Dynamic Modeling of Ecological-Economic Systems

An Introduction for
International Resources Group
and the
United States Agency for International Development Africa Bureau

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This report follows a March 15, 2000 workshop on ecological-economic modeling held at International Resources Group, Washington D.C. The workshop was sponsored by the U.S. Agency for International Development.

Background

During 1999, USAID compiled several data series on major ecological and economic trends in Africa. These compilations were the catalyst for a broader discussion, among USAID personnel, of development theories and ecological-economic linkages in Africa. In that discussion, many views were brought forth concerning development theories: the role of community involvement, population growth, resource use, carrying capacity, indicators, data collection, and many other aspects of the development challenge facing USAID in Africa. One of the sentiments expressed in that discussion is that "we need a new hypothesis." This current effort is intended to help fulfill that objective – to review hypotheses concerning ecological-economic linkages in Africa, and to help develop some new ones.

Introduction

One traditional approach to guiding development efforts involves collecting data, designing indicators based on those data, running regressions to reveal statistical relationships among those indicators, and using the results to guide further development activities, and further analyses. In this approach, the measurable results of the development efforts are reported in these indicators. This process is data-intensive, and considerable effort goes into developing the indicators used in the analyses. The analyses yield statistical relationships, not necessarily causal relationships, among these indicators.

Figure 1: A traditional approach

This traditional approach is particularly useful for predicting results within the range of the available data. When the indicators are valid; that is, when they closely approximate the variable or condition that we want to measure, when the relationships among variables are linear, and when the analyses produce statistically significant results (and sometimes when they do not), this approach can yield valuable information to steer development efforts.

An alternative approach focuses instead on the causal relationships among variables. In this approach, many of the important variables may be difficult or impossible to measure. Natural capital, well being, sustainability, human or social capital, among others, are difficult or impossible to measure directly. In the traditional approach, indicators would serve as proxies for these variables, and then statistical analyses might reveal statistical relationships among those indicators. In this systems approach, the emphasis is on the causal relationships among the variables, with less emphasis on the development of regression-ready data.

Figure 2: A systems approach

Whereas the traditional approach is well-suited to testing hypotheses, the systems approach is well-suited to developing hypotheses. It is also well-suited to laying out future scenarios that provide answers to “if-then” questions about possible policies, events, or relationships among variables. These future scenarios can help extend the intuition and reach of those decision-makers that necessarily operate at, or beyond, the scope of the available data.

Two Approaches to Problem-Solving

In the traditional approach, relationships among the variables are statistical, or empirical. The following diagram of an empirical model of production was creating in the STELLA modeling environment.

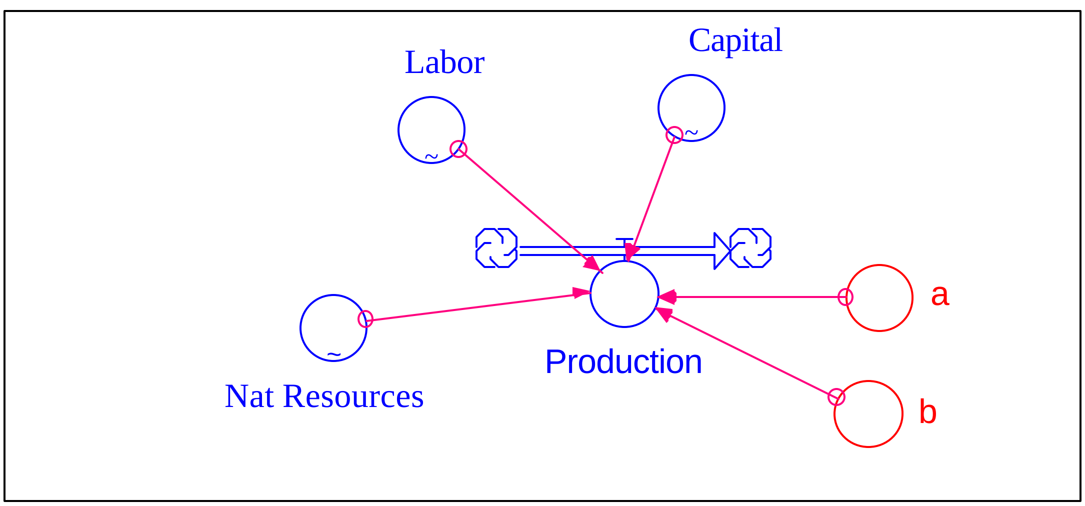

Figure 3: An empirical model of production, employing statistical relationships among the variables (after Costanza, 1997)

