Sustainable Development
A Systems Approach

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Foreword

This Status Report summarizes the final report of the IIASA Environment and Development Study which was submitted to the Secretariat of the United Nations Conference on Environment and Development (UNCED) in December 1991. As a systems analysis institute, IIASA was asked by UNCED in mid-1990 to explore the usefulness of systems analysis in: identifying some of the important linkages among population, environment, and development; examining some of the underlying causes of environmentally unsustainable development; and in formulating and implementing policies for more sustainable development. The work first involved the formulation of conceptual models of the socio-ecological system in which we live. The application of systems analysis to environment and development was then examined in several case studies. The case studies, based mainly upon past and present work carried out here at IIASA, indicated that systems analysis is potentially very useful in helping us towards a sustainable future. However, the work that is described in the report gives only a few examples of what could be done in the years following UNCED.

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Sustainable Development: A Systems Approach

1. Background and Purpose of the Report

1.1 Background

The United Nations Conference on Environment and Development (UNCED), to be held in Rio de Janeiro, Brazil, in June 1992, will be a unique opportunity for collective cooperative action among nations to:

- Improve the standard of living of the 75% of the world population living in developing countries.
- Prevent further environmental damage.
- Reverse the environmental damage that has already occurred.

In early 1990 Maurice Strong, Secretary-General of UNCED, asked IIASA to provide input to the conference by examining the usefulness of systems analysis in identifying some of the important linkages among population, development, and the environment, and in helping decision makers with formulating and implementing policies for sustainable development. His motivation for doing so was that the UNCED agenda, established by UN General Assembly Resolution GA 44/228, is largely sectoral in nature; it will be dealing with traditional topics such as protection of the atmosphere, conservation of biological diversity, etc., as separate issues. Although certain cross-sectoral issues such as financial resources and technology transfer will also be dealt with at UNCED, there is a need to identify and focus discussion on those cross-sectoral linkages which lie at the root of unsustainable development and which, therefore, may hold the key to better policies for the future.

Responding to Mr. Strong's invitation, the IIASA Environment and Development Study was initiated in July 1990. Our work during the following 17 months brought us to the conclusion that the linkages among population, development, and the environment are indeed complicated. It is essential to examine these linkages in a holistic way if we are to formulate truly sustainable development strategies: systems analysis affords us an opportunity of doing so. This is the theme running through our final report to the UNCED Secretariat in December 1991 (Shaw *et al.*, 1991), of which the following is a summary.

1.2 Purpose

We were given very specific objectives, which were to:

In general

- Examine the usefulness of systems analysis (in its broadest sense) in helping to formulate and implement policies towards sustainable development.

In particular

- Stress the importance of taking the holistic view in examining the issue of environment and development so as to not overlook important linkages.
- Examine the underlying causes of unsustainable development resulting from the activities of both rich and poor.
- Develop conceptual models of environment and development that will be useful in identifying problem linkages and potential solutions.
- Identify characteristics of sustainable development and the challenges that they pose for systems analysis.
- Through case studies, demonstrate how systems analysis may meet these challenges using concepts such as ecological limits, indicators of change, and boundary conditions.

It was **not** the purpose of the report to define sustainable development: we worked under the general spirit of the Brundtland definition "*to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, 1987). Nor was it our task to prove whether or not our present development pathways are in fact sustainable. Although we worked under the general umbrella of UNCED, whose position is that the present development pathways are not sustainable, the outcome of our work does not depend upon that position.

1.3 Premises

The premises upon which our work was based are as follows:

- Many aspects of current development are not sustainable. This is due to a phenomenal growth in the scale and intensity of human activities (UN, 1990; Speth, 1990). Unsustainable development is a feature of both the North and the South. The commercially successful development path followed by the North cannot be generalized (Daly, 1990). Past development in the North has foreclosed many development options for the South (Pearce *et al.*, 1989).
- The aim of development should be to enhance the quality of people's lives, considering both material and non-material factors, and to lessen disparities across social groups, regions, and generations. Reducing poverty is more than a moral imperative. The persistence of poverty and the widening gap between rich and poor place extra burdens upon the environment and threaten global security.
- The relationships that exist between humankind and the environment are much more complex and interlinked than ever; this will require new ways of thinking and acting. A change in one part of the socio-ecological system may reverberate in non-obvious ways through one or more causal chains, eventually triggering unforeseen changes in other components.
- Sustainable development should promote resilience in socio-ecological systems at all scales from the local to the global; it should increase the capacity of systems to deal with change, and to be self-reliant.
- Decision makers must look strategically and holistically at the broader context and longer time frame, even when making decisions which are local and short-term. The key is to search for integrated solutions to problems rather than for alleviation of symptoms, since this is far more effective.

We acknowledge that some of the above premises are debatable, and indeed are being debated in the literature more fully than we are able to do.

2. Tools Available for Systems Analysis

Systems analysis, as it is usually carried out at IIASA, is the examination and use for practical purposes of the elements and linkages of systems, i.e., regularly interacting or interdependent groups of items forming a unified whole. This report reviews various systems tools that are available. These tools should carry out several tasks:

- Identify the important or potentially important elements in socio-ecological systems.
- Describe possible linkages among the elements of such systems (including causal pathways and feedbacks) and their relative importance.
- Allow for the examination of various scenarios including discontinuities ("surprises").
- Develop anticipatory and response strategies, and assess their possible effects.

To carry out these tasks, systems analysis may also need to:

- Organize large amounts of disparate information in a readily accessible and usable form.
- Allow for sensitivity and error analyses in the face of uncertainty and ignorance.

Models, the central tools of systems and policy analysis, come in a great variety, ranging from simple conceptual models to elaborate mathematical structures that challenge the computing capacity of the world's largest supercomputers (Miser and Quade, 1988).

Conceptual models are essential in the initial analysis of a problem. Their formulation requires insight, judgment, and imagination about essential elements of a system, and the chains of influences, feedbacks, and inter-dependencies. They may include estimates of the direction and relative strength of linkages without attempting to quantify them. Conceptual models are capable of storing information about intangibles such as motivations and values; they can also make creative associations and analogies. However, it is difficult for them to store and keep track of many interlocking factors in a reproducible way. Where possible, this is a task better performed by more formalized models based upon knowledge of the linkages.

Formalized models are based upon conceptual models, but the linkages among elements are expressed in a more formalized fashion; they might be expressed quantitatively or qualitatively. These models can have any degree of sophistication; beyond a certain point, it is usually necessary to computerize them and they are usually referred to as such.

Mathematical models of large, dynamic socio-ecological systems have had, at best, a checkered record of success. Some of the failures of the past were attributable to naive expectations about their ability to make detailed and precise predictions about the behavior of the system. Starting with the experience of the Club of Rome (Meadows *et al.*, 1972), it is now apparent that even the largest computer and most complex model cannot encompass all aspects of the environment–development nexus. A comprehensive, predictive model of humanity's interaction with the natural world still lies far beyond our reach.

Nevertheless, modeling remains a valuable tool for examining complex systems. Models can force the analyst to look at systems (in our case, socio-ecological systems) as a whole, to clarify the important elements and linkages, to point to how the system may be most critically bounded, and to examine the relative merits of various management strategies, especially with respect to the desired attributes of sustainable development.

Models, particularly those that are at least semi-quantitative, need to be able to receive information as input in an organized fashion, and to store and display their results in a way that is easily digestible and informative to the user. Information bases are systems of storing, retrieving, and displaying large amounts of information in a structured manner. At present, information bases are often computer-based, although they may be on paper or even mentally based. Information may also be stored, processed mathematically, overlaid, and displayed geographically. In this case, the data base is called a Geographical Information System (GIS).

