erosion will occur as a result of such intensive land use. Under these assumptions, land yield increases are easily able to stay ahead of the growth in both population and indicated food per capita. Land yields grow to over 20 times their 1970 value by the year 2100, even though physical agricultural inputs *decrease* during that period. Either genetic changes have vastly increased the efficiency of the conversion of sun energy by green plants or, perhaps, an increase in sun energy has been engineered. Furthermore, although industrialization is expanding exponentially and population continues to increase, the rate of removal of land for urban-industrial use declines to zero after the year 2000 due to technological advances in the efficiency of land utilization (perhaps all new cities are built over the ocean).

In the pollution sector, pollution generation per unit of industrial and agricultural output declines exponentially at 4 percent per year during the model run. By the year 2100 each unit of industrial output generates less than one one-hundredth of the amount of pollution that a similar unit of output generated in 1970. Even though population and industrial output continue to increase exponentially through the year 2100, the index of persistent pollution PPOLX is declining in the year 2100. Run 7-18 also assumes that air pollution control technologies increase fast enough to offset the adverse effects of air pollution on land yield during the model run. Finally, the run assumes that technological advances in methods of production ensure that the growth in industrial output will never be curtailed by a labor shortage.

When the assumptions behind Run 7-18 are made explicit, the reason for the radical change in the behavior of the model becomes obvious. The assumption of continuous exponential advance in technology at 4 percent per year and at no cost eliminates all the assumed limits in the model. Resource usage declines essentially to zero by the year 2100, which implies the building and maintenance of an immense capital stock with no net physical consumption of any resource, including land. Exponential land yield increases assume that the energy or caloric conversion per hectare of land has no limit—even though this energy is supplied at a finite rate from the sun. Exponentially decreasing pollution levels imply that practically no materials are involved in the industrial process by 2100, or that pollution control is nearly perfect and cost-free. Because the social and political limits to growth that may be associated with increasing population densities were not included in the model, there are no reasons for growth to stop.

Although we believe that new technologies are certainly capable of extending some of the natural limits modeled in World3, we do not believe that these new technologies can eliminate the effects of those limits altogether, as depicted in Run 7-18. Successful advances in technology are by no means an automatic, continuous exponential process. They are subject to decreasing returns and increasing costs and to physical laws (for example, the second law of thermodynamics, which implies that recycling cannot be 100 percent effective or cost-free). Technological development is a delayed and costly process that occurs only in response to perceived social needs. The next set of runs tests the behavior of the system if this more realistic representation of technological advance is explicitly modeled.

Adaptive Changes in Technology

The first set of technological policies tested in this chapter assumed that new technologies tend to be implemented in discrete increments, with no costs and no development or implementation delays. Next, a run was presented in which the effectiveness of new technologies was assumed to increase exponentially, again with no costs and no delays in development or implementation. These representations of technology appear to be unrealistic. Technological improvements seem to arise only in response to a perceived need for the improvements and as a result of a costly and time-consuming period of scientific development and social implementation, not through some automatic process that causes improvements to increase regularly each year.

We have labeled this model of technological development an adaptive process because the technological improvements tend to move the system toward a desired set of goals in response to a perceived need for such technological developments. The following set of policy runs tests the effects of this adaptive process of technological development on the behavior of the model as shown in the reference run (Figure 7-7). The parameter changes and structural additions for each adaptive policy run may be found in the appendix to this chapter.

Adaptive Technological Policies—No Delays, No Costs Run 7-19 (Figure 7-24) shows the behavior of the model under the assumption that technological advances in reducing resource usage, reducing pollution generation, and increasing land yields all occur in response to a perceived need for the technologies. In this run it is still assumed that these advances in technology are achieved with no delays in development and implementation, and at no cost. Figure 7-25 illustrates the structural additions in the resource, pollution, and agriculture sectors inserted for this run. In the resource sector, technological advances in recycling reduce the nonrenewable resource usage factor NRUF as annual resource usage rises above a desired rate, set at the 1970 rate of usage. In the pollution sector, technological advances in pollution control are developed as the level of pollution rises above a desired pollution level, here assumed to be 3 times the level of pollution in 1970. Pollution control technologies then reduce the pollution generation factor, representing a decrease in the pollution generated per unit of industrial and agricultural output. In the agriculture sector, technological advances raise the land yield as the food per capita drops below the desired level, which is assumed to be 3 times the subsistence level. In each case, the maximum rate of technological change is assumed to be 5 percent per year.

In addition to the three adaptive technological policies shown in Figure 7-25, discrete increases in resource exploration and extraction technologies, land maintenance technologies, and air pollution technologies are assumed to occur in 1975. Note that these technological advances could have been modeled as adaptive policies, but they are modeled here as step increases to simplify the presentation in this section. These three additional technologies are included in each succeeding adaptive policy, Runs 7-19 through 7-23.

The behavior mode exhibited by Run 7-19 is similar to that of 7-18, where