This model includes six variables: three data series include natural resources, labor, and capital; two parameters, a and b, and a production function. The relationships among these variables as they are expressed in the model are statistical, not causal. In contrast, the following systems model of production shows the causal relationships among the variables included in the model. Stocks are represented as boxes, flows as large arrows, auxiliary variables as circles, and connectors where there are no flows, as narrow arrows.

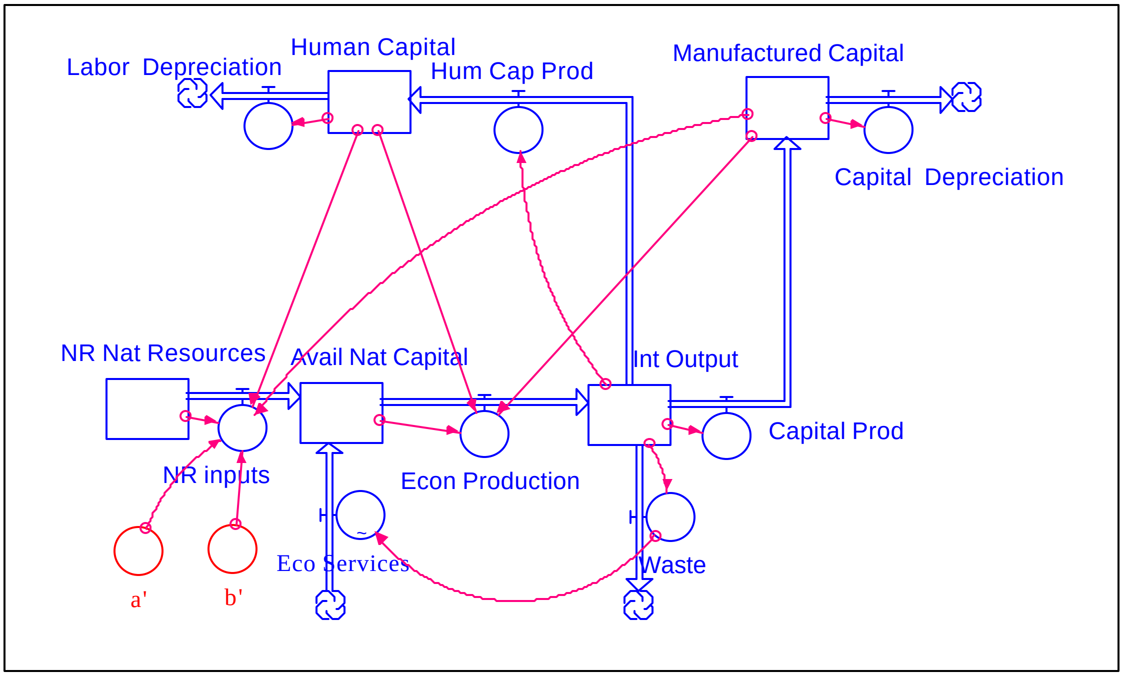

Figure 4: A systems model of production employing causal relationships among the variables (after Costanza, 1997)

The model may include some statistical relationships, but the relationships are predominantly causal. For some people, this systems approach is more intuitive, especially if they participate in construction of the model.

A Demonstration of the Approach

The indicators in the following table are selected from the trends that USAID reviewed in 1999. One way to read the table is to enter it through the second column, "We settle for." This second column contains the indicators. These indicators reflect data that we can observe and measure, and express reasonably easily in a quantitative way. The first column is this author's appraisal of what we truly want to know, but which is more difficult, or impossible, to measure directly. The last two columns are a first appraisal of what the indicators also reflect, and what they may miss.

