expectations, or dissatisfactions that cannot be measured exactly and are not included in any standard compilation of statistical data. Though they are important, these intangible variables are seldom measured, because their dimensions are difficult to define operationally. However, they have often been experienced, in a casual and imprecise way, and mental models contain numerous accurate impressions of their role in social systems. Estimates of such unmeasured, intuitive variables are generally included in system dynamics models on the assumption that their inclusion, even with some inaccuracy, produces a more useful and accurate representation of the total system than does their omission.

Sensitivity to Parameter Changes

World3 is a device for testing the implications of alternative assumptions, not a predictor of future events. Numerous simulations of the model system with different sets of parameter values indicate the range of behavior modes that the system can exhibit and the sensitivity of those behavior modes to parameter changes. Since many of the model's parameters may be inaccurate, it is especially important to understand how the conclusions drawn from the model may be influenced by errors in their values.

In keeping with the purpose of the model, we identify sensitive parameters by observing changes in the model's qualitative behavior, not its quantitative output. For example, a change that causes the population in World3 to level off at 6 billion instead of 7 billion would not be considered significant—the population still levels off, and its behavior mode is still stable. On the other hand, if a small change in one parameter causes the model to shift from an overshoot mode to a stable equilibrium, we would regard that parameter as sensitive and would put considerable effort into estimating it as accurately as possible.

Fortunately, given the inaccuracy of most social data, the behavior of complex feedback systems is generally not qualitatively sensitive to parameter values. In such systems numerous negative feedback loops, each acting to maintain a system variable within a certain range of values, tend to offset small numerical changes in any one loop by inducing opposing changes in other loops. Thus complex systems tend to exhibit the same behavior mode over a wide range of parameter values; their behavior is determined more by their structure than by the precise values of their numerical parameters. The behavioral stability of complex systems can be illustrated by many common examples: the ability of the human body to maintain a constant internal temperature when the external temperature fluctuates, the tendency of commodity prices to oscillate regularly in many different countries under a variety of political systems, and the energetic stability of a diverse tropical forest ecosystem (as contrasted with the instability of a monoculture, which is no longer a complex system).

There is one important exception to the general rule that complex systems are insensitive to parameter changes. Sensitive points may exist within the system structure, where a change in a certain combination of parameters becomes equivalent to a major structural change. These points are rare, and they generally occur at the intersection of several positive and negative feedback loops, where a small shift in numbers may change the relative dominance of loops and thus the tendency of the

entire system to grow or decline. An important purpose in making a dynamic model is to locate these points because they indicate relationships on which more research may be necessary to understand the system fully. They also indicate decision points in the system where new policies may be effective in altering system behavior.

Physical Limits in World3

One group of parameter values in World3 is of particular importance, not because the model behavior is sensitive to their values but because their estimation reflects most directly the ecological or technological bias of the modeler. These are the values that express the ultimate physical limits in World3.

We found only subjective, imprecise, and inaccurate information to use in estimating the limits beyond which growth in land development, capital intensification of agriculture, resource acquisition, and pollution assimilation would produce socially unbearable costs. Although reasonable estimates of some limits, given present technologies, are available, there is no way of knowing how they may be affected, positively or negatively, by future technologies. Extreme assumptions about ultimate limits may render the model output either uninteresting (by setting the limits so high that they are ineffective before the model year 2100) or unhistorical (by setting them so low that they stop growth before the model year 1970). The model itself cannot determine which set of values is correct; it can only serve as a device within which any set can be tested and evaluated.

For the reference run of the World3 model (Figure 7-6), we attempted to assign values to the limit parameters that are consistent with present global resource estimates and currently foreseeable technologies. Other values, both higher and lower, were tested in subsequent model runs. The values assumed in the reference run are:

1. Potentially arable land—3.2 billion hectares, or about twice the area currently under cultivation.
2. Maximum yield per hectare—6,000 vegetable-equivalent kilograms per hectare-year, or three times the global average yield in 1970.
3. Nonrenewable resources (total exploitable stock)—250 times the amount consumed globally in 1970.
4. Persistent pollution assimilation rate (per year)—25 times the amount of pollution rendered harmless by natural ecosystems in 1970.

Our justification for these values and the tests of alternative values are presented in the relevant sector descriptions. We believe that the assigned values represent an intermediate position between the extreme ecological and technological views. They allow for considerable progress beyond the limits attainable with present technology, but they do not assume that technology will be able to push back the physical limits indefinitely.

1.9 EVALUATION OF MODEL UTILITY

After the feedback-loop structure has been established and quantified, the model can be analyzed on the computer to calculate from the entire set of structural and