When quantitative information on linkages is missing, it is still possible to embed the judgments of experts in the analysis (Helmer, 1988). The expert opinion may be recorded for subsequent use in various ways, including in a computer, when it is called an expert system. One way of obtaining expert opinion is the Delphi technique which uses successive questionnaires circulated among a number of experts. In each questionnaire after the first, the respondents receive feedback information about the outcome of the previous round without knowing from which expert it came. The additional information gathered after each round may influence the respondents to change their opinion, with the ultimate aim of attaining some convergence of views or identifying irreconcilable differences.

Our report deals with the development and use of some of the analytical tools described in the previous section, primarily models and data bases.

As a first step, we develop conceptual models of the inter-linkages among the social, economic and ecological sectors of complex socio-ecological systems. Second, in several case studies, we examine the applicability of certain specialized versions of these conceptual models.

3. Humanity and Nature: Linkages and Conceptual Models

The notion of linkages is an essential part of systems analysis, where a linkage is, in general, some kind of relation between two or more elements of the system. The elements may be physical entities, concepts, subsystems, or mathematical entities such as variables, etc. The nature of the linkages may vary just as widely. Perhaps the easiest forms of linkage to conceptualize are physical flows of matter and energy, such as when a pollutant moves from the source of emission into the atmosphere, the biosphere, the land and the oceans, and then up the food chain back to humankind. Linkages may also represent causal influences between elements of a system that are not described as flows of matter or energy. An example is the correlation between education of women and the size of families.

The existence of many inter-linkages among the elements of a system implies that a perturbation or change in some component may reverberate through one or more causal chains, eventually triggering changes in other components that may not be immediately obvious. It is possible that the relatively few most important chains, which also hold the key to sustainable development, may be missed if, because of a narrow jurisdictional or scientific specialty, only some of the components and linkages in the system are analyzed. If that were to happen, we may treat symptoms rather than causes.

Despite the possibility that, ultimately, there is a relatively small number of key linkages in a system, the chances of discovering them are greatest when as much of the system as possible is included in the search. As the capability of humankind to change the face of the Earth increases with technological and economic development, it is more important than ever to start to think in cross-sectoral, multi-generational ways about the global society/economy/environment system as a whole so that the important linkages can be discovered and used to advantage. The transition to an inter-sectoral approach can bring not only scientific and technical benefits but political ones as well. Since international cooperation is often rooted in the self-interest of nations, benefits for some nations in some sectors have to be traded with benefits in other sectors for other nations.

A *socio-ecological* system is defined here as any system comprising a societal (or human) component and an ecological (or biophysical) component (Gallopín *et al.*, 1988). The levels of aggregation may range from a local household and the surrounding environment with which it directly interacts, to the system composed of the whole of humankind and the ecosphere.

The basic criteria that we used to design the conceptual models of the socio-ecological system were as follows:

- They were restricted to those factors most directly related or otherwise most relevant to the understanding of the nexus between society and nature, i.e., those that can potentially be used not only for explaining the problem but as entry points for solutions.
- They were designed to be as *neutral* and as *universal* as possible. *Neutral* in the sense that they should be usable not only for the identification of causal chains leading to the generation of problems, but also those that could be managed to implement solutions. *Universal* in the sense that they should be capable of highlighting the relations between society and nature in developing and developed countries, and within market and non-market economies. They should also be able to depict the linkages between society and nature associated with poverty as well as over-consumption.
- They were designed to represent socio-ecological systems at different scales, from the local to the global.
- They were intended to be capable of representing the basic concerns to be discussed at UNCED; specifically the sectoral and cross-sectoral environmental issues and the stated global goals. They were also intended to form a basis for action.

Using these criteria, a family of conceptual models of socio-ecological systems was developed. The complete conceptual model is shown in *Figure 1*. It comprises three main subsystems: the societal subsystem; the ecological subsystem; and the economic subsystem.

3.1 The societal subsystem

The societal subsystem includes demographic aspects, per capita demand, and social structure and relationships (such as social, political, legal, and

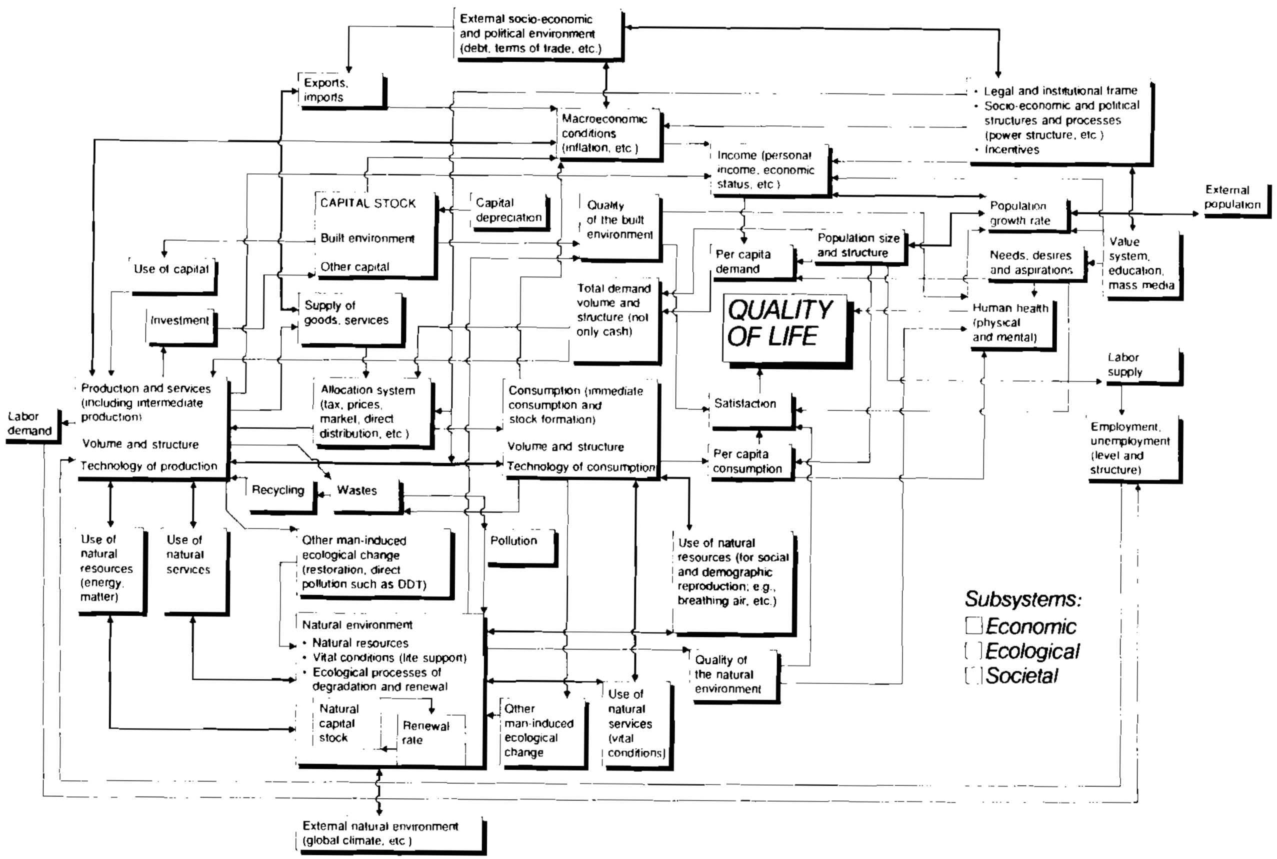

Figure 1. A generalized conceptual model of the basic inter-linkages in socio-ecological systems.

cultural elements, and power relationships). The combination of total population size, per capita demand, and social organization are considered to determine the total demand for goods and services in the economy.

As stated in Section 1.3, quality of life is considered to be the ultimate goal of development, an indicator of the degree of achievement of human development, and the central criterion that helps to characterize the human environment. The level and variation of quality of life among the members of a given society determines the pattern or strategy of development of the society.