Table 1: What Indicators Show

We want to know	We settle for	Which also reflects	And we miss, or we don't measure and deduct
true income	GDP	natural capital depletion counted as income; defensive expenditures including some health care, cleanup of pollution, restoration of degraded areas, police & security measures	some services of capital; in-kind payments for goods and services; household production including child-rearing; much of women's work; nonmarket services of nature
total productive capacity; or total capital, natural, human, & manmade (a stock)	domestic investment (a monetary flow)	mining of natural capital to finance investment; defensive expenditures, as with GDP	nonmarket services of natural capital; depreciation
health	expenditures on health care	defensive expenditures, pollution of environment, poor diet induced by overcrowding and depletion of resources	contribution of a clean, functioning environment; diet; true well being
potential for increasing yields in agriculture	fertilizer & pesticide use	negative effects of past pesticide & fertilizer use on current productivity	natural productivity of soils, effectiveness of government in regulating agricultural chemicals, distribution of chemical use, adverse effects on the environment
degree of industrialization, development	energy consumption	mining of natural capital	efficiency
sustainability; intensity of land use; potential for intensive land use	protected areas		implementation, degree of local support
sustainable harvest	agricultural yield	mining of natural capital including soil erosion	loss of diversity, loss of the services of forests and other natural lands converted to agriculture

The constraints of data collection, computational efficiency, and simplicity mean that these indicators are necessarily simplifications of more intricate variables. The simplification carries a cost, in that some relationships among the important variables may be obscured, or lost. This problem is more pronounced when the true relationships are non-linear, involve thresholds, or involve long lag times. The following systems model is designed to help illustrate how these limitations of the indicators may obscure some of the important relationships among the underlying variables.

This systems model of production includes stocks of three forms of capital: natural, manmade, and human. Mining of natural capital is modeled as a flow, which can be adjusted, or turned off entirely. True income and gross domestic product are each modeled as a flow. The services of each form of capital (as indicated by the thin arrows) enter both true income, and GDP. Consistent with the Hicksian definition of income, or the similar concept of sustainability, the mining of natural capital is counted only in GDP.

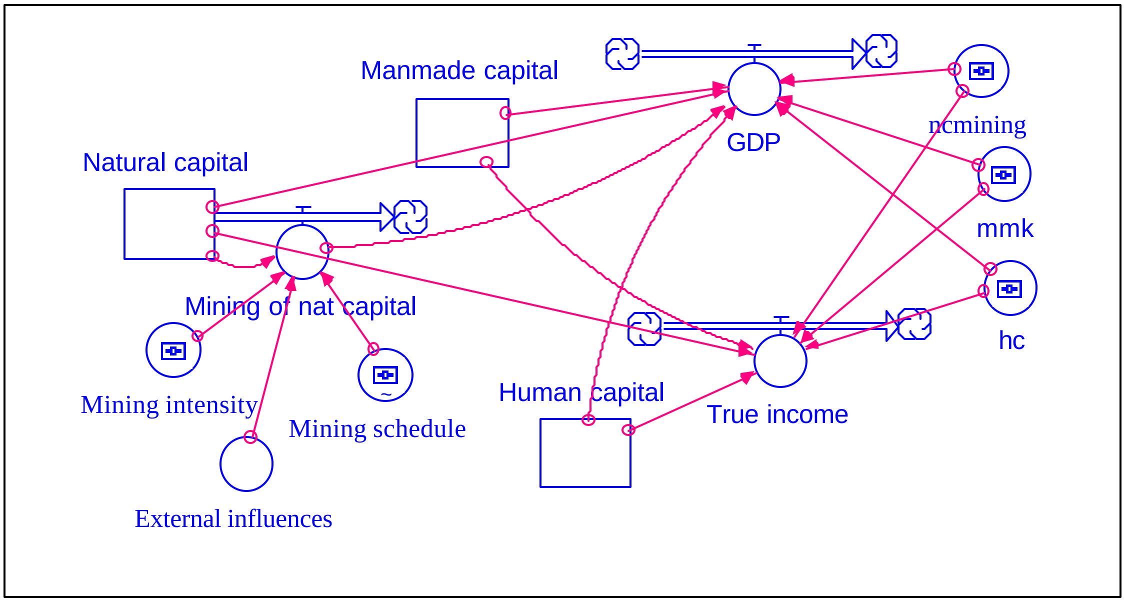

Figure 5: A systems model of a simple economy

In the following 50-year model run, there is some mining of natural capital. The two indicators – mining of natural capital, and GDP – are shown on the graph. Viewing these data, one could reasonably conclude that increased mining increases GDP, and that a regression would confirm this relationship.

