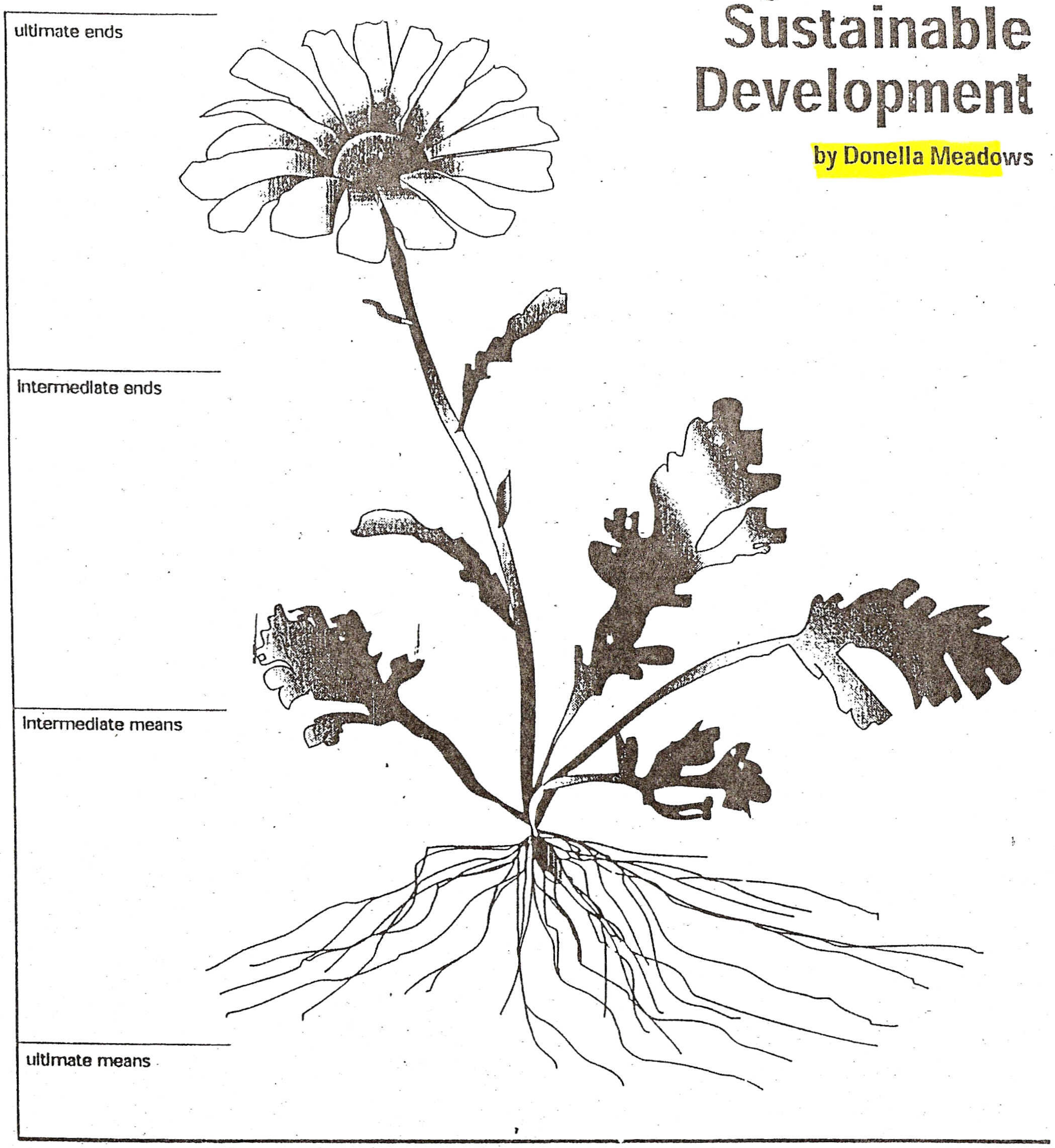
Indicators and Information Systems for Sustainable Development

by Donella Meadows



A Report to the Balaton Group • September 1998

1. The nature of indicators, the importance of indicators

If we could first know where we are, and whither we are tending, we could better judge what to do, and how to do it...

— Abraham Lincoln, speech to the Illinois Republican state convention, June 16, 1858

Indicators are natural, everywhere, part of everyone's life.

Intuitively we all use indicators to monitor complex systems we care about or need to control.

Mothers are alert to the activity level of their children, the brightness of their eyes, the way they breathe in sleep.

The learning of every school child is expressed as test scores and grades.

Farmers scan the sky for weather fronts, squeeze the soil to measure its moisture, watch how many earthworms are turned over in a shovelful of earth.

Doctors take your temperature, look at your tongue, do blood tests and CAT scans.

Mechanics use calipers and pressure gauges and listen to the sound of the motor.

Pilots and power plant operators have whole panels of instruments in front of them.

Economists use leading indicators, lagging indicators, cost-of-living indicators, employment indicators, the Nikkei or Dow-Jones index, and the most famous and criticized of all indicators, the GDP.

Some indicators are legends — the canary in the coal mine, the sea bird that hints of the yet-invisible land, the puff of smoke from the Vatican chimney.

We have many words for indicator — sign, symptom, omen, signal, tip, clue, grade, rank, data, pointer, dial, warning light, instrument, measurement. Indicators are a necessary part of the stream of information we use to understand the world, make decisions, and plan our actions.

Indicators arise from values (we measure what we care about), and they create values (we care about what we measure).

What do you keep an eye on, to be sure your home or workplace or community is in good shape? What would you ask about a place you might move to, to find out if you would like to live there? What would you want to know about your society fifty years from now, to be sure your grandchildren are living good lives? The answers people give to questions like these reflect their *values*.

Various U.S. communities, asked to define indicators of their own long-term welfare, have responded with:

- whether we have to lock our houses and cars;
- whether the children will go on living here or move away;
- whether wild salmon still run in the rivers (Seattle);
- whether, when we open the windows, we can smell the sage (Denver).

A group of Portuguese young people once listed as the top three questions they would ask about a strange country:

- how many days in a year does the sun shine?
- how many kilometers are there of clean beach?
- when you walk down the streets, are the people warm and friendly?

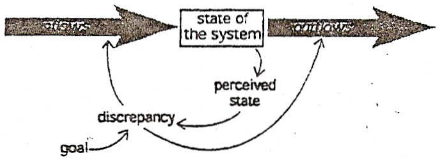
Clearly some values (and hence indicators) are place- or culture-specific, others are common to all humanity. Some are quantitatively measurable, while others, which may be equally important, can only be felt qualitatively.

Not only do we measure what we value, we also come to value what we measure. The Dow-Jones index arose from the information needs of stockholders, but now the general public sees it as an indicator of national economic health. No one cared about a blood cholesterol level over 200 until doctors started including it in our annual checkups. Opponents of the Vietnam War made converts by creating an indicator: the nightly body count.

Indicators can be tools of change, learning, and propaganda. Their presence, absence, or prominence affect behavior. The world would be a very different place if nations prided themselves not on their high GDPs but on their low infant mortality rates. Or if the World Bank ranked countries not by average GDP per capita but by the ratio of the incomes of the richest 10 percent to the poorest 10 percent.

We try to measure what we value. We come to value what we measure. This feedback process is common, inevitable, useful, and full of pitfalls.

When indicators are poorly chosen, they can cause serious malfunctions.



If you manage a national economy to maximize GDP, you get GDP. You do not necessarily get justice or freedom or environmental quality or even, sometimes, real wealth.

If you run a company to increase its stock market value, you may very well produce a rise in the stock market value — perhaps at the cost of underpaid workers or poor quality products, and therefore, over the long term, a downturn in the stock market value.

When the success of the family planning program in India was measured by the number of intra-uterine devices (IUDs) inserted per month, some family planning workers, it is said, inserted IUDs in unknowing women, in infertile women, and even in women who already had IUDs. The indicator looked fine, but the birth rate, the actual target, was hardly affected.

Indicators are both important and dangerous because they sit at the center of the decision-making process. Nearly every human decision is intended to bring some important system condition or state (literacy of the population; pollution in the lake; national debt) to some desired state. Action is taken depending on the discrepancy between the desired state or goal and the **perceived state** of the system.

The **perceived state** is an indicator. It may not be measured accurately. It may measure not the actual system state, but some proxy or associated state. (It's impossible, for instance, to measure the exact population of fish in the ocean, so we measure the catch and assume the population.) The indicator may be delayed. It may be "noisy," so its central tendency is hard to deduce. It may be deliberately or accidentally biased.

If an indicator of the state of the system is poorly chosen, inaccurately measured, delayed, noisy, or biased, decisions based on it cannot be effective. Misleading indicators will cause over- or under-reactions, changes that are too weak or too strong to bring the system exactly to the desired state. We can't steer accurately, if we don't know where we are.

Indicators are often poorly chosen. The choice and use of indicators are processes full of pitfalls.

Pitfalls in the process of choosing and using indicators include:

Overaggregation. If too many things are lumped together, their combined message may be indecipherable. The GDP is the classic example, adding together money flows caused by "good" economic changes (more education, say, or better food) and "bad" changes (more hospitalizations from automobile accidents). Another example: measuring the strength of a fishery by total tons of fish caught may disguise the fact that more valuable species are diminishing, but smaller, less desirable fish are being substituted.