3.2 The ecological subsystem

The ecological subsystem is considered to be the basic provider of natural resources for development, of basic ecological functions such as waste assimilation capacity, and of life-support functions affecting humans and other organisms. Both natural and managed ecological systems were included within this subsystem. For the purpose of our analyses, resources were defined as material or energy inputs to economic processes.

Two particularly relevant attributes of the ecological subsystem were considered to be the renewal rates of its constituents and the robustness or vulnerability of the ecological systems. Both can be affected by human activities. Renewal rates determine the natural or managed productivity – the rate at which the natural "goods and services" can be provided or replaced. Robustness indicates the capacity of the subsystem to continue providing goods and services, without suffering deep behavioral or structural ecosystemic changes.

3.3 The economic subsystem

The economic subsystem, in terms of the linkages between development and the environment, was considered to impinge upon the ecological subsystem mainly through the production and consumption processes, mediated by the technology that is used. The larger the production and the consumption processes, the greater the demands exerted upon the natural environment, due to both the input and output sides of the activities.

Consumption was defined broadly as including not only the consumption of commercial products, but also the direct consumption by the population of natural goods and services, such as the physiological consumption of oxygen in the air for breathing, and the direct collection and consumption of fuelwood for cooking.

The built, man-made environment represents part of the accumulated capital stock generated by investments and includes the urban environment and infrastructure. The built environment sometimes has an impact on the ecological subsystem through, for example, encroachment by urbanization on unmanaged and agricultural lands. It was included in our conceptual models as one of the central factors in the whole system because its quality, together with the quality of the natural environment, directly affects the health and satisfaction of the population and, hence, the quality of life of its members.

At all scales except the global, exports and imports of economic and non-economic items such as materials, energy, or information can exist in our models and could be very significant in economic and ecologic terms through, for example, exporting pollution and externalizing environmental costs.

Finally, our conceptual models took into consideration the growing realization that a number of important planetary-scale "megaprocesses" are likely to induce deep changes (some beneficial, some harmful) in the local, national, and regional socio-ecological systems. Some megaprocesses, such as the current techno-economic wave or "third industrial revolution", are new. Others, such as urbanization, population changes, and industrial growth, are not new but have reached global proportions and are now increasing or even accelerating. It is predicted that some of these megaprocesses, such as global warming, will have their full effects only after at least several decades. The megaprocesses are diverse: cultural homogenization, economic restructuring, socio-economic polarization, the globalization of the economy, the information revolution, the waning of nation-states, the increase in the North–South gap, the expansion of democratic regimes, the dispersion of species, diseases, and pathogens, the pollution of the oceans, and the depletion of the ozone layer.

4. Meeting the Challenge: Case Studies Using Systems Analysis

A number of applications of systems analysis, carried out mainly at IIASA but also elsewhere, were examined with respect to their usefulness in indicating and implementing policies toward sustainable development in connection with four basic human needs: food, water, energy, and materials. These case studies used "operationalized" versions of the conceptual model described above and in *Figure 1*, and data bases. In these studies, systems analysis was assessed in the light of several challenges, i.e., that it should provide us with the opportunity to:

- Conceptualize the environment–development problem in a holistic, integrated way and identify the most important elements and linkages.
- Take account of the separation of cause and effect by geographical region, economic sector, and in time, so that root causes rather than symptoms are addressed.
- Provide targets for our policies, based upon ecological limits and an equitable sharing of resources.
- Enable us to alter our policies to account for the fact that we are dealing with a dynamic system whose characteristics are changing.
- Enable us to estimate the costs of action or inaction, often through impact assessments.
- Allow us to address the ever-present problem of uncertainty and the need to meet multiple criteria.

What follows is a brief overall description of the dozen or so case studies. For purposes of illustration, a few are described below in detail: the reader is referred to the main report (Shaw *et al.*, 1991) for detailed descriptions of the remaining case studies.

4.1 Strategic and holistic approaches toward sustainable development

Although the case studies that were examined dealt with only some of the linkages in the socio-ecological system, the systems that were used were holistic enough to show that the human needs for food, water, energy, and assimilative capacity for wastes are interrelated. The production of food, of course, depends upon water. However, food production can also compete for the use of fossil hydrocarbons which are needed to manufacture fertilizers and for fuels; the latter are in turn used to manufacture and transport food. The use of energy can also affect food production because growing conditions for crops may be affected by the climatic changes that may result from the emission of greenhouse gases. Furthermore, reforestation to sequester carbon from the atmosphere to counteract the effects of greenhouse gases should be carried out on marginal lands unsuitable for agriculture so that the potential growing area for food crops does not decrease.

Changes in water supply will affect not only food production but other uses of water such as the generation of hydro-electric power. These changes are related to energy through climatic change and greenhouse gases. Water demand is a product of population change and water use per capita. Per capita use is dependent upon the technology that is used, especially for agriculture, as well as the willingness and ability of the population, through education and training, to use these technologies.

Our use of the environment as an assimilator of industrial wastes could affect our food and water supply through toxification. An application of a systems approach to as many as possible of the industrial and natural pathways of an industrial product can alert us to important sources and linkages that will help us design more holistic management strategies and avoid mistakes that could be costly in both financial and human terms. One case study in the main report (Shaw *et al.*, 1991) showed that banning cadmium in consumer products such as batteries and pigments would not necessarily reduce the amounts circulating in the biosphere. The reason is that cadmium is obtained as a major by-product of the refining of zinc ores. Banning it in consumer products would only increase the amount of cadmium in the wastes from zinc refineries. There, it would be in a form which is more easily transferred to the environment than if it were in some of the banned products, notably plastics (Stigliani and Anderberg, forthcoming).

Qualitative, as well as quantitative, systems analysis can be useful in bringing about a holistic approach to environment and development. This is especially important in developing countries where quantitative information and modeling results are often scarce or missing. In one example, qualitative systems analysis was applied to the Salto Grande Dam on the Uruguay River. Although the purpose of the dam was to generate electricity, there would be important implications for navigation, irrigation, fisheries, the urban water supply, and recreation. As described by Gallopín *et al.* (1980), a Uruguay–Argentina Technical Commission was formed not only to design, construct and operate the dam but, because of the expected impacts of the dam on the local environment, to design a decision system, which is shown in ***Figure 2***. It comprises three main subsystems: economic, socio-cultural, and biophysical. As shown in the figure, each subsystem contains sectors; for example, the socio-cultural subsystem comprises health, culture, and population.

It was then necessary to establish the linkages within and among the subsystems and sectors. It was decided that the most practicable approach was a questionnaire in which experts in a given sector would be asked their opinions as to the indicator best describing the state of their sector, and the