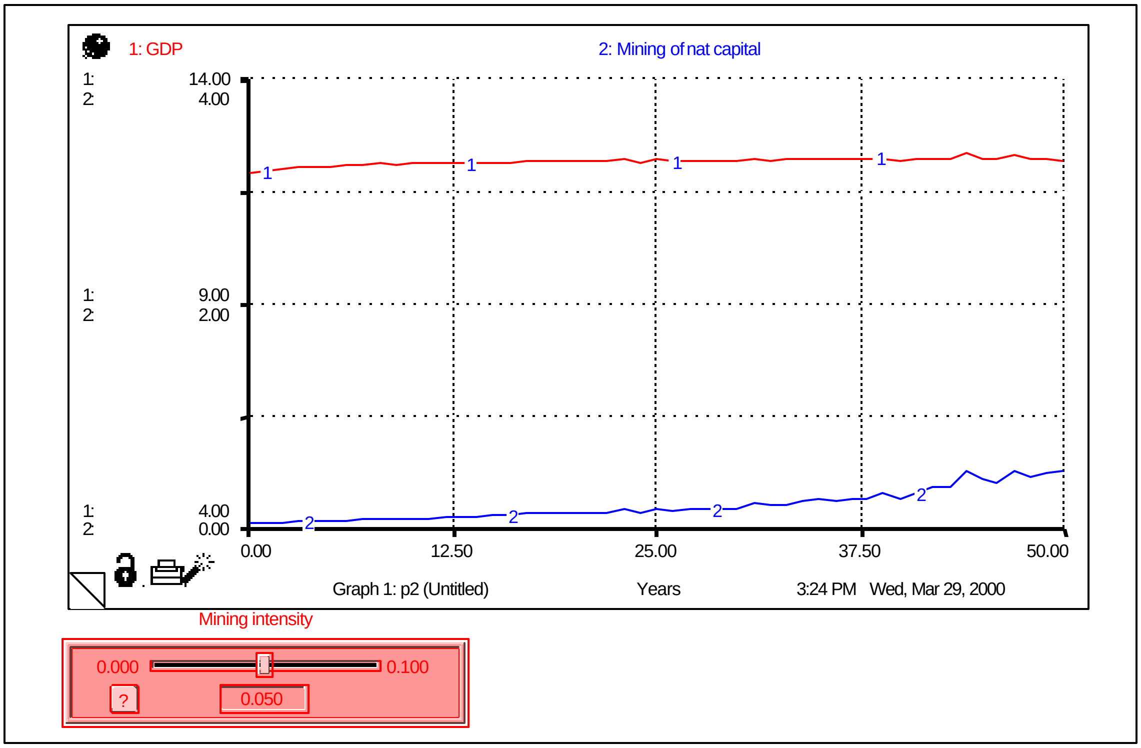

Figure 6: A simple economy model, traditional indicators, 50-year run

The next 50-year run is identical to the previous run, except that here we view two additional variables that we usually don't measure, and usually don't view in a quantitative sense, in the real world – true income, and the stock of natural capital. These data suggest a different set of relationships: mining natural capital boosts GDP, but by reducing the stock of natural capital, mining also reduces true income.

