STATISTICAL MEASURES OF UNSUSTAINABILITY

by

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95/84/EPS
(Revised Version of 95/72/EPS)

This working paper was published in the context of INSEAD's Centre for the Management of Environmental Resources, an R&D partnership sponsored by Ciba-Geigy, Danfoss, Otto Group and Royal Dutch/Shell and Sandoz AG.

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Abstract

Statistical measures are needed to reveal at a glance how far (or near) various countries are to meeting the conditions of long run sustainability, and how conditions are changing on a year to year basis (i.e. whether sustainability is being approached or not). The scheme proposed in this paper presents numerical comparisons of energy and materials use in the real world *vis a vis* an ideal case where all of the identifiable criteria for sustainability are satisfied. Apart from population stabilization, five general but quantifiable criteria for sustainability are suggested, including (1) stabilization of greenhouse gas concentrations in the atmosphere, (2) stabilization of acidity (pH) in rainfall, (3) reduction of dissipative uses, and wastes, of heavy metals to natural mobilization rates, or lower, (4) elimination of agriculture based on pumping "fossil" water from non-renewable aquifers and (5) elimination of loss of arable land because of salination or erosion. Other criteria, such as preservation of biodiversity and socio-economic equity between countries and generations might be added to the list. They introduce more difficult measurement problems, however, which are not considered further in the paper.

Having fixed the list of criteria, the next step is to identify measures that either go to zero or unity, as the system approaches more and more closely to sustainability, at least in the limited sense defined above. Various types of measures of sustainability/unsustainability can be developed, viz. (i) measures of relative **dependence** of the economy on non-renewable sources of energy and materials, (ii) measures of the **productivity** of energy and materials consumed by the economic system and (iii) measures of **dissipative loss**, especially of toxic and hazardous substances. Specific examples of each type are discussed.

1. Introduction: Criteria for sustainability

Until the last decade, many discussions of long-term economic sustainability focussed on physical resource availability. There was a long-running, if not particularly enlightening, debate between "neo-malthusians" and "cornucopians".[1] The neo-malthusians tended to assert that economic growth cannot continue for lack of (exhaustible) resources, while some cornucopians went so far as to claim that, thanks to technological progress, there are no effective limits on economic growth at all. The arguments *pro* and *con* need not be recapitulated here. Suffice it to say that a sort of consensus has now been reached on two points. The first is that economic growth has a higher priority for most of the world than environmental protection. The second point of consensus is that "growth versus environment"

1. For a review see [Ayres 1993].

is probably a false dichotomy, inasmuch as the availability of physical inputs to the productive process appears to be less immediate than had been previously thought by some. These two realizations have led to the notion of "sustainable growth" as a political goal [Brundtland *et al* 1987].

It is not at all clear, however, whether sustainable growth is a feasible goal, either technically or politically. The political and institutional problems involved are far beyond the scope of this paper. What many environmentalists today suspect, however, is that the trends are unfavorable. The limiting factors are less a question of mineral resource availability than scarcity of renewable resources such as forests, topsoil and groundwater, and excessive anthropogenic pressure — or stress — on environmental systems. This pressure arises from several causes, including the conversion of complex natural ecosystems into unstable, artificially simplified and managed systems for producing food and fuel (with the threat of collapse if a new disease organism should appear suddenly) and consequent destruction of habitats for many wild species.

But the single most important impact of human economic activity is excessive and inadequately controlled emissions of chemically or physically active wastes and toxic materials, both from industrial processes and "final" consumption. These residuals inevitably disturb natural systems that had evolved over millions, even billions, of years. The emission of waste residuals, in turn, is closely connected with recycling/re-use efficiency of materials, including fuels. A good general measure of potential environmental *pressure (or stress)* is the loss and dissipation of substances that can cause environmental harm after being released. A detailed catalog of such substances is not needed here. It can even be argued that any material that is released into an environment where it was not previously present, or was present in lesser amounts, is a potentially disturbing element.[2] However, it is obvious that some waste residuals are especially disturbing to environmental systems, including combustion products, CFC's, toxic heavy metals, and pesticides.

From an economic perspective, this raises the distinction between *inherently dissipative* uses[3] and uses where the material could be recycled or re-used, in principle, but is not. The latter could be termed *potentially recyclable*. Thus, there are really three important cases: (1) uses that are economically and technologically compatible with recycling under present prices and regulations, (2) uses that are not economically compatible with recycling but where recycling is technically feasible e.g. if the collection problem were solved, and (3) uses where recycling is inherently not feasible. These points are discussed later.