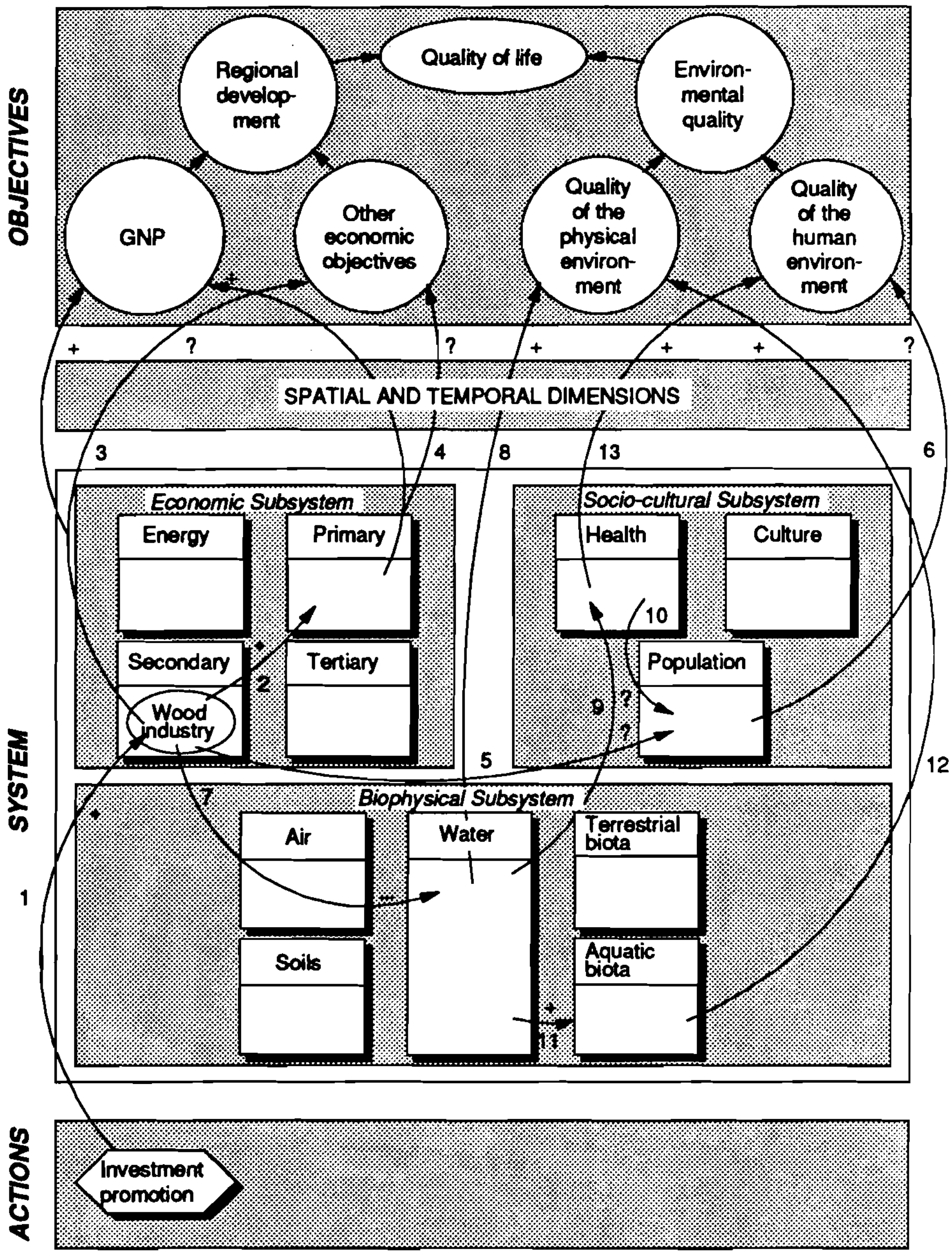

Figure 2. Subsystems and elements of the decision system for the Salto Grande Dam on the Uruguay River. Linkages among the wood industry and other elements of the system are shown.

information that is needed to predict the direction and intensity of change in the sector. Some of the results are shown as arrows in *Figure 2*. A plus sign (+) over an arrow from sector X to sector Y implies that if X increases so does Y, or if X decreases Y also decreases. A minus sign (–) indicates an inverse effect. An arrow labeled plus and minus (+–) would indicate that the causal relation may change sign according to the size or level of the sectors. A question mark indicates that the sign is not known, and that more data or research on this link are needed.

In the particular case shown in *Figure 2*, the stimulation of the wood industry in the region through the availability of credit initiates a chain of consequences which are listed below and indicated by the numbered links in the figure:

1. The availability of credit stimulates the wood industry.
2. The increase in the industry creates a demand for wood.
3. The growth of the wood industry increases income and has an effect upon "other economic objectives."
4. The associated increase in forest production also has a direct effect upon "other economic objectives."
5. An increase in the activities of the wood industry will have an effect upon population growth through employment.
6. Population change will affect the "quality of the human environment."
7. The increase in activity in the wood industry is expected to affect water quality negatively.
8. Changes in water quality will directly affect the fulfilling of the objective "quality of the physical environment."
9. Changes in water quality, if uncontrolled, will also have a direct effect upon health.
10. Changes in health will affect the size of the population and, ultimately (via link 6 described above), the "quality of the human environment."
11. Changes in water quality will have a direct effect upon aquatic biota.
12. The preceding will directly reflect upon the objective "quality of the physical environment."
13. Health will directly reflect upon the objective "quality of the human environment."

Although the model shown in *Figure 2* is not necessarily optimal, the holistic systems approach, even when it was qualitative, was a device to bring together various parties in the region who have different interests to give useful insights into important cross-sectoral linkages and the possible risks and benefits of development. While some of these risks and benefits may seem obvious in retrospect, they are more likely to be detected through the creation of a conceptual model before development takes place.

4.2 Staying within the limits of the biosphere

The case studies in the main report (Shaw *et al.*, 1991) show that the ecological limits of a given region must be examined in terms of our specific demands upon the environment, such as food or water or assimilative capacities for wastes. It is best to determine which of these demands is the most constrained ecologically. Although these limits can sometimes be defined as a relatively fixed quantity in biogeophysical terms, as in the "critical loads" for acidic pollutants, systems analysis shows that there is not usually a fixed number in terms of population, for several reasons.

First, the productivity of food and water for a given region can be increased or decreased by the application of technology. For example, one of the case studies involved an analysis of the water requirements in the year 2025 for the region consisting of Morocco, Algeria, Tunisia, Libya, Egypt, Israel, Jordan, Syria, Iraq, Kuwait, Iran, and Saudi Arabia. The linkages for this analysis are shown by the conceptual model in *Figure 3*. From data provided by the World Resources Institute (WRI, 1990), there is a strong linkage between water and food; 88% of the withdrawal in the region is for agriculture. The water used per tonne of grain produced varies greatly among countries (from 800 to 17,400 m^3), probably depending upon the need for and efficiency of irrigation.

The relationship between regional population and per capita water consumption for agricultural purposes is shown in *Figure 4*. The solid diagonal line labeled "370 km^3 per year" represents an ecological limit as expressed by the availability of renewable fresh water (precipitation minus evapotranspiration), i.e., combinations of population and per capita water consumption for agriculture that would use up the available renewable fresh-water supply. The point labeled "1990 Actual" represents the actual situation in 1990: the regional population of 230 million used only about one-half of the renewable fresh water for growing grain but, as shown in WRI (1990), only one-half of the consumed cereal was produced in the region.

Although it appears that, at present, the region as a whole and most of the countries within it are within the ecological limit with respect to renewable water, the system is not static and will probably change in terms of population and climatic conditions. The United Nations estimates that