Measuring what is measurable, rather than what is important. The area covered by forest rather than the size, diversity, or health of the trees; tons of hazardous chemicals rather than toxicities; the amount of money people have rather than the quality of their lives; the amount spent per school child rather than actual learning.

Dependence on a false model. We may think that the birth rate reflects the availability of family planning programs, when it may actually reflect the freedom of women to use those programs. We may think the price of oil tells us about the underground abundance of oil, when it primarily tells us about the built capacity of oil wells relative to the built capacity of oil-consuming devices.

Deliberate falsification. If an index carries bad news, someone may be tempted to alter it, delay it, change terms or definitions, unfund it, lose it, or otherwise suppress it. For example, the U.S. counts as unemployed only those people who are actively looking for jobs, not those who have given up looking. Some governments have been known to report agricultural yields based on five-year plans, rather than actual harvests.

Diverting attention from direct experience. Indicators may mesmerize people with numbers and blind them to their own perceptions. The stock market is going up, so the economy must be in great shape, despite the fact that many of us are decidedly poorer.

Overconfidence. Indicators may lead people to think they know what they're doing, or to think what they're doing is working, when in fact the indicators may be faulty.

Incompleteness. Indicators are *not the real system*. They may miss many of the subtleties, beauties, wonders, warnings, diversities, possibilities, or perversities of the real system.

The choice of indicators is a critical determinant of the behavior of a system.

Indicators are leverage points. Their presence or absence, accuracy or inaccuracy, use or non-use, can change the behavior of a system, for better or worse. In fact, changing indicators can be one of the most powerful and at the same time one of the easiest ways of making system changes — it does not require firing people, ripping up physical structures, inventing new technologies, or enforcing new regulations. It only requires delivering new information to new places.

For example, when a new U.S. law required every plant emitting toxic air pollutants to list those pollutants publicly, an indicator was created. Local newspapers began reporting the "top ten polluters." Companies acted quickly to get off that list, and toxic emissions decreased by over 40 percent in three years, *though there was no law against them.* The presence of the indicator was sufficient in itself to change behavior.[1]

Similarly, when new Dutch houses were built with the electric meter in the front hall where it was easily visible (instead of out of sight in the cellar), electricity use in those houses went down by one-third *though there was no change in the price of electricity.* There was simply a clear indicator of electricity use situated where no one could avoid seeing it.[2]

People can't respond to information they don't have. They can't react effectively to information that is inadequate. They can't achieve goals or targets of which they are not aware. They cannot work toward sustainable development if they have no clear, timely, accurate, visible indicators of sustainable development.

Conversely, if there are good indicators of sustainable development, it will be almost impossible *not* to make decisions and take actions that make the indicators improve.

[1] Environment Today, 6, no.1 (Jan/Feb 1995): 16. The 40 percent reduction was achieved not so much by reducing the generation of toxics as by diverting them from disposal into the air to disposal by injection into the ground (and hence into groundwater). This example illustrates another hazard of indicators — bizarre behavior designed not to solve a problem but to evade revelation by an indicator.

[2] This story was told in 1973 at a system dynamics workshop in Kollekolle, Denmark, and its source is lost — but systems people tell it over and over until it has become legend.

2. Indicators, models, cultures, worldviews

The real act of discovery consists not in finding new lands but in seeing with new eyes.

— Marcel Proust

Indicators are partial reflections of reality, based on uncertain and imperfect models.

The grade is not the knowledge in the head of the student. The stock market price is not the value of the company. No indicator is the real system. Indicators are abstractions from systems. Furthermore, they are abstractions from abstractions, from **models**, or sets of assumptions about how the world works, what is important, what should be measured.

We experience the world through models, most of them filtered through our senses and hidden in our minds. We don't carry reality in our heads, we carry **mental models**, assumptions about the world, based on our personality, culture, language, training, and experience.

Our mental models are enormously varied, which is one reason why we have trouble agreeing upon common indicators with which to inform our decisions.

Some of our models are formal, written down or otherwise expressed outwardly so others can see them. For instance spreadsheets, maps, written papers, or mathematical equations are formal models.

All our models, mental and formal, are only models. They are necessarily incomplete. None of us has perfect information. We don't understand everything that is happening. We're unclear about what causes what. Even with the help of computers, there is a limit to the degree of complexity we can comprehend or process. If we somehow could assemble all relevant information, we wouldn't be able to absorb its full buzzing complexity. We would have to abstract and simplify. The astonishing success of our species testifies to our ability to do so accurately enough to serve many purposes. The record of our failures, accidents, surprises, and disasters testifies to the limits of our modeling ability.

It helps to maintain humility about our models as we search for indicators of sustainable development. Sustainable development is a social construct, referring to the long-term evolution of a hugely complex system — the human population and economy embedded within the ecosystems and biogeochemical flows of the planet. Our models of this system are and will always be incomplete. Our indicators will be imperfect. We will be making decisions under uncertainty. Our task is to reduce that uncertainty. We will not be able to eliminate it completely, at least not any time soon.

We need many indicators, because we have many purposes — but there may be over-arching purposes that transcend nations and cultures, and therefore there may be overarching indicators.

Football scores are meaningful indicators to football fans and gibberish to everyone else. A farmer can read signals from a field of growing grain that the rest of us don't even perceive. Every jiggle in stock prices carries vital information only to those who watch the market every day. An indicator is useful only if it carries its information to a mind prepared to receive it, educated to its terms and units of measurement, and actively engaged with the system illuminated by that indicator.

Therefore we will probably never settle on a single global index of sustainable development — too many different people work on different problems and need different kinds of information. Some people are more interested in "development," others in "sustainability." Some are looking for "warning lights" telling when a key resource will become scarce or an ecosystem is likely to be driven into irreversible collapse. Others are interested in the welfare of a particular city or nation, or in bringing to public attention a particular pocket of poverty or pollution or under-capitalization.

So, rather than a single index, we need an information system — one at least as sophisticated as the system that presently tracks flows of money around the world — to inform various decision makers at various levels with various purposes related to sustainability and development.

Having said that, I must also say something that sounds contradictory. The comprehensive task — bringing about a socioeconomic system that

enhances quality of human life while preserving natural support systems — is particular to cultures and ecosystems, but is also, in essence, the same everywhere. Planet Earth operates by just one set of physical and biological laws, though they manifest as diverse climates and ecosystems. Human beings have the same fundamental needs for sustenance and belonging and meaning, though their ways of meeting those needs are culturally varied. Global resources such as the oceans and atmosphere are important to everyone. Therefore it may be possible to derive from a multiplicity of specific local indicators an overarching set of global indicators that inform common problems and purposes. These indicators can report to all of us about the increasingly integrated global socioeconomic system contained within the undeniably integrated global biogeochemical system.

I suggest a few overarching indicators later in this document.

We need many indicators because we have many worldviews — but indicators may help narrow the differences between worldviews.

The deepest reason why people need different indicators is that they have different fundamental worldviews or paradigms. Worldviews are mental models about the very nature of reality. They tell us what the environment is (limited and fragile or infinite and robust, outside ourselves or continuous with ourselves, a luxury or the most basic of necessities), what human beings are (honest, devious, generous, greedy, fallen angels, unrecognized buddhas, competitive rationalists, myopic egotists), and how people and nature should interact (through dominion, stewardship, harmony, partnership, competition, exploitation, love). Our worldviews define what is important, what questions can be asked, what goals are possible, *what can and should be measured.*

Worldviews not only give meaning to information, they actively screen information, only admitting what fits our preconceived models. Someone who is convinced that technology can solve any problem, for example, can read the newspaper and find articles about wonderful new technologies. Someone with a skeptical view can read the *same paper* and see nothing but articles about technical foul-ups. Each is screening for the information that fits his or her paradigm. If contrary evidence does penetrate our paradigmatic screens, we have ways of dismissing it or discounting the people who present it to us. We see information that disconfirms our worldview as the exception and information that confirms our worldview as the rule.

Therefore people of different worldviews live literally in different worlds. They see different things and take their information from different indicators. Scientists who see the world as flows of energy will want different indicators than will economists who see the world as flows of money — who will want different indicators than will people who see the world as flows of time or social relationships or moral obligation or political power. Our worldviews don't even use the same currency! No wonder we argue about indicators!

Given the multiplicity of perspectives, one option is to disagree endlessly. We can promote our own indicators and ridicule others'. Another option is to acknowledge the inherent ambiguity in the choice of models and the design of indicators. If that is done, if worldviews and models are exposed to view, if their plurality is not only recognized but appreciated, indicators can play an emancipatory role. Different indicators giving conflicting reports about the state of the global system can provide an opportunity to inquire into the underlying models that produced the discrepancy. Indicators can be a tool for expanding, correcting, and integrating worldviews.

(Note: everything written here about worldviews is a worldview.)

Indicators need not be purely objective, and in fact few of them are.