As regards environmental loading, there is a clear need for quantitative measures of the "distance" of the environment from a hypothetical state of long term sustainability. The argument of this paper proceeds from several assumptions which must now be made explicit. In the first place, there is a considerable controversy over the appropriate definition of sustainability. There has been much academic debate on the exact meaning that should be ascribed to the term 'sustainability'. Tietenberg suggests that sustainability means "future generations remain at least as well off as current generations" [Tietenberg 1984 p.33]. In more

2. There are technical grounds for arguing that the most general measure of the potential environmental harm that can be caused by an emitted substance is the "exergy" content of the residual, or the potential increase of entropy that results when that material finally reaches a new chemical and physical equilibrium with its environment. See [Ayres & Martinàs 1995].

3. The formal distinction between dissipative and structural uses was first introduced in the economics literature nearly two decades ago [Ayres 1978], but the first comprehensive attempt to catalog and quantify such uses did not occur until very recently [Rogich *et al* 1992].

formal language, the above formulation implies that sustainability means "non-declining utility". Repetto states, in the same vein, that "current decisions should not impair the prospects for maintaining or improving future living standards" [Repetto 1985 p.16]. The World Commission on Environment and Development suggests, in the same vein, that sustainable development "meets the needs of the present without compromising the ability of future generations to meet their own needs" [Brundtland *et al* 1987]. Pearce *et al* and Stavins have collected a number of other definitions in the literature [Pearce *et al* 1989]].

Apart from being unsatisfactory from the standpoint of reflecting non-economic elements of sustainability, these definitions share another common feature: they are unquantifiable and, (absent quantitative measures), unverifiable. Some are sufficiently vague as to permit contradictory conclusions as to whether, or not, the conditions for sustainability are being met in any particular case. This permits — perhaps, indeed, encourages — perverse interpretations of sustainability to justify continued business-as-usual by business, governments and even the World Bank.

There is a considerable disagreement among economists with respect to the extent to which environmental assets can be sacrificed to economic objectives within the general criterion of sustainability. Most economists have tended to assume (at least implicitly) that all environmental and economic goods and services are effectively substitutable, and that economic measures of welfare (e.g. GNP) are sufficient[4]. However, the more traditional approach, as noted above, assumes essentially complete substitutability of both inputs and outputs, at some price. In other words, it assumes that capital, labor, land and other economic factors of production are substitutable for each other, effectively without limit. Similarly, it assumes that man-made goods and services are possible substitutes for environmental services [e.g. Solow 1986, 1992; Dasgupta & Måler 1990]. Solow proposed that "an appropriate stock of capital — including the initial endowment of resources — (be) maintained intact" [op cit 1986], but he assumes that technological and natural capital are complete substitutes; only a few natural or cultural artifacts (e.g. the Grand Canyon, Yosemite, Chartres Cathedral, the Taj Mahal) can be regarded as unique and non-substitutable.

Some economists have recently acknowledged what seems obvious to many non-economists: that man-made capital is not always substitutable for natural capital. Nor can man-made services, regardless of price, always replace the services provided by nature [Ayres 1978 p. 6]. Similar ideas have been articulated more recently and comprehensively in writings by Pearce and his colleagues [Pearce 1988; Barbier & Markandya 1989; Pearce *et al* 1989]. In this "ecological perspective", a separate and necessary (but not sufficient) condition for sustainability is the maintenance of an adequate "environmental resource endowment". This endowment constitutes the environmental assets necessary to provide needed and wanted environmental services. The most critical environmental services include the basic conditions of life-support on the earth, namely climate stabilization (temperature, rainfall, etc), food supply (the `food chain'), and biological waste disposal and materials recycling. It is noteworthy that climate, the ozone layer, the carbon-oxygen cycle, the balance between alkalinity and acidity, mature forests, soil fertility and bio-diversity are not technologically

4. The inadequacy of GNP as a unique measure of social welfare is well known. However, most economists regard the omissions and double-countings as being sufficiently minor in quantitative importance to justify their continued neglect. However, the justifications for continuing to use the present version of GNP are much more robust in the context of making short-term performance comparisons than they are in the context of assessing long-term problems. This is one of the other reasons for restructuring the SNA and incorporating environmental elements explicitly.

replaceable by other forms of capital. Nor are some kinds of damage reparable, by any conceivable human intervention, at least for the planet as a whole[5].

