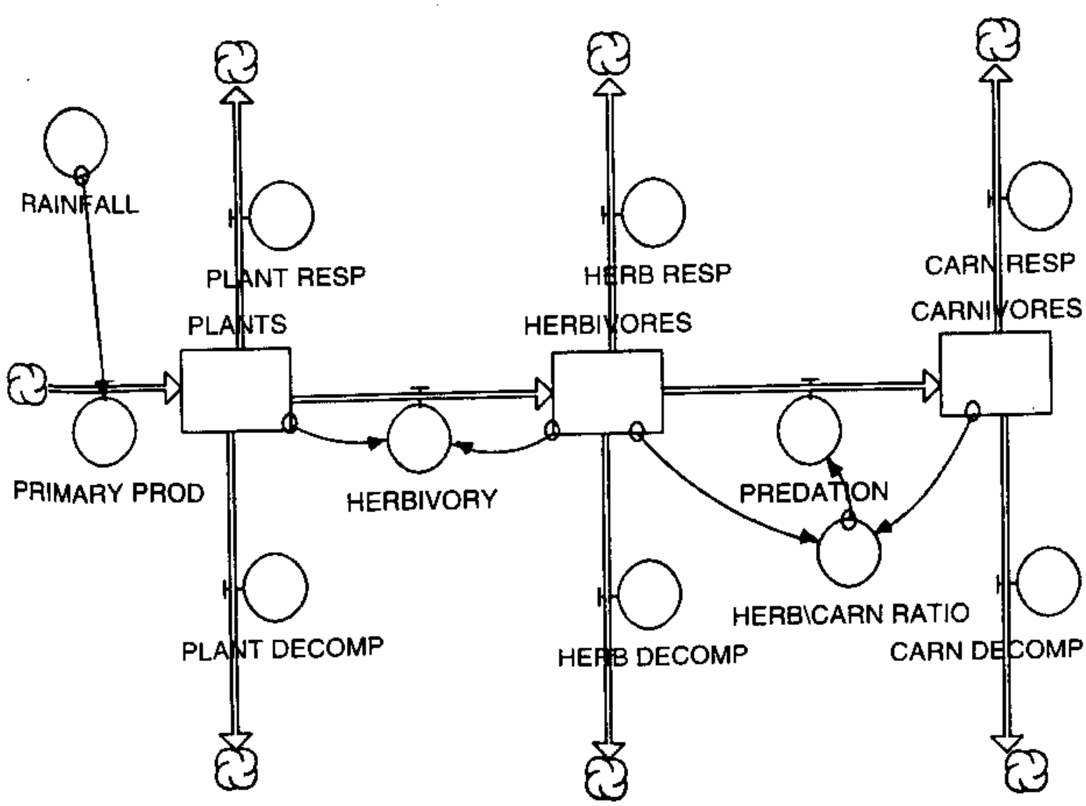

Figure 3.6 Conceptual-model diagram representing energy flow through an ecosystem.

fishing grounds. Obviously, these rates do not affect season. In the weight model, season affects the rates of consumption and respiration (indirectly through available food and environmental temperature—both auxiliary variables that we will define shortly). Whereas we associate some driving variables with specific units of measure, such as the rainfall (mm) driving variable in Figure 3.6, others can be unitless. Season, for example, often is described as taking on values of 1, 2, 3, and so on, to represent January, February, March, or first quarter, second quarter, third quarter of the year. (The way this technique works will become clear when we discuss quantitative specification of the model in Chapter 4.)

3.4.3 Constants

Constants (Figure 3.5) are numerical values describing characteristics of a system that do not change, or that can be represented as unchanging, under all of the conditions simulated by the model. Coefficients appearing as part of rate equations, such as the consumption coefficient in the original weight fluctuation model (Figure 3.2), are common examples of constants. Factors such as environmental temperature and rainfall, which more commonly are represented as driving variables, also are represented as constants, by definition, if they do not change under the conditions simulated.

3.4.4 Auxiliary Variables

Auxiliary variables (Figure 3.5) arise as part of calculations determining a rate of material transfer or the value of another variable, but represent concepts that we wish to indicate explicitly in the model. Auxiliary variables also may represent an end product of calculations that is of particular interest to us. For example, we may wish to represent the transfer of energy from herbivores to carnivores as a function of both the number of herbivores and the number of carnivores. Further, the ratio of herbivores to carnivores may have a special meaning for us over and above the fact that it is an intermediate step in calculations determining the transfer of energy from herbivores to carnivores. Thus, we represent the herbivore/carnivore ratio as an auxiliary variable (Figure 3.6).