It is conventional within a scientific worldview to distinguish between "objective" and "subjective" indicators. Objective indicators are sensed by instruments outside the individual — thermometers, voltmeters, counters, dials, rulers. They can be verified by others. They can be expressed in numbers. Subjective indicators are sensed only within the individual by means that may not be easily explained and in units that are probably not numerical. Objective indicators primarily measure quantity. Subjective indicators primarily measure quality.

Objective indicators are usually considered more reliable and valuable. They are certainly more easily communicated and validated by others. But there are vital purposes that depend on subjective, qualitative information. The scientific worldview is just one way to see the world, a very useful one, but not comprehensive enough to be used exclusively. A choice to pay attention only to what is measurable is itself a subjective choice, and not a wise one. Every human being knows that some of the most important things in life — freedom, love, hope, harmony, even the beauty of scientific precision — are qualities, not quantities.

All indicators are at least partially subjective. The very choice of an indicator is based upon some value, some inner human purpose that tells us what is important to measure. The choice of what is important is inherently subjective.

Indicators of quality, "subjective indicators," are worthy of respect, however hard they may be to define. The fact that people consider something ugly or beautiful, harmonious or dissonant, noble or ignoble, is not to be swept away as "mere opinion." If we guide our decisions only by quantitative indicators and not qualitative ones, we will produce a world of quantity without quality. Many of our social and personal problems arise from the fact that we are well on our way to doing exactly that.

Despite their difficulties and uncertainties, we can't manage without indicators.

Indicators are hard to define. They are based on uncertain models. Their selection and use are full of pitfalls. They carry different messages to different minds. These difficulties don't mean, however, that we shouldn't use indicators. We have *no choice*. Without them we fly blind. The world is too complex to deal with *all* available information. We have to choose a set of indicators small and meaningful enough to comprehend. Rather than discourage us, the pitfalls and difficulties should give us ideas about how to design better indicators, and motivation to do so.

The search for indicators is evolutionary. The necessary process is one of learning.

A lot of planes crashed before people learned what instruments to put in the cockpit. Many patients died before doctors figured out how to take temperatures and blood tests. When a system is extremely complex, it takes trial, error, and learning to produce a serviceable set of indicators.

The human economy and the planet Earth together make up a system we can't afford to crash. We have to learn from the experience of local economies and ecosystems (some of which have crashed or are crashing) and improve our indicators as best we can, using many types of human experience and knowledge and models.

That is an enormous job. While we're learning, we should view our indicators and models with utmost humility. We should open ourselves to *disproof*, which is a faster way of learning than looking only for proof. (Scientists are trained not to prove a theory but to try to disprove it.) We should subject every model, especially our favorite ones, to as much scrutiny and as tough testing as possible. There's no shame in having a wrong model or a misleading indicator, only in clinging to it in the face of contradictory evidence. The more flexible we can be, the faster we will find good sustainable development indicators.

3. Why indicators of sustainable development?

Indicators of sustainable development need to be developed to provide solid bases for decision making at all levels and to contribute to the self-regulating sustainability of integrated environment and development systems.

— Chapter 40.4 of Agenda 21, from the United Nations Earth Summit in Rio, 1992

Development and sustainability are old problems; now they come together on a global scale and in an urgent time frame.

The world economy is doubling roughly every twenty years. The world population is doubling every fourty to fifty years. The planet that supplies the materials and energy necessary for the functioning of the population and economy is not growing at all. That means whatever planetary resource was one-fourth-used a generation ago is half-used today. Whatever waste sink was half-full a generation ago is full today. Whatever was full a generation ago is overfull today.

Each successive doubling of the human system causes new stresses and raises new questions, or rather brings two old questions together with new urgency. Question one is *how can we provide sufficiency, security, good lives to all people?* (The development question.) The second is *how can we live within the rules and boundaries of the biophysical environment?* (The sustainability question.) With the economy globally linked, the ocean fisheries depleting, the atmosphere changing in composition, open spaces filling in, and much of the human population still living in poverty, these two questions now come together with urgency. *How can we and our children live good lives without eroding the health and productivity of the physical planet — and therefore the possibility for future generations to lead good lives?*

The indicators we need to answer that question are not immediately obvious, because the question is so new. It is new because most human history thus far has occurred in a world with few apparent limits. With twenty-year doublings, however, the human endeavor is rapidly approaching and in some cases exceeding physical limits. The unsustainability of many of our activities is becoming apparent. Suddenly we need indicators that we never needed before.

"Sustainability" and "development" are value words. Like all value words — freedom, fairness, beauty, justice, security, sufficiency, democracy — they are subjective, nearly impossible to define, nevertheless possible to sense (or to sense their absence), and vitally important. Taken together — "sustainable development" — the two words may seem contradictory but nevertheless must be achieved together.

Good lives for all people in harmony with nature. The urgency and scale of achieving that goal challenge old models and worldviews. Hence the demand for new ways of thinking and the need for new indicators.

Sustainability indicators must be more than environmental indicators; they must be about time and/or thresholds.

Governments already maintain many environmental and resource indicators, such as the emission rate of sulfur dioxide, concentration of carbon dioxide in the atmosphere, concentration of lead in drinking water, estimated reserves of fossil fuels.

An environmental indicator becomes a sustainability indicator (or unsustainability indicator) with the addition of **time, limit,** or **target.** The central questions of sustainability are: How long can this activity last? *How long do we have to respond before we run into trouble? Where are we with respect to our limits?* Therefore sustainability indicators are ideally expressed in time units. If we keep on mining or fishing or logging at this rate, how many years will the resource last? If we keep emitting this pollutant at this rate, how long before we accumulate a dangerous concentration in nature or in ourselves?

Ecological sustainability is the domain of the biologist and the physical scientist. The units of measurement are different, the constructs are different, and the context and time scale is different.

— Ismail Serageldin, Vice President, Environmentally Sustainable Development, World Bank

For example, a common resource indicator is the amount of fossil fuel reserves known and estimated — roughly 1000 billion barrels of known oil reserves globally, plus perhaps 500 billion barrels estimated but undiscovered.[3] This amount by itself is not a helpful number. It is too huge to be imaginable, and it is not related to our own activities or limits.

If we compare the estimated supply of 1500 billion barrels to recent rates of oil consumption, about 25 billion barrels per year,[4] we can put that reserve in terms of a more understandable index: years of consumption remaining:

(1000+500)/25 = **60** more years of oil at present consumption rate.

If we assume not present consumption, but a rate of growth slightly higher than population growth — let's say 2%/year on average — we get a strikingly different number:

ln (.02*60 + 1)/.02 = **39.4** years with 2% consumption growth.

We may (and will) argue about how much more oil might be discovered and about what the future growth rate might be. Different estimates will produce different indicated lifetimes for the oil resource. For example:

Suppose four times as much new oil is discovered as is currently estimated, but consumption growth proceeds at 5% per year:

(1000+2000)/25 = **120 years** at present consumption rate, but

ln(.05*120 +1)/.05 = **38.9** years at 5% consumption growth.

Suppose twice as much new oil is discovered as is currently estimated but consumption growth stays as low as 1% per year:

(1000+1000)/25 = **80** years at present consumption rate.

ln(.01*80 +1)/.01 = **58.8** years at 1% consumption growth.

Even given great uncertainties about future oil discoveries and future consumption growth, a few calculations of such an indicator of *time remaining* gets across the central message: the time is bounded and limited to decades, not centuries, if oil consumption keeps increasing.

A useful indicator in such an inherently uncertain arena ought to cover the range of possibilities. Perhaps something like this: *Known and estimated and speculative oil reserves will last roughly approximately 60 to 120 years if there is no increase in consumption, and 30 to 60 years if there is steady exponential growth in consumption.*

[3] Worldwide Petroleum Industry Outlook. 14th ed. Tulsa, Okla.: PennWell Pub. Co., 1997; Energy Statistics Sourcebook. 12th ed. Tulsa, Okla.: PennWell Pub. Co., 1997.

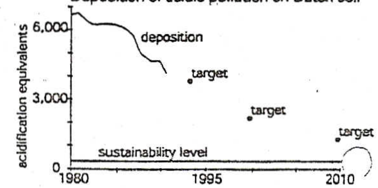
[4] Ibid.

The Intergovernmental Panel on Climate Change (IPCC) estimates that the world economy would need to cut its carbon dioxide emissions by 60% in order to stabilize the chemical composition of the atmosphere.[5] If we define the sustainable emission rate as 1.0, that means our current emission rate is 1.6 — clearly beyond sustainability.

Similarly, suppose that a fishery's biology experts estimate that the current rate of fish harvesting is about 20 percent above the rate that would allow fish populations to regenerate.[6] Sustainability index = 1.2 — over the limit.

Distance from a sustainability target can be expressed even more graphically by showing a time trend related to a target, as in the following example from the Netherlands.[7]

Deposition of acidic pollution on Dutch soil



[5] Intergovernmental Panel on Climate Change. *Climate Change: The IPCC Scientific Assessment*, edited by J. T. Houghton, G. J. Jenkins, and J. J. Ephraums. Cambridge/New York: Cambridge University Press, 1990.