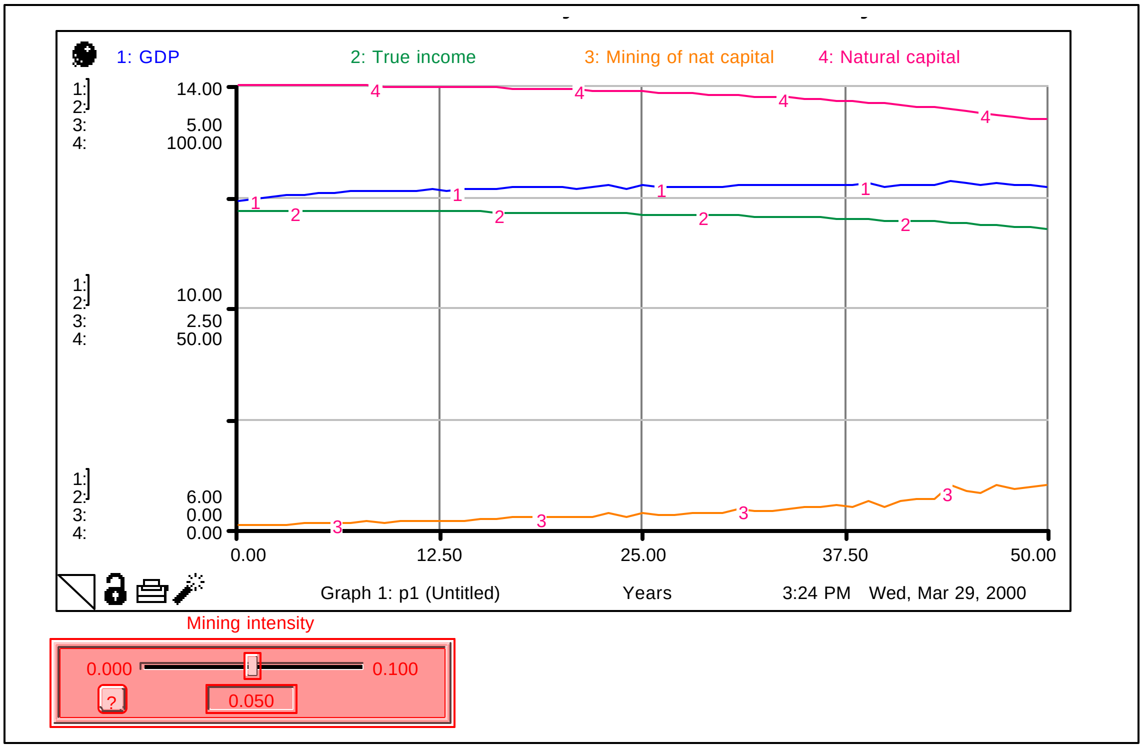

Figure 7: Simple economy model with two additional variables displayed

Increasing the length of the model run reveals further insights into the dynamics of this simple economy. In a 100-year run, effects of depletion, or depreciation, of natural capital become more pronounced. In this longer scenario, mining reduces the stock of natural capital to the point where GDP, not just true income, begins to decline. In this graph, a nonlinear relationship between mining and GDP becomes apparent. This relationship operates through a third variable, the stock of natural capital. Increased mining boosts GDP, but mining-induced reductions in the stocks of natural capital tend to reduce GDP. Also apparent in this graph is the long lag time – 60 years – between the start of mining and the first evidence of these feedbacks.