In our weight fluctuation model (Figures 3.2 and 3.3), available food and environmental temperature are auxiliary variables (as is resp rate). Both consumption and respiration by the animal ultimately are a function of season (driving variable). But the effect of season on consumption results from changes in available food, whereas the effect of season on respiration results from changes in environmental temperature. We call attention to this difference by creating auxiliary variables (available food and environmental temperature) mediating the effects of season on consumption and respiration. As an alternative version of the model in Figure 3.2, had we not wanted to call attention to the fact that available food and environmental temperature vary seasonally, we might have omitted season completely and represented both food and temperature as driving variables because neither is affected by the rest of the system. The model in Figure 3.3 also might be modified to represent temperature as a driving variable (with no link to season), but available food cannot be represented as a driving variable because it is affected by another system component (the population-density state variable).

3.4.5 Material and Information Transfers

A material transfer (Figure 3.5) represents physical transfer of material over a specific period of time: (1) between two state variables, (2) between a source and a state variable, or (3) between a state variable and a sink. As energy flows (in kcal/week) through the grazing food chain within an ecosystem, it is transferred from plants to herbivores to carnivores (Figure 3.6). As an animal gains weight (in g/day), biomass is transferred from a food source to the animal to a respiration sink (Figure 3.2). As fish enter and leave fishing grounds (in number of individuals/month), individuals are transferred from a recruitment source to the fishing grounds to a spawning grounds sink (Figure 3.4). Note that units of measure associated with material transfers always include a time dimension such as per hour or per year.

Information transfers (Figure 3.5) represent the use of information about the state of the system to control the change of state of the system. We may wish to represent the material transfer of energy from plants to herbivores as a function of both the number of herbivores and the amount of plants (Figure 3.6). Or, more strictly speaking, to calculate the rate of energy transfer from the plant state variable to the herbivore state variable, we need information about the number of kcal of herbivores and number of kcal of plants in the system. Likewise, to calculate harvest in our fish migration model (the material transfer of individuals from the fish on fishing grounds state variable to the fishing harvest sink), we need information about the number of fish on the fishing grounds and the management scheme (driving variable) (Figure 3.4).

3.4.6 Sources and Sinks

Sources and sinks (Figure 3.5) represent origination and termination points, respectively, of material transfers into and out of the system. By definition, we are not interested in the level of accumulation of material within sources or sinks. For example, we may note that energy enters an ecosystem by being transferred from sun to plants, but we may have no interest in the amount of energy in the sun (solar energy source) (Figure 3.6). Likewise, we may note that energy is lost from the grazing food chain both through respiration of plants, herbivores, and carnivores, and as plants, herbivores, and carnivores are eaten by decomposer organisms. But we may not be interested in the level of accumulation of respired energy (respiration sink) or of energy in decomposers (decomposition sink) (Figure 3.6).

3.5 IDENTIFY THE RELATIONSHIPS AMONG THE COMPONENTS THAT ARE OF INTEREST

Step 4 of conceptual-model formulation consists of identifying relationships among system components that are of interest. There are two ways that system components may be related: by material transfers or by information transfers (Figure 3.5). Material transfers can leave sources and state variables and enter state variables or sinks. Units of measure of state variables, sources, and sinks connected by material transfers must be the same. "Information" transferred within the system refers to information about current values of state variables, driving variables, constants, and derived auxiliary variables. This information is "transferred" for use in determining the rate at which specific material transfers occur or for calculating specific results, or "output," required of the model. Information transfers can leave state variables, driving variables, constants, and auxiliary variables and can enter material transfers and auxiliary variables. Units of measure of variables affecting a given material transfer or auxiliary variable need not be the same. Respiration rate in our weight fluctuation model (the material transfer from animal state variable to respiration sink) is determined by information about weight of the animal in g and environmental temperature in °C.

3.5.1 Submodels

We have seen that the system-of-interest may be described by more than one attribute, but that material transfers can occur only among state variables, sources, and sinks described by the same attribute. This brings us to the concept of submodels within a model.