[6] That is roughly what the Food and Agriculture Organization (FAO) has estimated for excess fishing capacity on average worldwide, though such an indicator makes most sense only when it is calculated fishery by fishery. See, for example: J. A. Gulland, ed., *The Fish Resources of the Ocean*. Surrey, U.K.: Fishing News Ltd., 1971; M. A. Robinson, *Trends and Prospects in World Fisheries*, Fisheries Circular No. 772. Rome: FAO, 1984; FAO, *Marine Fisheries and the Law of the Sea: A Decade of Change*, Fisheries Circular No. 853. Rome: FAO, 1993; FAO, *The State of World Fisheries and Aquaculture 1996*. Rome: FAO, 1997.

[7] Dr. A. Adriaanse, *Environmental Policy Performance Indicators*. Sdu Uitgeverij Koninginnegracht, May 1993, pp. 33.

If they are not expressed in units of time, sustainability indicators should be related to carrying capacity or to threshold of danger or to targets. Tons of nutrient per year released into waterways means nothing to people. Amount released relative to the amount the waterways can absorb without becoming toxic or clogged begins to carry a message.

Development indicators should be more than growth indicators; they should be about efficiency, sufficiency, equity, and quality of life.

In an empty world, development can easily be confused with growth. Growth simply means getting larger — not necessarily getting better. Most of our economic indicators, es-

To take a more ambitious example, Wackernagel and Rees have defined the "ecological footprint" — a rough estimate of the average amount of land required by a given nation to supply all that nation's physical consumption (food, energy, water, materials, waste purification).[8] If the ecological footprint is larger than the actual area of the nation, then that nation must be either importing resources from outside its borders (which is fine, as long as the exporting countries' footprints are smaller than their actual area) or drawing down its own or other countries' resources (which is clearly unsustainable).

Here are some Wackernagel and Rees estimates of ecological footprints related to land capacity for selected nations of the world:[9]

Nation	Ecological Footprint (ha/cap)	Available Capacity (ha/cap)	Surplus or Deficit (ha/cap)
Australia	8.1	9.7	+1.6
Bangladesh	0.7	0.6	-0.1
Brazil	2.6	2.4	-0.2
China	1.2	1.3	+0.1
Germany	4.6	2.1	-2.5
Indonesia	1.6	0.9	-0.7
Japan	6.3	1.7	-4.6
New Zealand	9.8	14.3	+4.5
Russia	6.0	3.9	-2.0
United States	8.4	6.2	-2.1

tablished several doublings ago, are defined around growth, with the GDP per capita as the most obvious example.

In a full world, development and physical growth must be decoupled. As economist Herman Daly has pointed out, growth is about getting bigger, development is about getting better.[10] Development indicators must begin to reflect quality, equity, efficiency, and sufficiency. They must shift emphasis from money to physical units and from quantity of material throughput to quality of life. These distinctions begin to point to the real *purpose* of economic development, which is not to have money but to have better lives. This sort of rethinking can also create openings for concepts not only of under-development but of over-development, and therefore for concepts of "enough."

[8] M. Wackernagel and W. Rees, *Our Ecological Footprint.* Philadelphia: New Society Publishing, 1996.

[9] M. Wackernagel et al., "Ecological Footprints of Nations," Center for Sustainability Studies, Xalapa, Mexico, March 10, 1997.

[10] R. Goodland, H. Daly, and S. El Serafy, introduction to *Environmentally Sustainable Economic Development: Building on Brundtland.* The World Bank Environment Working Paper no. 46, July 1991, pp. 2-3.

One of the first attempts to indicate actual human development rather than money flows is the Human Development Index, pioneered by the UN Development Programme. The HDI is a (fairly complex) mathematical average of three indicators: average life expectancy, average educational attainment, and GDP per capita. Here are some sample HDI values for selected countries (1993 data).[11]

Nation	Human Development Index (HDI)
Canada	0.951
USA	0.940
Japan	0.938
Russia	0.804
Brazil	0.796
Indonesia	0.641
China	0.609
Kenya	0.473
Nigeria	0.400
Afghanistan	0.229
Somalia	0.221

In a similar vein, the health-based magazine *Prevention* has invented an index to measure the healthfulness of a nation's lifestyle. It is an aggregation of twenty-one indicators, determined largely by polling data. They include:[12]

What percent of the adult population:

- do not smoke?
- engage in frequent strenuous exercise?
- maintain proper weight?
- get 7-8 hours of sleep a night?
- fasten seat belts while riding in a car?
- refrain from excess alcohol consumption?

[11] United Nations Development Programme, *Human Development Report 1996.* New York: Oxford University Press, 1996, pp. 136-137.

[12] The "Prevention Index" is available from *Prevention* magazine, 33 East Minor Street, Emmaus, Pennsylvania.

4. The challenge of coming up with good indicators

Indicators must be simultaneously meaningful in two different domains: that of science and that of policy.

— Wouter Biesiot

It's easy enough to list the characteristics of ideal indicators.

Most study groups on indicators start by making a list of the qualities of a good indicator. Just about every indicator report contains a list similar to the following.[13]

Indicators should be:

Clear in value: no uncertainty about which direction is good and which is bad.

Clear in content: easily understandable, with units that make sense, expressed in imaginable, not eye-glazing, numbers.

Compelling: interesting, exciting, suggestive of effective action.

Policy relevant: for all stakeholders in the system, including the least powerful.

Feasible: measurable at reasonable cost.

Sufficient: not too much information to comprehend, not too little to give an adequate picture of the situation.

Timely: compilable without long delays.

Appropriate in scale: not over- or under-aggregated.

Democratic: people should have input to indicator choice and have access to results.

Supplementary: should include what people can't measure for themselves (such as radioactive emissions, or satellite imagery).

Participatory: should make use of what people can measure for themselves (such as river water quality or local biodiversity) and compile it to provide geographic or time overviews.

[13] For a definitive list agreed upon by a large international body of experts, see "The Bellagio Principles," in B. Moldan, S. Billharz, and R. Matravers, *Sustainability Indicators: A Report on the Project on Indicators of Sustainable Development* (SCOPE). Chichester and New York: John Wiley, 1997.

Hierarchical: so a user can delve down to details if desired but can also get the general message quickly.

Physical: money and prices are noisy, inflatable, slippery, and unstably exchangeable. Since sustainable development is to a large extent concerned with physical things — food, water, pollutants, forests, houses, health — it's best wherever possible to measure it in physical units. (Tons of oil, not dollars' worth of oil; years of healthy life, not expenditures on health care.)

Leading: so they can provide information in time to act on it.

Tentative: up for discussion, learning, and change. (We should have replaced the GNP index decades ago, for example, but it became too institutionalized to do so.)

Oh please! Not again new indicators! I only want to see simple indicators that can be used by politicians and let the scientists stop with ever more complicated stuff!

— A very high UNEP official

It's not so easy to find indicators that actually meet these ideal characteristics.

Having made a list like the one above, the typical indicator study group disbands, encouraging someone else to come up with actual indicators that meet all these wonderful criteria. Or alternatively, the study group proceeds to recommend a long list of indicators that don't meet the criteria. As one of our Balaton colleagues has written: "International organizations, dependent on consensus of their members, assemble indicator sets that measure the noncontroversial issues in overwhelming detail, while leaving out information on controversial issues. It's like cramming an airliner's cockpit with ship chronometers, cuckoo clocks, swatches, hour glasses, and thermometers, without making sure that vital instruments like airspeed indicators and compass are on board."[14]

Having tried the exercise ourselves, however, the Balaton workshop members found ourselves in sympathy with others who have failed to come up with perfect indicators. It was easier to complain about other indicators, to spew out theoretical lists of hundreds of (mostly unmeasurable) indicators, or to philosophize about the Ideal Indicator, than it was to produce a limited, comprehensible number of compelling, effective indicators. Our understanding is im-

[14] H. Bossel, "Finding Indicators of Sustainable Development," Center for Environmental Systems Research, University of Kassel, draft, September 1997.

perfect, our worldviews get stuck, systems are complex, people disagree, we fall back on our narrow specialties, we fail to summon the enormous creativity we need. One wants to throw up one's hands and go do something easy.

To keep ourselves from ducking the difficulties, some of us created, at irregular intervals throughout the workshop, an imaginary challenge to come up with ten, just ten, crucial indicators we would recommend to the nations of the world, "or else be shot at dawn." Under that pretended pressure, most of us did produce indicators.[15] We were unhappy with our forced lists and pleaded for more time. We repeated the exercise and our lists changed as the workshop proceeded and we thought more deeply. We didn't like to be forced to produce (who does?) but in fact even our imperfect suggestions were probably improvements on existing indicators. And the forcing exercise brought out questions, considerations, doubts, and ideas that led us to more creative indicators.

If you aren't too dignified, I would recommend the "ten indicators or be shot at dawn" exercise when you find yourself bogging down. Otherwise it's too easy to indulge in theorizing or politicizing or some other evasive activity.

Most of us already have indicators in the backs of our minds, "beloved indicators" that reflect issues of great concern to us. It's important to get them out on the table.

We noticed each time we did the forcing exercise that we each had "beloved indicators," which we kept putting back on our lists because we just plain wanted them there. (See the list on the next page.) These indicators were different for different people; they may not be the best ones to put into the cockpit of the sustainability jetliner, but they are worth paying attention to. When we try to explain *why* we want them, we find ourselves bringing out our deepest worldviews and values. They may suggest practical indicators of great importance — or at least once they've been acknowledged and talked through, our minds can be at rest and ready to think about other indicators.