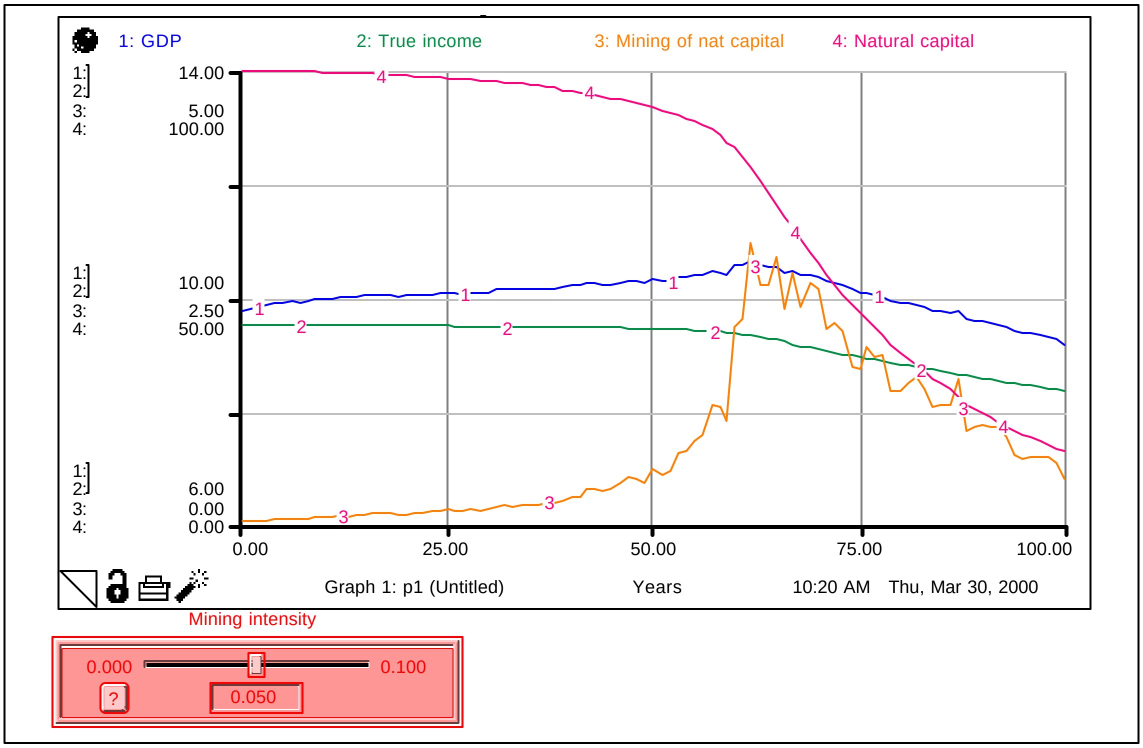

Figure 8: Simple economy model, 100-year run

If we were to follow only the indicators of the first model run, we might respond to this declining GDP by increasing the rate of mining. The next scenario does just that – around year 60, when GDP begins to level off, the rate of mining is increased to boost GDP. The policy is successful, for a while. With more intensive mining, GDP continues to rise for several more years. However, the longer-term effect is to cause both GDP, and true income, to fall more precipitously, and to a lower level, than ever before.