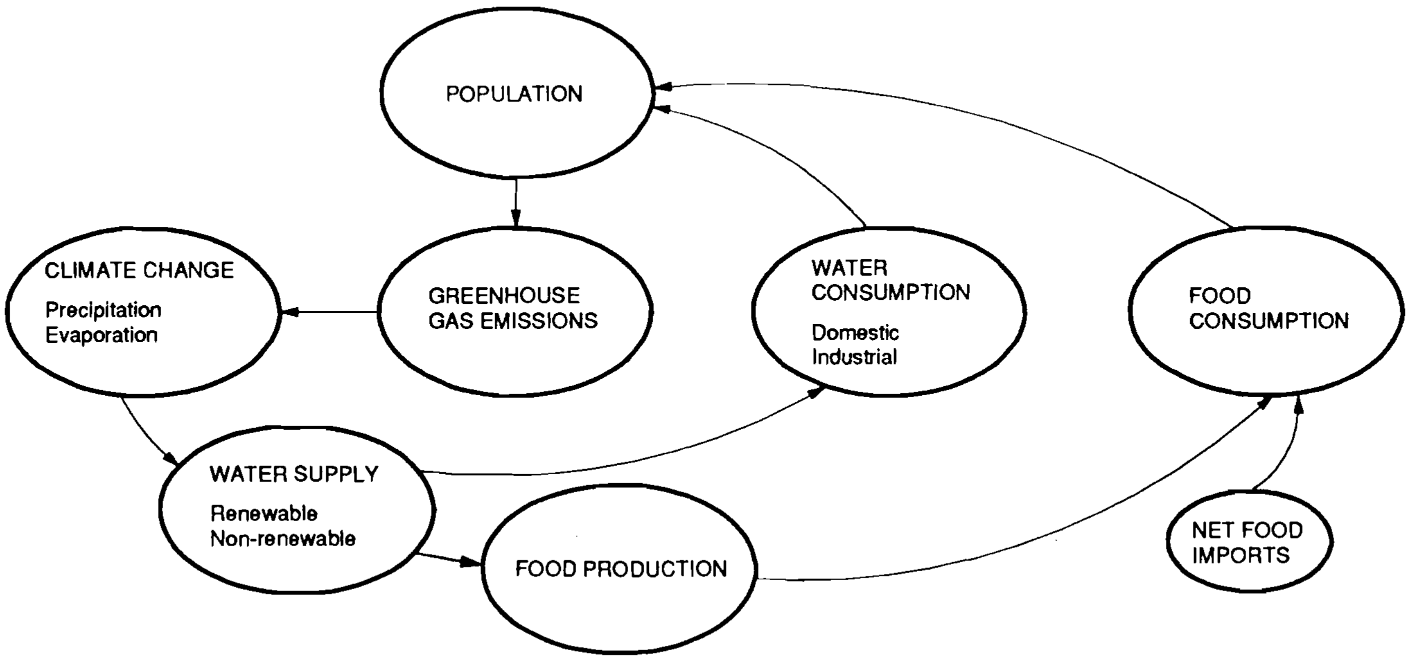

Figure 3. Conceptual model showing some of the linkages among population, water, and environmental change.

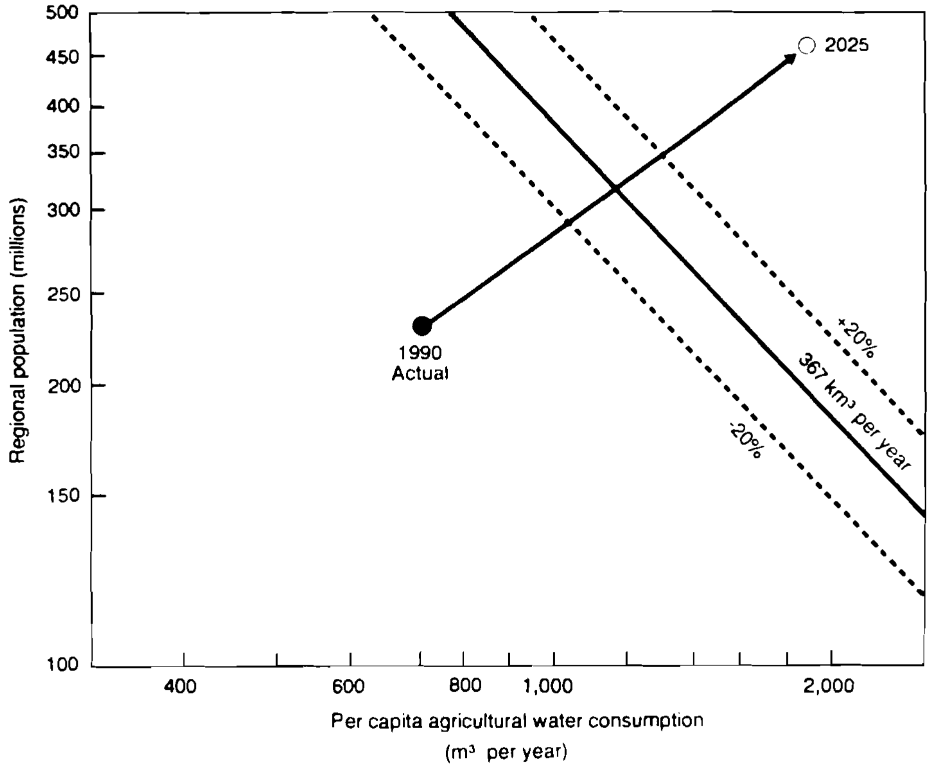

Figure 4. Relationship between population, per capita agricultural water consumption, and supply of renewable fresh water for the North African/Middle Eastern region. The situation in 1990 is represented by "1990 Actual", the diagonal line marked "367 km^3 per year" represents the supply of renewable fresh water. The dashed lines indicate fluctuations of ±20% due to climatic change. The point labeled "2025" represents a scenario where sufficient food is grown for the population of the region in 2025.

by the year 2025 the population of the region will be 489 million (UN, 1989). In our analysis, the per capita consumption of water for domestic purposes is assumed to be the same as in 1990; that for industrial purposes is assumed to be double that of 1990, to reflect some industrial development in the region. In addition, in each country the per capita consumption of cereal and the consumption of water per tonne of cereal grown was assumed to remain constant between 1990 and 2025, i.e., no water-conserving developments in growing and processing grain are assumed to have taken place.

In one scenario in the case study, shown as point "2025" in *Figure 4*, total water supply is assumed to be sufficient to allow cereal production to meet the per capita consumption levels for 1990, without specifying exactly how. A total of 983 km^3 of water would be consumed; 912 km^3 for agricultural purposes. Because only 370 km^3 can come from renewable sources, the remaining 643 km^3 of the total must be supplied from other sources.

It is possible that climatic change will alter the availability of fresh water in the region. Predictions of changes in regional climates brought about by increasing greenhouse gases are still very uncertain. There is a considerable amount of disagreement among models, even to the sign of the change (IPCC, 1990). The two dashed diagonal lines in *Figure 4* represent a change of plus or minus 20% in available fresh water due to a combination of changes in precipitation and evapotranspiration. Climate change could, therefore, either exacerbate or counteract a water shortage that is already made acute by population change.

Water use and/or the amount of available water could be changed. During the next three or four decades, there is little flexibility in the population projections, although, in the long run, population issues must be addressed. However, the efficiency of water use for domestic, industrial, and especially agricultural purposes can be increased. The ecological limit itself, which in the foregoing analysis was defined only in terms of renewable fresh water in the region, can be extended by providing for additional sources of water, such as pipelines and plants for the desalinization of seawater. This would require proper incentives and financial allocations. The application of improved water technology would be linked to the level of education that would be available to operate the technology, and an increase in incentives through the removal of imported food grown under subsidies in more developed countries (MDCs).

A second reason why ecological limits cannot be expressed simply in terms of population is that the per capita demand for food, water, energy, and assimilation of wastes is (as shown by the general conceptual model in *Figure 1*) linked to both needs and desires, which in turn are linked to values and education and to income and affluence. Therefore, systems analysis shows that an "ecological limit" is not a simple concept but depends upon many elements in the socio-ecological system. This implies that sustainable development which heeds the ecological carrying capacity must examine all of these interlinked factors.

Third, sustainability can be increased in a particular region by "exporting" unsustainability to other regions. This could be done by causing other regions to overload their food production systems or, as in the case of transboundary air pollution, by degrading their ecosystems through the export of acidic air pollutants. This would not be an equitable strategy on a global basis, however.

4.3 Sharing resources in an equitable and efficient way

The three cases that were examined in our report show that it is essential to account for linkages among sectors of the socio-ecological system, among geographical regions, and among generations if our resources are to be used in an efficient and equitable way. Management decisions which take into account only a limited part of the system run the risk of being inefficient or even harmful in a holistic sense.