[15] Some of us considered the whole exercise undignified and refused to participate. Others declared that the process of choosing indicators was more important to them than the product — and that the proper broad base of constituents was not present at the workshop.

Here are some of the beloved indicators that participants in the Balaton workshop kept insisting upon (which may tell you more about us than about sustainability indicators):

- Percent of the food supply that is grown organically. We are worried about the effects of chemical agriculture on ecosystems and human health.
- Percent of streams you can drink from safely. Seems to us it should be 100 percent.
- Average age of the trees in the forest. Old ones signify to us undisturbed ecosystems, too many young ones signify unsustainable forestry.
- Population trends of migrating songbirds. To us life would be unbearably sad without songbirds, and migrating birds are sensitive measures of environmental health over large areas.
- Food miles (average distance an item of food travels before being eaten). Local food is likely to be more fresh, nutritious, good-tasting, and resilient to supply interruptions. It has also used less packaging and transport energy.
- Average distance between creators and consumers of art and media. Preferably there is no distance at all — a measure of community, participation, identity, self-expression.
- Percent of elections in which you get to vote for a politician you really trust. This one could be an embarrassing indicator of real democracy.
- Average distance between living places of members of extended family. For affection, social resilience, and energy efficiency, the closer the better.
- Average number of minutes spent daily in prayer, meditation, or quiet time.
- Percent of people who say they have "enough." We wonder if a society is happy if significant numbers of people, however rich, constantly want "more."

Indicators can take many forms. They don't have to be numbers. They can be signs, symbols, pictures, colors.

We thought of many different types of indicators — digital and analog, monetary and physical, aggregated and disaggregated, static and dynamic, additive and multiplicative, normalized and absolute.

We particularly distinguished between three types of indicators that would be necessary in any airplane cockpit, for which there are obvious analogies in sustainable development:

- gauges and warning lights to signal obstacles or dangers ahead;
- indicators of the comfort and safety of the passengers;
- measures of the heading and distance to go toward the destination.

We got into long, hot discussions about the meaning of symbols (more about this later). We began to imagine different ways of presenting indicators — illuminated control panels, hypertexted Web pages, pictures, dynamic models, maps, compasses. We talked about the power of the famous *Bulletin of Atomic Scientists* "Minutes to Midnight" clock that powerfully, if qualitatively, measures the political tension of the nuclear arms race. We thought of the creative ways that TV weather reporters deliver complex information.

Surely as much effort and ingenuity ought to go into reporting to the people of the world about their welfare and the sustainability of their planet as goes into reporting to them about tomorrow's weather!

What is needed to inform sustainable development is not just indicators, but a coherent information system from which indicators can be derived.

As we went back and forth, suggesting specific indicators, then backing off to talk about the philosophy of what we were doing, we realized that we were searching not just for **indicators** but also for an **information system** about sustainable development, of which indicators are just one part. That is to say, we were talking about the design not only of the instrument panel (indicators) that governments and citizens need to see to steer the ship and avoid obstacles, but also the design of the background wiring (information system) that collects and sorts information and delivers it to the panel.

We saw that we were working on three levels. First, we were evolving ideas for **process, linkage,** and **worldview explication** that could aid the search for indicators. Second, we were developing a **framework** (a model) to organize and link together an entire sustainable development information system. Third, we were coming up with **indicators.** Our discussions on these three levels constitute the next three sections of this report.

5. Suggestions for indicator process and linkage

Everything should be as simple as possible, but not simpler.

— Albert Einstein

Hierarchy: Coherence up and down the information system

The information system should be organized into hierarchies of increasing scale and decreasing specificity.

Whether or not the world is actually arranged in hierarchies, our mental models perceive the world that way. We see a hierarchy from the individual to the family, the neighborhood, the community, the region, the nation, the world. Or from the organism to the population to the ecosystem to the biome to the planet. Or from the employee to the division to the firm to the sector to the national economy to the global economy. At each of these levels, actions are taken and information is needed. So we picture a nested set of indicators, each informing the "system in focus" at its own level (say, actual water quality in this lake) and aggregating to inform the system at the next higher level (average water quality in the region's lakes).

Aggregation is necessary to keep from overwhelming the system at the higher levels of the hierarchy. The brain cannot and need not process everything happening to every cell in the body. The leaders of nations can't keep track of every family, species, business, or lake. But actors down the line, in the family, near the lake, need detailed information to keep their part of the system functioning well.

Aggregation must be done with care, because information is lost at each stage. Ideally only important information should be passed up to higher levels, but what information is important will change over time and with different purposes. Therefore it should always be possible to go down as many levels as necessary to see the numbers that have been put together to make the aggregate indicator and to create new indicators. (For example, it should be possible for anyone to find out not only *that* the GDP went up, but *what* went up — home construction or weapons construction, cleaning up after natural disasters or cleaning up the environment.)

"Clicking a hypertext page" is the phrase we used to indicate our vision of the way a user could navigate a hierarchical information system.

The main "cockpit" would show the most critical and aggregated indicators (say, for example, the quality and adequacy of human capital). A "click" on that indicator would open a more detailed set of information (say, size of population and primary attributes — age, sex, health status, education, income, employment). Another "click" on health status could open boxes of information about age-specific mortality and morbidity rates and causes. Further "clicks" could give the same information about specific geographic sub-areas. And so forth.

Information from the hierarchy at all levels should be available to people at all levels.

Like a library, an information system rich at every hierarchical level yet clearly organized so that one can find one's way among the levels, would be maximally useful for matching diverse kinds of information to the diverse purposes for which people need information.

One of the pitfalls of such a flexible information system, however, is that it can be manipulated. It allows the user to choose only those indicators that serve a pre-conceived outcome. Selecting information to justify only one point of view is a trap that even well-meaning users can fall into. The only way to get around it is to be sure the information system is accessible to users with many points of view. Then multiple interpretations can emerge and can be discussed not at the futile level of throwing contradictory statistics at each other, but at the level of examining the models and purposes that cause those statistics to be selected from the full set available.

Making sure that "cockpit indicators," the aggregated ones at the top of the hierarchy, are comprehensive can also help overcome the all-too-human tendency to pay attention only to the news you want to hear. If, for example, economic productivity indicators are improving nicely,

It comes back to local knowledge. People have said that the beaches are more polluted than what they've been. I could have told you that. Because I've seen from upstairs for thirty years and looked out the window every day and seen the color of the sand change color. Whereas it used to be like everyone imagines sand, it's now a browny color.

— focus group participant, Lancashire County, UK[16]

but indicators of the security of households, say, or the integrity of communities are falling apart, and if the cockpit indicator blends those two sources of information, then at least the question will rise, "why isn't this indicator rising, when the economy is doing so well?" Presumably a scan of the indicators at the next level down in the hierarchy will answer that question.

Information should also come from all levels. The public can be important contributors to, as well as users of information and indicators.

Governments have the scientific and financial resources to gather information that is inaccessible to citizens, such as satellite imagery or radiation leaks. Citizens can provide detailed ground-truth that is inaccessible to governments.

For example, a nongovernmental organization called River Watch in the United States organizes high school science teachers to involve students in regular chemical and biological monitoring of a stream near each school. The schools link their findings through computer networks, thereby creating monitoring networks for entire streams and rivers. They have been able to detect changes in water quality quickly, and even, by comparing data on successive reaches, to pinpoint the source of a problem emission. If enough sections of river could be covered this way, the information could be aggregated upward into, for example, an index of what percent of the nation's surface water is of swimmable and drinkable quality, and how that index is changing over time.[17]

Costa Rica has organized through its Instituto Nacional de Biodiversidad (INBio) thousands of its citizens as local naturalists, trained to collect and preserve insects, plants, birds, and to send them to taxonomists for classification. Working in their spare time, the laborers, students, housewives, and retired people in this program are cataloguing the vast biological diversity of their nation. They have discovered hundreds of new species. The species catalog is computerized and made available at libraries and schools throughout the country. When the catalog is done, the citizen naturalists can become monitors of population size, breeding success, and other attributes of biological diversity.[18]

Similarly the Christmas Bird Counts conducted by Audubon Society volunteers, originally in North America, now throughout the Western Hemisphere, are proving one of the most reliable long-term bird population data bases in existence.[19]

Citizens could survey many things at the local level: soil erosion, child nutrition, adequacy of housing, use of local energy sources, quality of roads, water, jobs, schools, or forests. Citizen monitoring not only can provide excellent information at low cost, it can also contribute to the education of the people and to widespread appreciation for natural and societal wealth.

THE SELECTION PROCESS: EXPERTS AND CITIZENS TOGETHER

The process of indicator development for social systems is as important as the indicators selected.

As indicators are selected and defined, values are expressed, purposes are agreed upon, worldviews are at play, and models are developed and shared (implicitly or explicitly). Therefore the selection process is the place where legitimacy and comprehension are built, as people see their values and worldviews incorporated into the indicators. The process of indicator selection is also one of the key places where social learning about indicators and models takes place.