If we wish to represent the transfer of different materials within a system, we must represent each set of transfers associated with a given material in a separate submodel. Various submodels, or sets of material transfers, may be connected by information transfers but not by material transfers. Material transfers in Figure 3.3 include both biomass and individuals, but they follow different routes within the model. They are in different submodels connected only by an information transfer from the population-density state variable to the available food auxiliary variable.

As another example of use of submodels, suppose that we wish to modify our weight fluctuation model (as conceptualized in Figure 3.2) to simulate nitrogen balance as well as weight fluctuations. Further suppose that nitrogen intake is a function of the nitrogen content of available food and the food consumption rate, which we already know is a function of animal weight, a consumption rate constant, and the amount of available food. Nitrogen output is a function of animal weight and nitrogen content of the animal.

We might model this new system by adding a new submodel consisting of a state variable representing g of nitrogen in the animal, a constant representing the nitrogen content of available food, and material transfers representing nitrogen consumption and loss (Figure 3.7). We then would use information on the weight of animal state variable, consumption rate constant, available food auxiliary variable, and the nitrogen content of available food constant to determine the material (nitrogen) transfer from the nitrogen source to the nitrogen in the animal state variable. We would use information on the weight of the animal state variable and nitrogen in the animal state variable to determine the material (nitrogen) transfer from the nitrogen in the animal state variable to nitrogen sink (Figure 3.7). Our model now has a weight submodel and a nitrogen submodel, each representing dynamics of a different

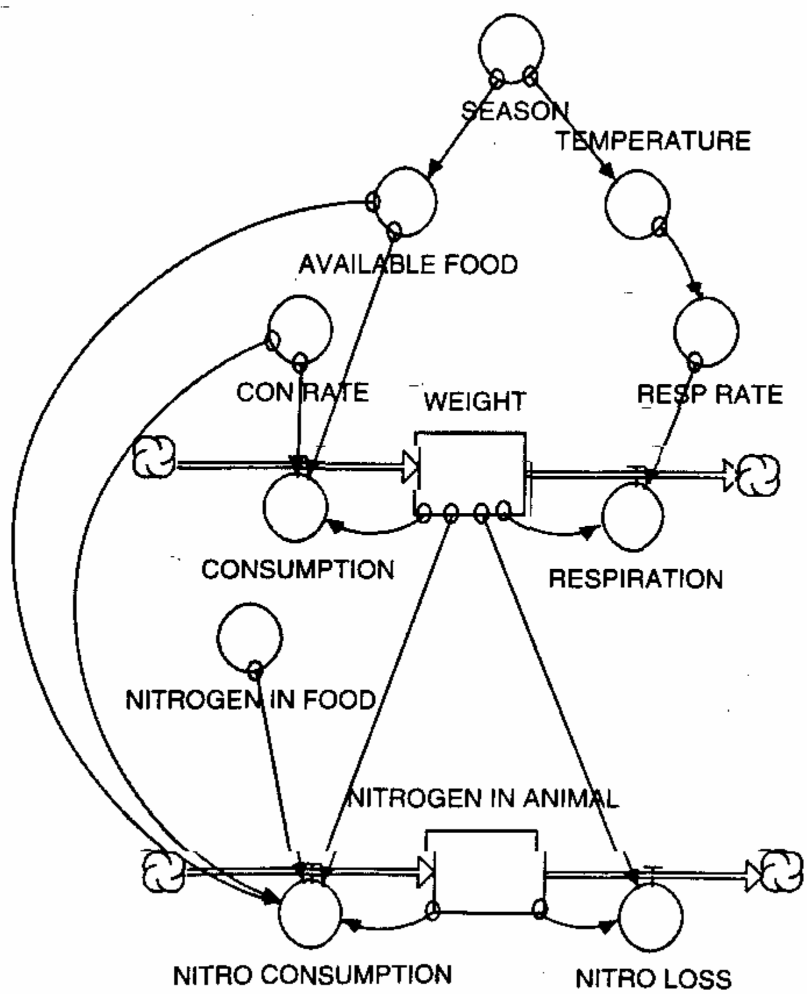

Figure 3.7 Conceptual-model diagram of the weight fluctuation model (Figure 3.2) modified to include nitrogen balance as well as weight fluctuation submodels.

attribute of the system-of-interest, connected only by information transfers or by the "information network."