For example, in one of the case studies, a piece of software being developed at IIASA, the Food Information System, pointed to the possibility that there was considerable potential for an increase of yield in Africa through the use of chemical fertilizers. However, the manufacture of these fertilizers requires fossil hydrocarbons which are also being burnt as fuels. This means that we should consider reserving some of these fossil hydrocarbons to provide us with fertilizers that may be badly needed in the future. The Food Information System also showed that developing countries currently depend upon imports of animal protein from the developed world. Therefore, the radical reduction of livestocks in the developed world might in the short run have a serious effect upon the food supply of groups such as babies and pregnant mothers in developing regions (Heilig, 1991a).

The application of systems analysis to acidification in Europe showed that reductions of emissions in countries where the marginal costs of control are high may be inefficient. It would be better to pool financial resources and to spend them in emitter regions where marginal costs are lower and which are most closely linked via the atmosphere to sensitive ecosystems.

Finally, an equitable allocation of per capita emissions of the long-lived greenhouse gases to keep their atmospheric concentrations within a specified limit within the next few decades indicated that the behavior of past generations must be taken into account. Fujii (1990) has developed an accounting system to allocate among nine regions of the world per capita emissions of CO_2 from fossil fuel combustion, using as a boundary a specified increase in atmospheric CO_2 concentrations between 1988 and the year 2100. In one example, Fujii used a simple equity criterion for allotting the emissions

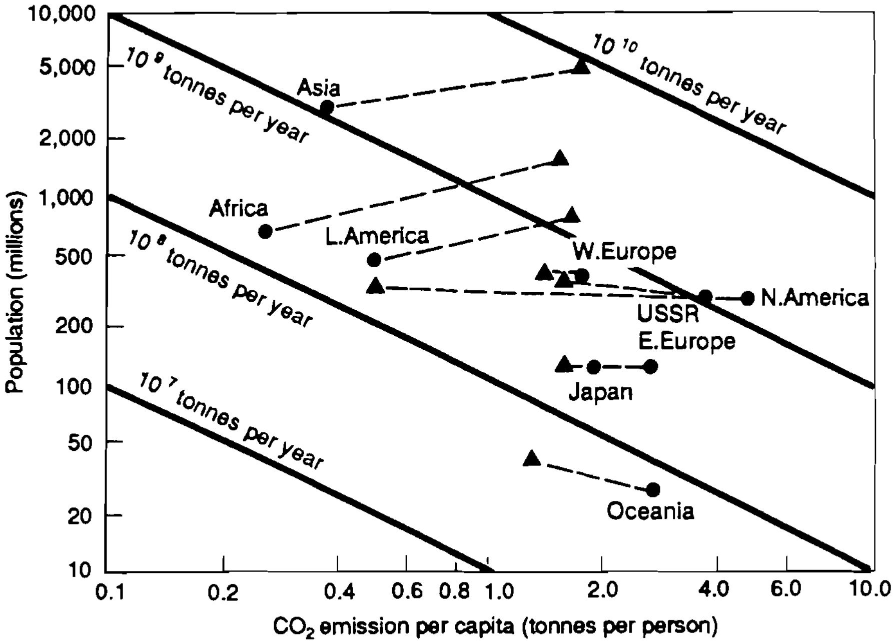

Figure 5. Population and per capita CO_2 emissions from fossil fuels for several world regions. The diagonal lines represent combinations of population and per capita emissions that would produce 10^7, 10^8, 10^9, and 10^{10} tonnes of CO_2 emissions per year. The dots represent the situation in the year 1985; triangles represent emission targets in the year 2025 if per capita emissions were allocated according to the equity criterion to keep atmospheric CO_2 concentrations below 620 ppm (see text for details).

during the accounting period 1800–2100: everyone has an equal emission quota irrespective of both the country he or she lives in and the generation he or she belongs to.

Some results are shown in *Figure 5*. Not surprisingly, in 1985 (heavy dots in *Figure 5*), developed regions have greater per capita CO_2 emissions than developing regions, with North America having the greatest.

The triangles in *Figure 5* show how the per capita emissions would have to change in the future in each region to satisfy Fujii's criterion of an equal per capita CO_2 emission for all individuals if the atmospheric CO_2 concentration is to be kept within a limit of 620 ppm by the year 2100. Per capita emissions in all developed regions must decrease substantially;

those in North America by about an order of magnitude. This is because developed regions, especially North America, have already used up much or (depending upon the CO_2 boundary condition) all of their allotment. (If the boundary were 480 instead of 620 ppm, North America would be allotted zero per capita emissions under the scheme.)

On the other hand, because they have not emitted much in the past, per capita emissions in developing regions (Africa, Asia, Latin America) would be allowed to increase substantially under the allocation scheme. Whether or not the developing regions would be able to develop quickly enough to use up their allotment is uncertain. If they were not, there could be a transitional period of industrialized regions purchasing CO_2 emission allotments from developing regions, i.e., there could be an international market in tradable emission allocations. This would provide MDCs with an incentive for reducing their emissions (because it is costing them money) and less developed countries (LDCs) with a source of much-needed funds. The costs of these permits would be determined by the market and should reflect the environmental costs of emitting greenhouse gases.

Whether or not tradable emission allotments are used in the interim, profound changes will eventually be needed in the socio-ecological structures of the various regions of the world, especially in the developed regions. In North America, radical changes will be required in energy technology through, for example, the use of more energy-efficient industries, transportation systems, homes, and appliances. All of this will require changes in our infrastructure and investment. (Cities, particularly in North America, could be made more energy-efficient by halting urban sprawl.) A less energy-demanding lifestyle can be brought about by changes in the needs, desires and aspirations, and the value system in developed regions. (We may need to forgo some of the privacy and flexibility of the automobile and the desire to live in a large free-standing home instead of a flat.)

In developing regions, it is necessary that the physical standard of living be improved through an increase in the production and consumption processes and through improvements in the built environment. If the same technologies of production and consumption that are presently used in developed regions were also used in developing regions, which are expected to have a large increase in population, there could be a tremendous increase in CO_2 emissions. (This may easily be seen in *Figure 5*.) Obviously, the more efficient technologies for energy production and use that *must* be developed for the presently developed regions must also be made available to the developing regions as well.

4.4 Continuous management of a dynamic system

It is certain that the characteristics of our socio-ecological system will change in the future because of population increases and environmental change. This means that our management options for resources such as food and water, and for disposal of wastes will be different from the current ones. Systems analysis can be used to examine how these options might change in the future.

For example, on a global scale the area of grain-growing land and/or the yield will have to increase to meet the needs of a growing world population, even at present average calorific intakes. An example of a simplified operational model for food is given in *Figure 6* (Heilig, 1991b). It shows in a general way the linkages among human factors such as demography and dietary patterns, technological factors such as food-processing methodologies, and environmental factors such as the area of cultivated land and yield per hectare.

In *Figure 6*, food consumption is determined by a combination of population and dietary patterns, which is in turn linked to income level. The supply of food is met by net imports and agricultural production. The former is linked to income distribution, international trade, and debt. These links were also shown in the conceptual model in *Figure 1*. Agricultural production in a region is dependent upon the area of growing land and the yield. Growing area could be influenced by environmental factors such as climatic change, erosion, and reforestation (suggested as a mitigation measure against climatic change). Climatic change is, of course, strongly linked to our need for energy, which is also needed for the production, processing, and transport of food. Yield is influenced by sedimentation and by intensification, which is in turn linked to economic factors and to the use of fertilizers, some of which come from the same fossil hydrocarbons as our energy. In addition to the foregoing linkages among the various elements of *Figure 6*, each element is a system unto itself, complete with internal linkages.