For all these reasons — to be inclusive, to gather a full compilation of viewpoints, to legitimize the product, and to enhance learning — the more people involved in indicator selection the better. Indicators for an entire social system should not be determined by a small group of experts or politicians or civil servants sitting together in rooms out of contact with the people who are expected to understand and use the indicators.

The indicator selection process works best with a combination of expert and grassroots participation.

Many indicator-defining groups have found that they made greatest headway in finding useful indicators if they put together experts on the subject in question with interested non-experts.

Experts are necessary to supply comprehensive understanding, perspective on the development of the system over time, knowledge of what data are available, realism about what can be measured, and credibility to the process. But experts, left to their own devices, can get lost in details, can want to measure everything that is intellectually interesting rather than what is policy-relevant, can invent technical indicators that carry no meaning outside the expert community, and can be blindered by the narrow specificity of one area of study.

Non-experts tend to push to make the indicator relevant and understandable. The non-expert may be more open than the expert to creative linkages and syntheses, more likely to capture the "big picture," more likely to be sure a diversity of interests are represented. Just as the expert brings scientific credibility to the indicator selection process, the non-expert brings political credibility.

[16] Quoted in P. Hardi and T. Zdan, eds., *Assessing Sustainable Development: Principles in Practice*. Winnipeg, Manitoba: International Institute for Sustainable Development, 1997, p. 107.

[17] River Watch Network, 153 State Street, Montpelier, VT 05602. Another such organization is the Global Rivers Environmental Network (GREEN, 206 South Fifth Ave., Suite 150, Ann Arbor, Michigan 48104, U.S.A.)

[18] INBio, Sto. Domingo 3100, Heredia Costa Rica, Tel.: (506) 36-7690, Fax: (506) 36-2816.

[19] The data are complied and maintained by the Patuxent Wildlife Research Center, Laurel, Maryland. The CBC started on Christmas Day, 1900. Today, over 45,000 people from all 50 states, every Canadian province, the Caribbean, Central and South America, and the Pacific Islands (all areas where the breeding birds of North America spend their winter) participate in about 1700 counts held during a two and one-half week period. The Christmas Bird Count has evolved into the largest and longest-running wildlife survey ever undertaken.

But integrating expert and non-expert opinion has its costs and must be done with care.

Involving "everyone" can produce disproportionate representation of some stakeholders, too little technical knowledge, too much focus on immediate interests, risk of incomplete mapping of the area of interest, and no holistic understanding. Furthermore, it can be inordinately time-consuming, may be difficult to enroll sufficient participation, requires skilled facilitation, tends to get stuck in process discussions, and tends to produce low-level "concrete" indicators.

Some practitioners who have weathered these challenges suggest the following ten-step process for developing an indicator set.[20] They recommend that the process be managed by impartial facilitators whose role is to coordinate meetings, guide the discussion, prepare background documents, and synthesize results.

1. **Select a small working group, responsible for the success of the entire venture.** The working group needs to be multi-disciplinary, with strong ties to the community or audience for whom the indicators are intended. The working group is most effective when it combines experts and non-experts from the outset, but the critical element is long-term commitment to the process.

2. **Clarify the purpose of the indicator set** — whether it is meant to educate the public, provide background for key policy decisions, or evaluate the success of an initiative or plan. Different purposes give rise to different indicators and publication strategies.

3. **Identify the community's shared values and vision.** The indicator set must be able to speak to the hopes and aspirations of the people it is meant to serve.

4. **Review existing models, indicators, and data.** The working group takes a look at other indicator projects as examples to learn from. It also reviews what indicators are already published locally and what data are generally available.

5. **Draft a set of proposed indicators.** The working group draws on its own knowledge, the examples it has collected, and the advice of outside experts if needed to prepare a first draft. The draft may go through several revisions before it is ready for the next step. In particular, initial indicator sets tend to be very long. In later drafts, they need to be pruned down and made more focused and practicable.

[20] "The Community Indicators Handbook," available for US$20 from Redefining Progress, 1 Kearny Street, 4th Floor, San Francisco CA 94108. Tel.: (415) 781-1191, Fax: (415) 781-1198, Email info@RProgress.org

6. **Convene a participatory selection process.** The draft indicators need to be presented to a broad cross-section of the community for their input. This process serves several important goals. It educates the participants, gathers their collective creativity and expertise, and makes them stakeholders in the success of the project. Often it also gives rise to new relationships and alliances among the participants and can even generate new action initiatives to address problems identified by the indicators.

7. **Perform a technical review.** An interdisciplinary team of knowledgeable people sorts through the proposed final draft indicators and selects for measurability, statistical and systemic relevance, etc., trying to stay true to the intentions and preferences expressed by the citizen review process. The technical review helps to fill in gaps, weed out technical problems, and produce a final indicator set that is ready to be fleshed out with data.

8. **Research the data.** At this stage, the indicators are usually subject to additional revision, driven by data concerns and new learning.

9. **Publish and promote the indicators.** This requires translating them into striking graphics, clear language, and an effective outreach campaign. It helps to link the indicators to the policies and driving forces that affect them, to illustrate their linkages, and to point to the actions that can be taken to improve them.

10. **Update the report regularly.** Indicators make little difference, or indeed little sense, if they are not published periodically to show change over time. This requires an institutional base that can be relied upon to reproduce steps 8. and 9. on a regular basis, and to go back and revisit the other steps as needed. Each new version of an indicator report becomes an opportunity to revise the indicators, develop new research methods, and add linkages. If performance targets have been set, they can be assessed and, if necessary, adjusted. And when targets are met, celebrations can occur!

These steps may sound daunting, but they are being put into practice by hundreds of community- and regional-level indicator movements around the world.[21]

SYSTEMS: MAKING INDICATORS DYNAMIC

Systems insights can help in the design of indicators that identify critical linkages, dynamic tendencies, and leverage points for action.

We should not tackle vast problems with half-vast concepts.

— Preston Cloud

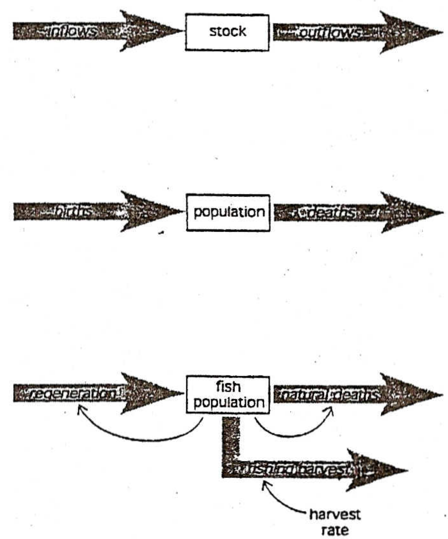
Systems change over time, and it is often exactly their dynamic behavior that we want indicators of sustainable development to tell us about. Is the population or the economy growing more or less rapidly than it used to be? Are

[21] Ibid.; and also P. Hardi and T. Zdan eds., op. cit.

weather patterns becoming more or less variable? For how long can the fish population support this rate of harvest, and what happens if it can't?

System dynamics is a field of expertise that specializes in understanding the unfolding *behavior over time of whole systems*. Therefore it can be useful in finding linkage indicators, leading indicators, and leverage points where systems are especially likely to signal change or respond to action.

This section contains a brief summary of some insights from system dynamics about how to design dynamic indicators.



Distinguish between stocks and flows. Stocks are indicators of the state of a system and its response time. Flows may be leading indicators of change.

Stocks describe the state of the system at any particular time — the amount of biomass in a forest, people in a nation, factories in an economy, money in the bank, water in an aquifer, greenhouse gases in the atmosphere. Stocks are accumulations of the past history of the system. The sources in nature from which raw materials are drawn are primarily stocks. So are the sinks in the environment into which pollutants are poured, or the factories and tools that make up the productive capital of a nation. Stocks are generally the most countable elements of systems, and hence they make obvious indicators.

Stocks are usually slow to change. Even if CFC emissions cease today, the accumulation of chlorine in the stratosphere will take decades to decline. If a new energy source is invented tomorrow, there would be a long delay before existing stocks of cars and furnaces and industrial boilers that burn the old types of energy can be replaced. Therefore the size and lifetimes of stocks can give us useful indicators of **response rates** — how long it will take a system to correct a problem, adjust to a change, or take advantage of a new opportunity.

Suggested dynamic indicators:

Turnover time, which is stock size relative to stock change rate. Especially relevant for understanding the time it takes for aquifers or surface water bodies (or the atmosphere) to flush out pollution, or for the time it takes for industrial capital stocks (such as the automobile fleet) to be replaced.

Coverage time, which is stock size relative to the drain on the stock. Especially relevant to calculate adequacy of supply. Fossil fuel reserve/consumption is an example already given here. Food reserves relative to food consumption (number of days current supplies can cover consumption), or inventory relative to sales rate are other examples. Note always the difference between coverage at steady consumption and coverage at exponentially increasing consumption.

For **leading indicators,** we need to monitor **flows.** Flows are the inputs or outputs (measured per time unit) that increase or decrease stocks. Harvest and growth of trees, births and deaths in the population, construction and depreciation of capital are all flows that change stocks. Flows in turn are driven by other stocks. (Tree harvesting depends on the number of chainsaws and loggers and trucks, as well as on the stock of trees in the forest.)