3.6 REPRESENT THE CONCEPTUAL MODEL

3.6.1 Conceptual-Model Diagrams

Formal representation of the conceptual model most commonly takes the form of a box-and-arrow diagram such as those we have been using to illustrate our example models thus far. As we have seen, such diagrams play an important role in modeling by helping us visualize the "big picture" and by facilitating communication between different people who are interested in a particular system. Although we present this as the fifth step in conceptual-model formulation, and indeed the conceptual-model diagram might be thought of as the end product of the first phase of systems analysis, diagrammatic representation of the conceptual model usually is concurrent with the earlier steps and aids them greatly. Conceptual-model diagrams also provide a framework that facilitates subsequent quantification of the model because equations can be related directly to specific parts of the conceptual model.

A variety of schemes exists for formal representation of the conceptual model. Diagrams based on symbols introduced in Figure 3.5 are particularly useful because they are simple, flexible, and defined in terms identical to those that we have chosen to describe components and relationships within the system-of-interest. These particular symbols are those used in the simulation program STELLA® II (High Performance Systems, Inc., 1994). They are similar to those suggested by Forrester (1961) for modeling dynamics of industrial systems, although the driving variable concept was added by Innis (1979) for modeling ecological systems. We will use these symbols to represent models throughout the text.

3.7 DESCRIBE THE EXPECTED PATTERNS OF MODEL BEHAVIOR

We usually have some expectations concerning patterns of model behavior before ever running the first simulation. These expectations are based on the same a priori knowledge that we draw on to formulate the conceptual model as well as what we have learned about the system-of-interest during the process of conceptual-model formulation. We formalize these expectations, most often as graphs representing changes in values of important variables over time, to (1) use as points of reference during model evaluation and (2) ensure that the model provides the type of predictions that allows us to address our questions directly.

During model evaluation, we will compare model behavior and the expected patterns of model behavior before more formally comparing model

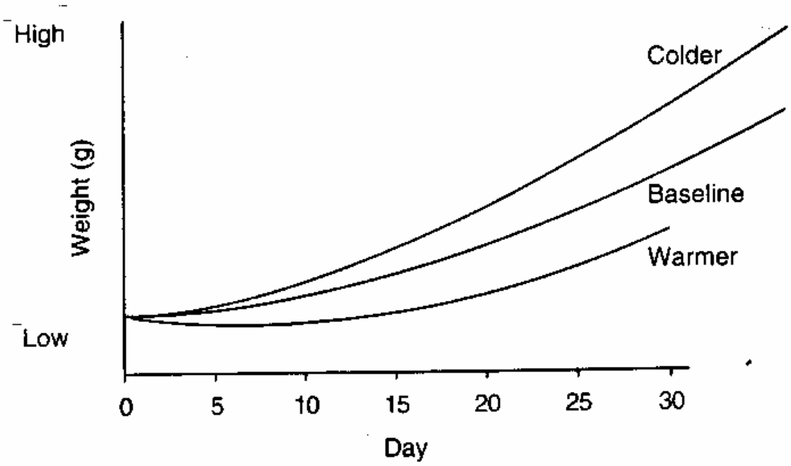

Figure 3.8 Expected patterns of animal weight fluctuations (g) under baseline, warmer, and colder temperature regimes.

predictions to data from the real system. Most often, we know more about relationships among variables within the system-of-interest than can be documented in a rigorous way by data. We want to describe the expected behavior of those variables that most effectively represent this broader knowledge, thus allowing a more extensive evaluation of model behavior than would be possible based solely on data. For example, recalling what we know about the relationship between environmental temperature and respiration in our weight fluctuation model, although we may not be confident about the exact form of the curve, we expect animal weight to decrease monotonically as temperature increases.

During model use, we will analyze and interpret patterns of behavior of selected variables under different management policies or environmental situations to meet our objectives. We want to describe the expected behavior of those variables that most directly represent hypotheses that we want to test. In this sense, expected patterns of model behavior often are a graphical representation of model objectives. For example, recalling the objective of our weight fluctuation model "to determine the effect of temperature-induced changes in respiration on weight fluctuations of an animal," we might graph a series of curves representing weight fluctuations under several different temperature regimes (Figure 3.8).