The linkage labeled S in *Figure 6* represents the relationship between grain production and human calorific consumption on the global scale; each tonne of grain grown represents 2.6 million calories available for human consumption. This empirical relationship was derived from a WRI report (1990). The ratio used for linkage S also incorporates losses such as spoilage and the way in which grain is processed and combined with other types of foods to supply calories.

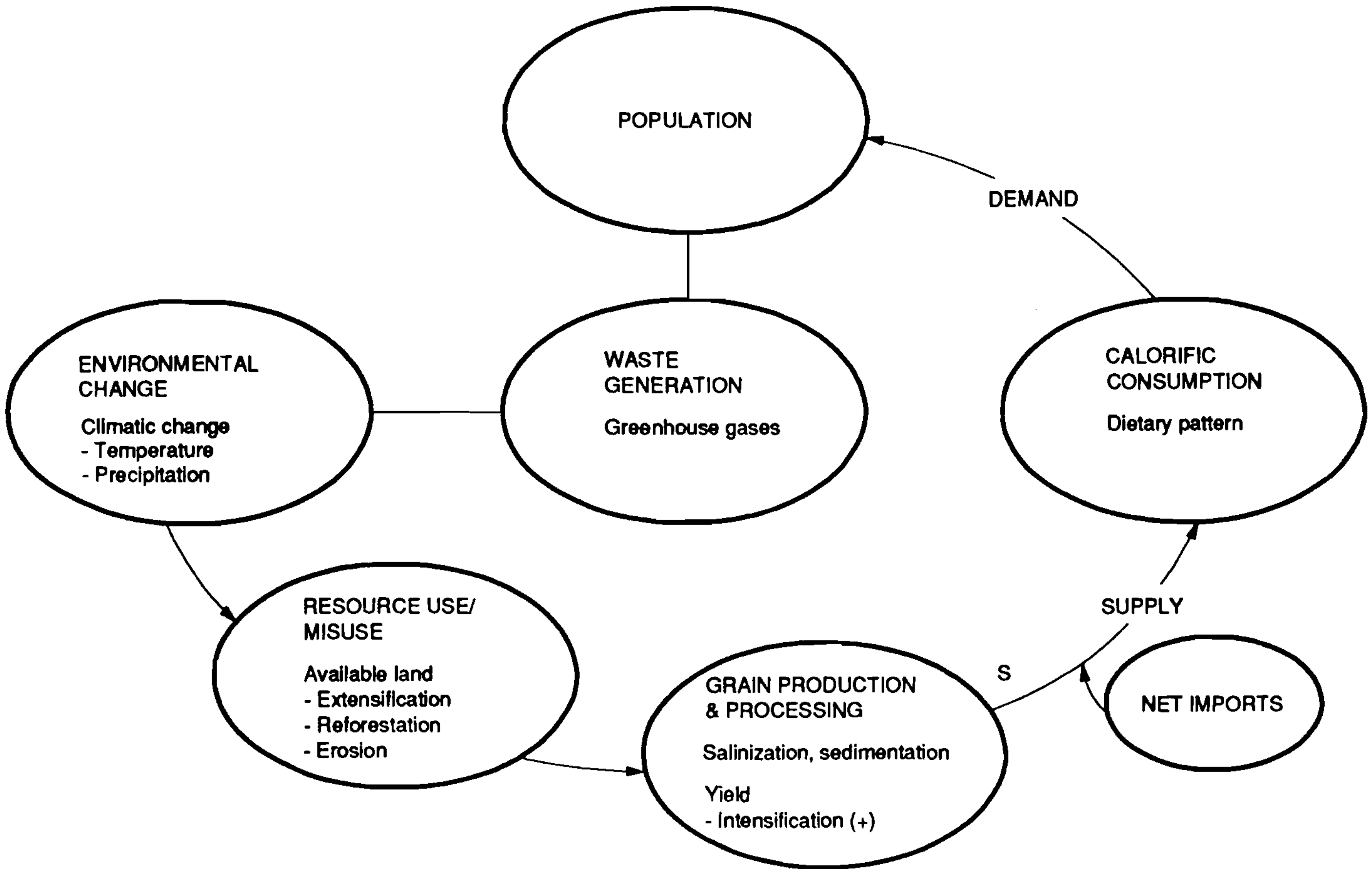

Figure 6. Conceptual model showing some linkages among population, food, and environmental change.

Using the above linkage, one can express graphically (as in *Figure 7*) the relationship between the global requirement for calories, using indicators such as population and daily calorific consumption (a measure of lifestyle), and the global supply, as indicated by area of cereal-growing land and yield per hectare. The left-hand and lower axes of *Figure 7* show food requirements; the diagonal line labeled "1.89×10^9 tonnes grain" is the locus of combinations of population and daily calorific consumption that would have required 1.89 billion tonnes of grain being grown yearly, the estimated requirement in 1985. The circle marked "1985" is the actual demand situation in 1985 when there was a population of 4.8 billion with an average daily calorific consumption of about 2,700 calories.

The upper and right-hand axes of *Figure 7* indicate the supply side of the picture; the same diagonal line "1.89×10^9 tonnes" represents the locus of combinations of area of cereal-growing land and yield per hectare that would have produced 1.89 billion tonnes of grain per year. The circle marked "1985", therefore, also represents the actual 1985 supply situation of 700 million hectares of grain-growing land and a global average yield of 2.5 tonnes per hectare.

The diagonal line labeled "3.21×10^9 tonnes" shows the same type of information, but for the year 2025 when it is estimated that, for a projected world population of 8.5 billion and an assumed world average calorific intake of 2,700 calories per day (the same as in 1985), about 3.2 billion tonnes of grain would need to be grown annually. In theory, an infinite number of combinations of population, daily calorific requirements, cereal-growing area, and yield are represented on this diagonal line. The dashed line joining points "1985" and A represents the situation if the present average global calorific requirement of 2,700 calories per day and yield of 2.5 tonnes per hectare were still the case in 2025: a growing area of over 1200 million hectares would be needed to meet the requirements. On the other hand, if the growing area in 2025 were the same as at present (about 720 million hectares), the average global yield would have to be about 3.8 tonnes per hectare to meet global grain requirements.

Depending upon the tonnage required, an infinite number of diagonal lines can be drawn. The portions of the axes between the upper right-hand corner of *Figure 7* and their intersection with a given diagonal line represent the management options open to us. The greater the tonnage required, the larger the yield and/or growing area must be. However, there are physical limits to these two factors; our range of management options may in fact be narrower. For example, there are potential losses of output due to land