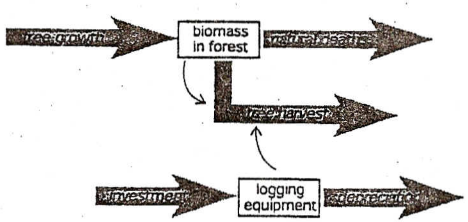
Advance warning comes from the balance of flows affecting a stock. A buildup of greenhouse gases in the atmosphere, for example, is predictable when the rates of emission of those gases begin to exceed their natural rates of recycling or absorption. Deforestation is indicated not when the forest is gone, but when the rate of harvest first exceeds the rate of regrowth.

Suggested dynamic indicators:

Harvest/regeneration, the essential measure of sustainable use of a renewable resource, whether fish, water, forest, soil. If the index is above 1.0, the harvest is not sustainable.

Emission/absorption, where absorption means any process, natural or human-mediated, that renders a pollutant harmless. This is an essential measure of the sustainability of any waste stream, with values above 1.0 indicating unsustainability.

Since some of these flows may be hard to measure directly (regeneration in a forest, absorption in the soil), they can be measured indirectly by changes over time in the relevant stock. *Any resource stock that is falling is being used unsustainably. Any pollution sink that is filling is being used unsustainably.*



The stock-flow orientation is related to the pressure-state orientation common to United Nations and other indicator systems. Stocks are measures of system states. Flows are measures of pressures that change those states.

Exponential growth rates (the strengths of vicious or virtuous cycles) are sensitive points in systems.

A revealing indicator in dynamic systems is the rapidity of exponential growth processes (which systems analysts call **positive feedback loops**). Exponential growth is growth that feeds on itself — the more you have, the more you get. The two most obvious places where that type of growth occurs are population and economic output. In fact, the most basic development indicator is the ratio between the two — the rate of growth of output per capita.

Positive feedback loops drive more than population and economy, however. Teachers teaching more teachers builds up the educational capacity of a nation. Knowledge leads to more knowledge. Natural populations, such as fish or trees, grow exponentially, when they grow at all.

Epidemics proceed through positive feedback loops — more sick people infect more people, who then infect more people. Pest populations can explode exponentially. Desertification and other erosion processes can degrade soil in a vicious downward spiral — fewer trees have fewer roots, which are less able to hold soil against erosion; less soil allows less plant growth, still fewer roots, still more erosion, and so forth. Interest on debt is also a downward exponential spiral, increasing the debt more each year than the year before, unless repayments exceed interest charges.

Whether the cycle is vicious or virtuous, small changes in growth rate can signal large potential changes in the system. For example, a growth rate of 1 percent per year means that over a century the population (or economy) will grow to 2.7 times its present value. A growth rate of 2 percent means that in a century the population or economy will grow by a factor of 7.4. A growth rate of 3 percent over a century will produce a population or economy twenty times its original size!

Suggested dynamic indicators:

Doubling time or halving time. Percent changes are hard to imagine; doubling times are more easily understood. The doubling time of an exponential growth process is 70 divided by the growth rate. So a city growing at 7% per year will double in 10 years (and double *again* in another 10 years, if that growth rate continues). A population growing at 3.5% per year will double in 20 years. An agricultural yield going up by 2% per year will double in 35 years.

Similarly, halving times of entities that are decreasing exponentially are 70 divided by the decrease rate. A forest being cut by 3.5% per year will be half gone in 20 years. Soil eroding at 1% per year will be half gone in 70 years. A fossil fuel resource being consumed at 7% per year will be half gone in 10 years.

(Calculating doubling or halving times does not imply that an exponential growth rate *will continue unchanged* over any future period. The point of a doubling or halving time calculation is usually to point out that it can't or shouldn't!)

Exponential growth against a limiting resource. A powerful way to communicate the implications of an exponential growth process is to relate it to a fixed or limiting resource — to show the exponentially shrinking resource per capita. For example, Hawaiians understood the implications of exponential population growth, when they started plotting over time the *miles of beach per person.* China took population growth seriously when it extrapolated figures for *cultivable land and available water per person.* Many cities would be shocked to plot over time their *miles of road per car.*

The ratio of change rate to response rate is a critical — and usually critically missing — indicator of the degree to which a system can be controlled.

Rates of change around positive feedback loops are even more useful indicators when they are combined with information about possible response times. *In fact, the combination of the two — change rate compared with response rate — makes an indicator of the controllability of the system.*

During the 1970s, the production of CFCs in the world was growing by about 7 percent per year. That makes a doubling time of 10 years. It takes a CFC molecule ten to fifteen years to rise from the earth's surface up to the stratosphere, where it breaks apart and starts destroying the ozone layer. Given that growth rate and that lag, *the problem doubled before it could even be measured.*

Clearly a system that is changing faster than anyone can know or react is a system that cannot be managed, controlled, or protected against damage. The concept of change/response as a measure of system safety has been highly developed in the field of

nuclear engineering. The time it takes for a nuclear reactor to "go critical" and reach an irreversible rate of neutron generation (in other words an explosion) is called the **respite time.** The **response time** is the time it takes for operators to notice a problem, track down its source, and mobilize control rods to absorb and slow down neutrons. A reactor with a response time longer than its respite time is inherently unsafe.[22]

So is any system in which problems are generated faster than they can be responded to. Even if technologies are powerful, even if financial resources and political will can be summoned, if a problem comes on faster than technologies, money, or will can take effect, that problem will be unsolvable. The situation will be equivalent to driving a car too fast — though the brakes may function perfectly, obstacles can't be seen in time to stop.

Therefore a powerful warning indicator can be created from the *rate of increase of a problem divided by response rate.* This ratio could be measured as rate of change in percent per year divided by rate of response in percent per year, an index that gets critical as it approaches 1.0. Or, if, as in the ozone case, the problem is a discrete lag in detection or response, the ratio could be measured as **response time/respite time.**

Such an indicator could be applied, for example, to:

- the depletion time of any resource relative to the time to develop a substitute;
- the rising educational needs of a growing population relative to the rate of training teachers and building schools;
- the spread of pesticide resistance relative to the time to develop a new pesticide;
- the doubling time of greenhouse gas emissions relative to the response lags in the climate system that allows climate change to be detected;
- population growth in a city relative to the rate at which the city can add infrastructure to handle sewage, garbage, or traffic.

Any system in which the rate of growth of a problem is significantly faster than the rate of response is, quite simply, out of control. There are only two ways to bring it back into the realm of manageability: either quicken the response rate (if possible) or slow the growth rate of the problem (or both).

The concept of respite time versus response time is new to many managers and missing from most indicator sets — and obviously critical to any hope of achieving a sustainable society.

[22] The respite time/response time indicator was suggested to us by Wouter Biesiot and the staff of the Center for Energy and Environmental Studies, University of Groningen, the Netherlands, November 1995, draft prepared for our workshop.

Watch for unbalanced or missing control loops.

Complex systems, whether natural or human-designed, are managed through control loops (negative feedback loops in systems terms) that monitor the state of a system and act to keep it in balance. A common example is the thermostat. When the temperature in a room falls, the thermostat switches on the furnace, causing the temperature to rise again. When the temperature rises, the furnace is switched off. Other common control loops maintain blood sugar level in the body, keep a plane flying in its intended direction, and adjust prices to equilibrate supply and demand in an economy.

When systems behave pathologically, it is often because balancing negative feedback loops are weak or missing. Overfishing is almost inevitable, if there is no system for regulating the catch depending on how many fish there are. Forests may be cut down uneconomically if those doing the cutting are not assessed the value of the services provided by standing trees (such as flood protection or carbon sequestration). Rivers are easily polluted if there is no way downstream populations can regulate or claim damages from upstream polluters. Those are all examples of **missing indicators,** which, once they are restored, will supply the necessary control loops to allow a system to adjust itself automatically.

The famous dilemma of "the tragedy of the commons" is an example of missing feedback control when there is a common resource and no price or penalty for use of the resource short of its exhaustion.[23]

[23] G. Hardin, "The Tragedy of the Commons," *Science* 362, no. 3858 (December 1968): 1243-48.

Examples of indicators and enforcement systems to supply missing feedback control:

A warning light on pumps taking groundwater from an aquifer, to indicate whether the aquifer is filling (green), stable (yellow), or falling (red). Ideally the cost of the water would rise steeply as the light turns red.

A meter on the dashboards of cars, showing the instantaneous rate of fuel consumption (measured in money expended) — which would give drivers feedback on more and less wasteful driving habits.

A permit system for boats in a fishery, cutting the allowed number of boats or fishing days if the fish population falls.

Required stickers (purchased from the municipality) on municipally collected garbage, so that people who generate more trash have to pay more for its disposal.

Emission quotas for large-scale pollutants such as sulfur dioxide or carbon dioxide, the total amount to be determined upon biophysical sustainability grounds, to be auctioned off regularly to the highest bidders. (Such a system would put a price on the commons of clean air and would allow the market to distribute efficiently the right to pollute. It would also provide a control mechanism to keep total pollution within health and safety guidelines.)