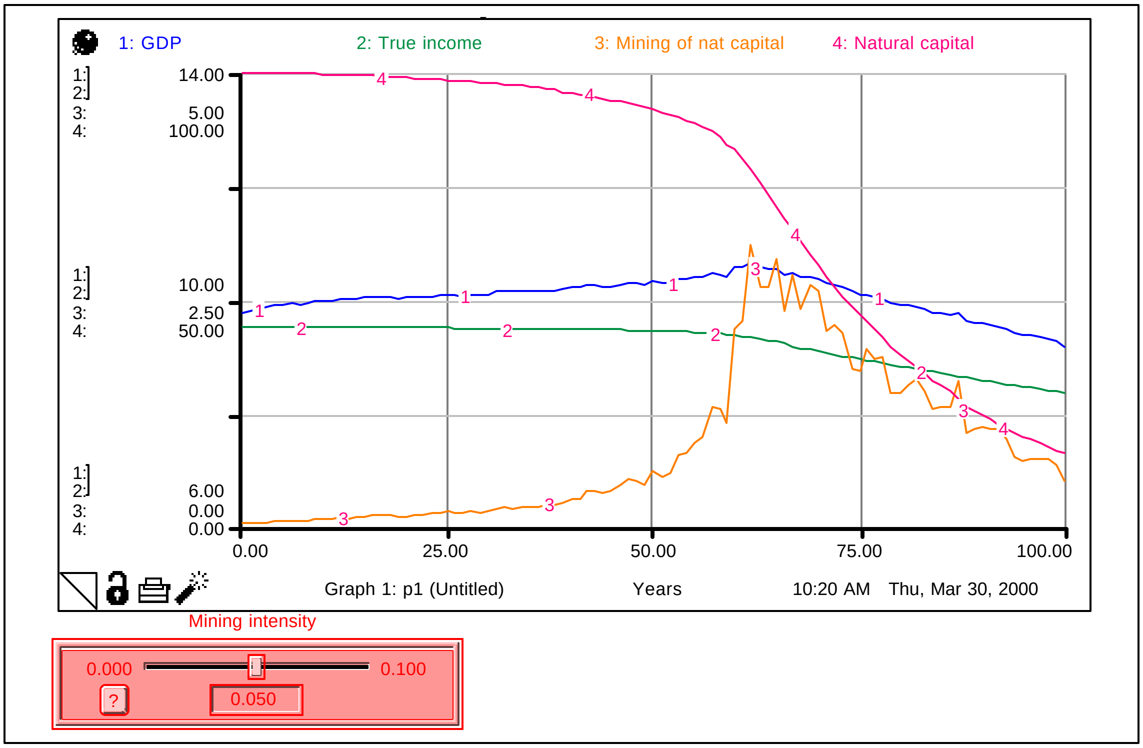

Figure 9: A simple economy with increased mining after year 60

The emphasis in this simple model is on the causal relationships, and it is these causal relationships, not the statistical relationships among the variables, that yield the insights this model provides. In this case in particular, data series for the stocks of these three forms of capital are very difficult to assemble in a meaningful way. It is easier to measure additions to the stock of manmade capital (i.e., investment in manmade capital, a flow) than it is to measure the entire stock of manmade capital. Similarly, it is much easier to measure mining rates (a flow, and a common indicator) than to measure the total stock of natural capital, and it is easier to measure rates of investment in education or health care (flows, and common indicators of the development of human capital) than to measure the stock of human capital.

These measurement challenges, however, in no way reduce the importance of the three stock variables. The same reasoning applies to true income (sustainable income). True income is notoriously difficult to measure, but the difficulty in measuring it in no way reduces its importance in our understanding of these ecological-economic relationships. By focusing effort on understanding the causal relationships among these difficult-to-measure variables we can produce models that yield insights that the traditional approach alone may miss.

The following table shows the relative strengths or characteristics of the two approaches.

Table 2: Relative Strengths of Empirical and Systems Models

Stochastic, Statistical, or Empirical Approach	Systems Approach
Relationships are statistical	Relationships are causal
Employ indicators; proxies for the preferred variables	May employ variables that are difficult or impossible to measure directly
Effort goes into developing numerical data	Effort goes into the causal relationships among the variables
Use to test hypotheses	Use to develop hypotheses
Employ linear relationships	Often employ nonlinear relationships
Good for predicting within the range of the available data	Good for demonstrating possible scenarios beyond the range of the data; for providing answers to if-then questions
May involve one researcher attempting to find certain statistical relationships	May involve a group using its collective experience to develop new insights
The formal model is the final product	The formal model may be the final product, or, when the insights are developed as the model is developed, the completed model may be a by-product of the development process

The emphasis in the development of these systems models is on the causal relationships among variables, rather than the statistical relationships. Shifting the focus to these causal relationships is one way to get around the limitations of data availability. These models are particularly useful for developing and illustrating hypotheses about how certain variables are related to one another. They are also useful for developing scenarios – answers to "what-if" questions concerning the ecological-economic system you are modeling. They are complements to, not substitutes for, stochastic models incorporating traditional indicators.

Systems Modeling as a Consensus-Building Exercise

Systems modeling can be used as a way to develop consensus among a group of interested individuals concerning the basic ecological-economic relationships in a given area. When used this way, it is the process of model-building, and the conversations that are involved, that are especially useful, sometimes more so than the final model. The final simulation model may be an end it itself, or it may be just a by-product of the model development process; a means to formally express, review, and develop hypotheses about these linkages.

Costanza and Ruth (1997) describe a three-step consensus modeling process. The process involves cooperative development of a scoping model, then a research model, and finally a management model. The first step involves developing a scoping model that reflects the important variables under consideration, and the basic relationships among them. These scoping models have a high degree of generality, that is, the relationships they reflect can often be applied broadly, and at many scales. The models described in this manuscript are scoping models.

Developing the model requires formally expressing one's basic understanding of underlying ecological-economic linkages, and facilitates their review. When the modeling process involves a group, the objective at this point is to state these basic understandings of these linkages and put them down on the page in a systems diagram, where the diagram establishes a formal structure of stocks, flows, and related variables. The formal structure brings a certain discipline to the conversation about these linkages, and makes it easier to identify points of agreement, and differences in basic understanding.