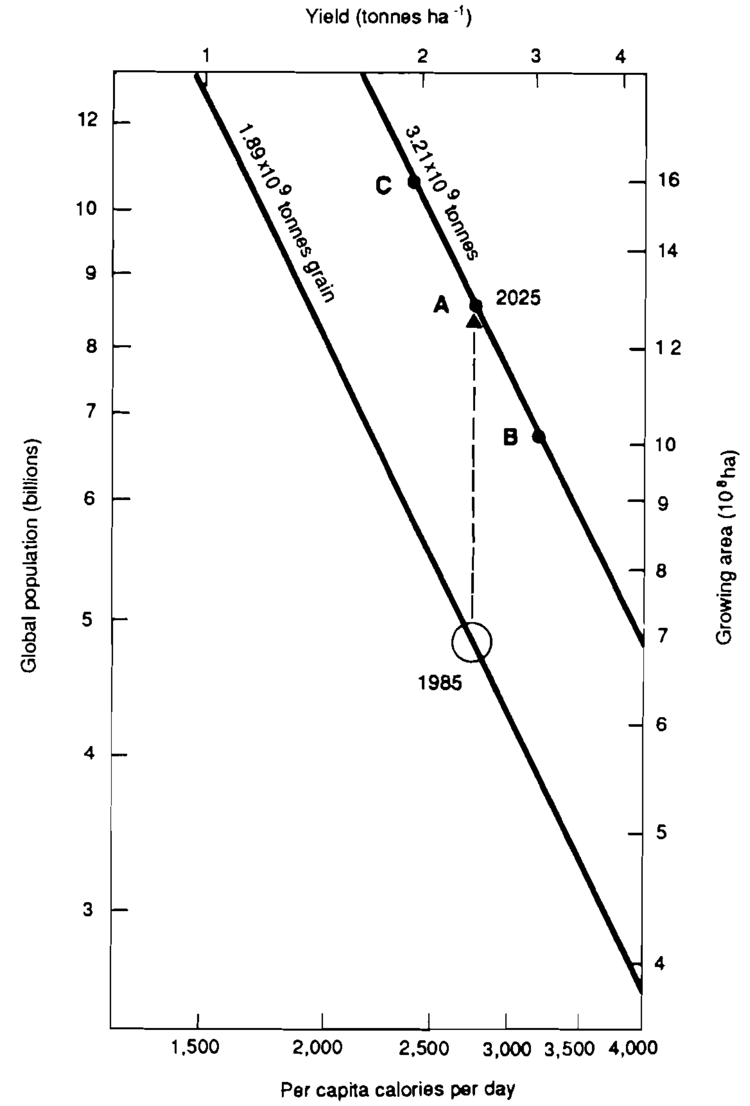

Figure 7. Global population (left axis), global average per capita calorie consumption per day (lower axis), global cereal-growing area (right axis), and global average cereal yield (upper axis). Diagonal lines represent combinations of population and per capita calorie consumption that would require 1.89 billion and 3.21 billion tonnes of cereal, and also the combination of growing area and yield that would be required to produce those amounts of grain. The large circle represents the actual situation in 1985; point A represents a possible situation in 2025.

degradation caused by toxification, erosion from increased storminess, flooding, and salinization from sea-level rise. There can also be damage to crops from air pollution, acid rain, and increased ultraviolet radiation. (These linkages to other environmental factors were shown in *Figure 6*.) For plausible changes in climate, the estimates of Parry (1990) for changes in yield are typically in the range of ± 20%; this is indicated by points B and C in *Figure 7*. Even with an increase in average yield to about 3.0 tonnes per hectare (point B), an area of over 1,000 million hectares of grain-growing land will be needed to satisfy a requirement of 3.2 billion tonnes of grain. A decrease of 20% in yield (point C) would increase the growing area needed to almost 1,600 million hectares. *Figure 7* shows, therefore, that the effect of climatic change on the balance between the requirement and supply of grain is not insignificant and may exacerbate the effect of increasing population. These limitations on growing area and yield due to climatic change or industrial toxification could be made less stringent through the use of appropriate technology which, as the general conceptual model in *Figure 1* shows, is linked to the availability of capital and operational skills.

In managing emissions of acidifying pollutants resulting from the use of fossil fuels for energy, one can use systems analysis to determine ecologically based indicators of change. In the case study on forest decline in Europe (Shaw *et al.*, 1991), the combination of an integrated assessment model for regional acidification, knowledge about the ecological carrying capacity of the environment for acidic deposition, and data bases on forest resources allowed us to use the volume of commercial wood receiving deposition above the ecological carrying capacity as both a target for management policies and an indicator of their success.

Finally, the management of by-products from human activities such as emissions from the burning of fossil fuels and toxic materials will have to take account of the complex pathways of these by-products, as well as the boundary conditions for their assimilation by the environment. A full knowledge of the pathways will help us to avoid costly management mistakes such as controlling one source while neglecting another. The assimilative capacity of the environment may change due to other human activities; for example, the ability of the soil to store toxic metals may be diminished by other human-induced changes such as acidification brought about by our use of fossil fuels for energy. The systems approach offers us the opportunity to understand and manage these in an integrated, dynamic way.

5. Concluding Remarks

- It is possible to formulate holistic conceptual models of the socio-ecological system in which we live. The model that is described in this report comprises three subsystems: societal, ecological, and economic. The linkages within the model are capable of describing both the causes of unsustainable development and possible remedies.
- Qualitative systems analysis can play an important role (especially in developing countries where quantitative modeling results and data are scarce or missing) in bringing parties with different interests together to gain useful insights into important cross-sectoral linkages, and the possible risks and benefits of development.
- Systems analysis can contribute significantly to our understanding of the constraints societies face in terms of population growth, life support, and the assimilative capacity of the environment for wastes.
- Systems analysis can provide guidance in sharing limited resources such as food, water, and the assimilative capacity of the environment for wastes, both among regions and among generations.
- In a world that is constantly changing, partly because of human activities, systems analysis can give an insight into how our management options will change. If ecological limits become more restrictive, management will need to be more imaginative and holistic in the future.

References

Daly, H.E., 1990, Toward Some Operational Principles of Sustainable Development, *Ecological Economics* **2**:1–6.

Fujii, Y., 1990, *An Assessment of the Responsibility for the Increase in the CO_2 Concentration and Inter-generational Carbon Accounts*, Working Paper WP-90-55, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Gallopín, G.C., Lee, T.R., and Nelson, M., 1980, The Environmental Dimension in Water Management: The Case of the Dam at Salto Grande, *Water Supply and Management* **4**:221–241.

Gallopín, G.C., Gutman, P., and Maletta, H., 1988, *Global Impoverishment, Sustainable Development and the Environment*, Report to the IDRC Project: Global Impoverishment and Sustainable Development, Ecological Systems Analysis Group, S.C. Bariloche, Rio Negro, Argentina.

Heilig, G., 1991a, *Lifestyles, Population, Environment and Development*, Manuscript in preparation, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Heilig, G., 1991b, Personal Communication, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Helmer, O., 1988, Using Expert Judgment, Chapter 3 in H.J. Miser and E.S. Quade, eds., *Handbook of Systems Analysis: Craft Issues and Procedural Choices*, John Wiley & Sons, Chichester, UK.

IPCC, 1990, *Scientific Assessment of Climate Change - Working Group 1*, World Meteorological Organization, Geneva, Switzerland.

Meadows, D.H., Meadows, D.L., Randers, J., and Behrems, W.W., 1972, *The Limits to Growth*, Signet, New York, NY, USA.

Miser, H.J. and Quade, E.S., 1988, *Handbook of Systems Analysis: Craft Issues and Procedural Choices*, John Wiley & Sons, Chichester, UK.

Parry, M., 1990, *Climate Change and World Agriculture*, Earthscan Publications Limited, London, UK.

Pearce, D.A., Markandya, A., and Barbier, E., 1989, *Blueprint for a Green Economy*, Earthscan Publications Ltd., London, UK.

Shaw, R.W., Gallopín, G.C., Weaver, P., and Öberg, S., 1991, *Sustainable Development: A Systems Approach*, Final Report submitted to the Secretariat of the UN Conference on Environment and Development, Unpublished, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Speth, J.G., 1990, Foreword in R. Repetto, *Promoting Environmentally Sound Economic Progress: What the North Can Do*, World Resources Institute, Washington, DC, USA.

Stigliani, W.M. and Anderberg, S., 1991, Forthcoming, Industrial Metabolism at the Regional Level: The Rhine Basin, in R.U. Ayres and U.E. Simonis, eds., *Industrial Metabolism - Restructuring for Sustainable Development.*

UN, 1989, *World Population Prospects*, United Nations Department of International Economic and Social Affairs, New York, NY, USA.

UN, 1990, *World Population Prospects*, Population Study No. 120, United Nations Department of Social and Economic Affairs, New York, NY, USA.

WCED, 1987, *Our Common Future*, Report of the World Commission on Environment and Development, Oxford University Press, Oxford, UK.

WRI, 1990, *World Resources 1990-91: A Guide to the Global Environment*, Report by the World Resources Institute, Oxford University Press, New York, NY, USA.