Notice that in the above systems, the indicator gains real force when it is coupled with a fee or regulatory system.

An important indicator of the resilience of a system is the redundancy of its controlling negative feedback loops.

When an ecosystem loses species, it may lose control mechanisms by which predators and prey keep their relative populations in balance. When a village loses access to lands from which it supplemented its food supply in times of famine, it has lost an element of emergency self-maintenance. Resilience is lost when family members are geographically scattered, or when a watershed loses wetlands that absorb floodwaters, or when a nation becomes dependent upon a single, imported source of energy, or when a government fixes a price so it can't respond to supply and demand, or when a body's immune system is compromised.

Removing or weakening feedback loops that provide resilience is equivalent to removing the fire detectors and sprinkler systems in a building, or the emergency cooling systems of a nuclear power plant, or the health care capacity of a society, or the insurance policies from a business. Resilience can be stripped away from a system without immediate cost (actually saving cost) and without affecting the functioning of the system, until a crisis comes that demands that resilience. At that point the cost can be tremendous.

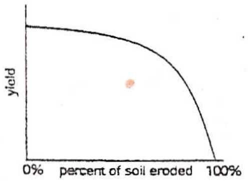
You can see why it is important to sustainable development to have indicators that measure resilience. If immediate operating cost is the only indicator, there can be great temptations to remove resilience or let it deteriorate in order to realize short-term cost-saving.

Resilience is not commonly or easily measured; it will take some creativity to invent good indicators here.

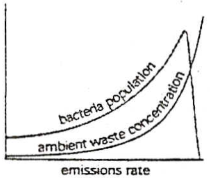
The only specific suggestion I can think of here is to use a concept familiar to most economic-minded persons: insurance. There must be simple indicators that calculate for an enterprise how much is being expended on insurance and how adequate that insurance is. (Companies willing to cut corners in all others areas rarely seem to stint on buying insurance.) Could that concept be extended to families? Communities? Ecosystems? Planetary geophysical flows?

Nonlinearities in systems (turning points, thresholds) are key points for the placement of indicators.

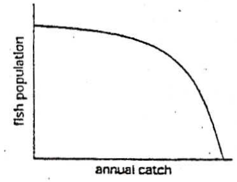
You can erode the soil right down to the depth of crop roots without much impact, but erode it a little past that point, and crop yields plummet:



You can emit nutrients into a stream and natural bacteria will clean them up, but if you emit too much too fast, the natural biota may be killed off, and the stream turned into a sewer where wastes pile up without amelioration:



You can catch fish and open up ecological space for immigration or reproduction of more fish — up to a point, after which the diminished population may be unable to breed or may be open to competitors, at which point it plummets:



Turning points like these mark thresholds beyond which the behavior of a system changes radically, sometimes irreversibly. Clearly we need indicators that signal them well in advance. These "distance from the edge" indicators are like radar warning a ship or plane of an obstacle ahead. The faster the ship or plane (or economy) is moving, the farther ahead they have to look, to allow sufficient braking or turning time. (Back to the change rate/response rate discussion!)

Suggested dynamic indicators:

Time to turning or irreversibility point. If the threshold or nonlinearity is well understood, the time to reach it, given current rate of approach, should be calculable.

Degree of risk. If the threshold is not well understood, which is often the case (how many species can you take out of an ecosystem before it collapses? how far down can you bring the fish population before it no longer can restore itself? how much money can you allow private persons to give to elected officials before all trust in democratic government is gone? how many greenhouse gases can you put into the atmosphere before you derail massive ocean currents?), the challenge is to design indicators that convey the degree of risk. One possibility is to deliver information about the full range of estimates (as the IPCC scientists have done painstakingly in communicating about climate change). Even when the uncertainties are great, considered guesses are better than no information at all.

A primary indicator of the long-term viability of a system is its evolutionary potential.

The resilience of a system is its ability to recover and repair itself from shocks. Short-term resilience depends on adequate controlling negative feedback loops, as discussed above. Long-term resilience depends on the evolutionary potential of a system — its ability to adapt to new conditions, to create new species, structures, technologies, or ideas — to evolve.

The most important reason why biological diversity should be preserved is because the gene pool is nature's raw material for evolution. For human societies, evolutionary potential lies in technology, knowledge, the variety of organizations in the civil society, foresight, tolerance, and the mental and social flexibility to be open to new ideas, to test them quickly, to select the ones that apply best under present and impending future conditions, and to evolve new ideas and institutions.

To measure sustainability, we need indicators of the potential for evolutionary change. These have to do with diversity, tolerance, ingenuity, open-mindedness, education, and truth-telling about the success or failure of experiments.

Possible indicators:

Ecological evolutionary potential might be measured by the rate of disappearance of species relative to the number of species originally there (equivalent to the rate of disappearance of books or journals in a library).

Technological evolutionary potential might be approximated by scientists per capita, basic research expenditures per capita, inventions or scientific prizes per capita (though the latter is a lagging indicator, reflecting the training of the past generation, not coming ones.) A better measure than any of the above would get more directly at creativity, originality, quickness of problem-solving, elegance and ingenuity of solutions. (Percent of high-school students working on solar cars? Truly original inventions patented per capita? Number of startup companies based on completely new concepts? Average length of time major technical problems persist before they are solved?)

Cultural evolutionary potential might be captured in the number of different races, cultures, religions that live together *in peace* within a given geographic area. A leading indicator of the breakdown of this potential might be the frequency of ethnic or cultural hate-talk in the public media, especially when it comes from public leaders. (Monitoring this indicator would have provided early warning of the development of the fascist regimes in Europe in the 1930s and the breakdown of Yugoslavia in the 1990s.)

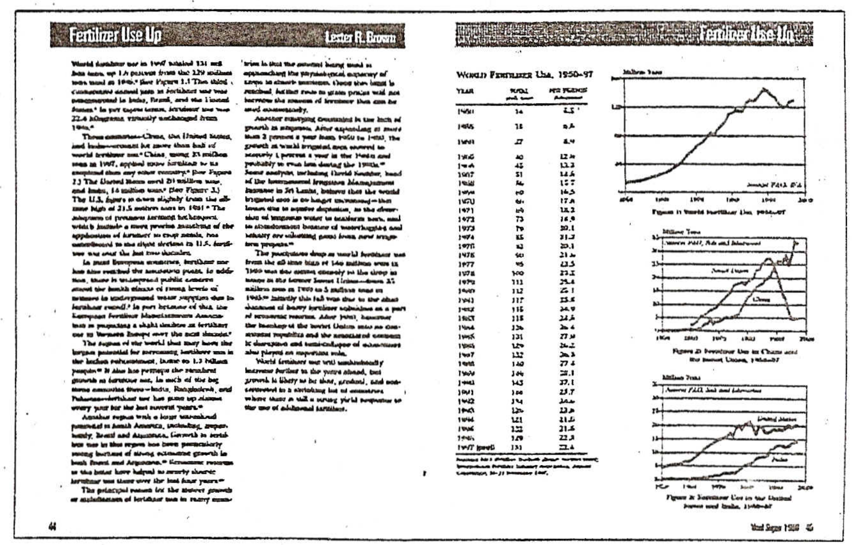
Wherever possible, indicators should be reported as time graphs rather than static numbers.

Time graphs show not only the present state of an indicator, but its trend over time — improving, declining, fluctuating, becoming more or less unstable. It's not really possible to understand an indicator unless one knows its dynamics. It is often especially illuminating to compare one time trend with another on the same graph and same scale.

Worldwatch Institute in its annual report *Vital Signs* devotes a two-page spread to each of its indicators (see below). One page is explanatory text, the other shows the development of that indicator over time, both as a table of raw data and as a time graph. Other graphs on the page may disaggregate the indicator to show its constituent parts or provide some other illuminating information.[24]

This is an economical way to communicate a great deal of information to a wide audience, and especially to give that audience a grasp of the history and potential future of each indicator.

[24] L. R. Brown et al., *Vital Signs 1998*. New York: W. W. Norton & Company, 1998, pp. 44-45.


Fertilizer Use Up
Lester R. Brown
World Fertilizer Use, 1950-97
44
Vital Signs 1998 45

Indicators should be combined with formal dynamic modeling.

Most of the indicators mentioned in this section are potentially powerful, but not easy to define or understand unless they are accompanied by a dynamic model that can help, for example, spin out the future consequences of present exponential growth rates, or calculate the ability of control loops to stabilize a system.

Models of this type are already being used to help understand climate change, fish population dynamics, changes in the stratospheric ozone layer, demographic developments in populations, and macro-economic growth.[25] The co-development of indicators and dynamic models can help not only to identify trouble spots in the system, but can help test, gauge, and time corrective actions.

Action will be taken on the basis of models in any case, mental models or formal models. The search for indicators is a search for better models, ideally dynamic models that can help us understand the timing of problems and solutions.

[25] The literature is vast. For a start, see any issue of the *System Dynamics Journal* or the following websites: http://web.mit.edu/jsterman/www/DID.html; http://home.earthlink.net/~tomfid/sdbookmarks.html; http://sysdyn.mit.edu/road-maps/rm-toc.html