Developing, reviewing, and revising these scoping models can continue indefinitely, just as the traditional approach toward indicators and their statistical relationships does. The objective in developing scoping models as a group effort is primarily to bring in a formal structure for reviewing these basic relationships. The objective is not necessarily to produce a final, definitive model. Rather, the continuing development and review of these models can lead to insights that would not otherwise arise.

Developing a research model or management model involves increasing the resolution beyond that of a scoping model. Adding these details tends to make the model more realistic, but the details make the model less generally applicable. While a scoping model may include relationships that apply broadly to various ecological-economic systems at differing scales, a corresponding research model or management model is site-specific. In developing these models, it is important to recognize that there is a tradeoff between resolution (detail; complexity) and predictability. Increasing the degree of detail in a systems model may reveal more about the real-world system it approximates, but predictive power tends to fall with the increase in detail.

Costanza and Ruth (1997) also review a number of models built by consensus. These include models of U.S. iron and steel production, U.S. pulp and paper production, the South African Fynbos ecosystem, Louisiana coastal wetlands, the Florida Everglades, the Patuxent River in Maryland, Banff National Park in Canada, and the Patagonia coastal zone. With the partial exception of the two models of U.S. industrial production, these models were all constructed (and in several cases, continue to be constructed) through an iterative process. The process involves a series of workshops where interested stakeholders offer feedback, and otherwise participate in developing the basic relationships within the model. The participatory approach means that the model has broad support at each step of development; those who have an interest in the policies that flow from development of the model also participate in construction of the model.

Possibilities for USAID

USAID's compilation of time-series data was the catalyst for a broader discussion about development models, and basic relationships among the natural environment and economic development. Similarly, the simple economy model illustrated in this paper raised many more questions about those relationships than it answered. Related topics that have come up in these discussions include the following:

Historical conditions that have bearing on current conditions:
- historical uses of land
- concepts of private property rights
- development of governing institutions and their role in establishing property rights

Population:
- rates and direction of change as a factor in development
- effect on governing institutions
- effect on the environment

Free trade:
- capacity to streamline the economy and make it more efficient
- capacity to accelerate the pace of unsustainable practices

Technology:
- capacity to use natural capacity more efficiently
- capacity to accelerate the mining of natural capital

Indicators:
- what we want to measure vs. what we settle for
- what we see in the relationships among these indicators vs. what is really happening

Broader development theories:
- Boserupian development dynamics
- resource exhaustion, overshoot, and collapse

To address these, or other related issues, USAID could employ a format that is similar to what has been used to develop other consensus-built models. The format generally involves a series of workshops over the course of weeks or months, or, in the case of larger models, several years, with as many as 30 participants. A shorter and less intensive approach could involve 6-12 people and 2-3 workshops over the course of weeks.

The purpose of the first workshop is to solicit issues or questions that participants are working on. These issues sometimes take the form "we want this, but we also want…." or "we have done this to produce that, but instead we got…." The objective here is to identify some problems to work with, put them on the table, and decide which ones the group will address in a modeling exercise. At this point, we should be able to work out some of the important variables, a first attempt at their relationships to one another, and assemble a STELLA diagram. Between workshops, the facilitator develops the equations and other aspects of the model, which the group then reviews and develops further in subsequent workshops. This iterative approach to model-building, group participation, and the stocks-and-flows structure of the STELLA modeling environment helps bring a certain formality to our mental models of these relationships.

The STELLA modeling software is available from High Performance Systems, Inc., Hanover, New Hampshire. A run-time only demonstration version is available free from the HPS web site at http://www.hps-inc.com/

Additional Reading

Costanza, R. and Ruth, M., 1997. Dynamic systems modeling for scoping and consensus building, in Dragun, A. and Jacobsson, K. (eds.) *Sustainability and Global Environmental Policy*. UK: Cheltenham, pp. 279-308

High Performance Systems, Inc., 1997. *An Introduction to Systems Thinking*. Hanover, New Hampshire.

Woodwell, J.C., 1998. A simulation model to illustrate feedbacks among resource consumption, production, and factors of production in ecological-economic systems. *Ecological Modeling*, 112, 227-47