I have argued elsewhere at greater length that a necessary (if not sufficient) condition for sustainability in the long run implies that several specific physical criteria must be satisfied, in addition to the obvious pre-condition of population stabilization. These conditions include the following [e.g. Ayres 1991, 1993-a, 1993-b]:

I. No further (anthropogenic) change in the climate, which implies stabilization of greenhouse gas concentrations in the atmosphere.

II. Stabilization (no further net increase) in the acidity (pH) of rainfall — and especially the fresh water lakes and rivers and forest soils — beyond some uncertain safety limit.

III. No further net mobilization or accumulation of toxic heavy metals, radioactive isotopes, or long-lived halogenated chemicals in soils or sediments, beyond some uncertain multiple of natural levels. This implies an end to virtually all dissipative uses of scarce metals and most other extractive resources i.e. closing the materials cycle.

IV. No further net withdrawal of fossil groundwater in arid regions.

V. No further net loss of topsoil by wind or water erosion, beyond the rate of natural soil formation. (This implies a radical change in agricultural practices, worldwide.)

Also, we could add

VI. No further net loss of estuarine zones, wetlands, old-growth forest or biological diversity, among other biological resources, beyond some (undetermined) limit of safety. A closely related criterion would be to limit the use of monocultural practices in agriculture and especially the use of artificial fertilizers and artificial means of controlling pathogens.

Measures of the extent to which condition VI above are being met, or violated, clearly belong in any theoretical measure of sustainability/unsustainability. However, the answer to this question is not directly accessible through economic data; only direct measurement of (many) environmental parameters can yield appropriate indicators. At a minimum, "model" relationships between them (and others, such as biodiversity and ecological stability, reflecting the state of the biosphere) and human actions such as agriculture and industrial production

5. For instance, there is no known (or imaginable) way of removing "greenhouse gases" from the atmosphere. There is no known or conceivable technology for replacing lost topsoil or recharging depleted "fossil" groundwater aquifers. There is no known or conceivable technology for removing toxic or radio-active elements from soil or ground water on a large scale. Similarly, sewage and industrial wastewater treatment generates residual sludges that are increasingly contaminated by viruses, toxic chemicals and heavy metals. No technology exists for decontaminating such sludges. (They are simply dumped in land-fills). Finally, there is no conceivable technology for recreating extinct species — notwithstanding the fictional recreations in Michael Crichton's "Jurassic Park")

would have to be established and quantified. This topic will not be considered further in this paper, for lack of space.

2. Economic implications of sustainability

The first five conditions for sustainability listed above can be linked in a relatively straightforward manner to economic variables and, potentially at least, to standard accounting categories. Let us consider them in order.

Criterion (I), climatic stability, has been the subject of intensive research for many decades. One the one hand, climatic conditions, including temperature, are directly measured and have been for a long time. Hence there is a large data base for constructing and verifying physical climate models. Based on this research, it is known that the mean temperature of the earth is determined by the radiation balance. This is controlled by changes in the atmospheric concentration of several so-called "greenhouse" gases, namely carbon dioxide, methane, nitrous oxide, and CFC's. One cannot avoid the conclusion that climatic stabilization means no further accumulation of greenhouse gases in the atmosphere beyond some limit of safety (to be determined).

Concentrations of these gases, in turn, depend on emission rates and lifetimes. Current emissions of carbon dioxide are largely attributable to — in fact, proportional — the use of fossil fuels. Methane is from various sources, including coal mining, gas flaring, gas distribution, wet rice cultivation, cattle, sheep, swamps and termites. All but the last two are essentially anthropogenic, being either energy-related or agriculture-related. As such, emissions can be approximately related to certain economic variables. Nitrous oxide, too, arises from several sources, notably the denitrification of nitrogen-based fertilizers, explosives, and the manufacture of nylon. CFC's, implicated in the destruction of stratospheric ozone as well as climate warming, are industrial products used for refrigeration, air-conditioning and as solvents.

It is possible to relate emission rates, at least approximately, to economic activity levels. An obvious implication of the above (though seldom acknowledged) is that it will be necessary to curtail fossil fuel use and the general use of synthetic nitrogenous fertilizers, as well as phasing out chlorofluorocarbons (CFC's), as already agreed in the Montreal Protocol. It follows, also, that possible measures of unsustainability include (i) anthropogenic CO_2 emissions in relation to natural CO_2 generation, (ii) the relative importance of fossil fuels (i.e. hydrocarbons) among all energy sources, (iii) anthropogenic N-fixation in relation to natural N-fixation, and (iv) absolute production of CFC's (since there are no known natural sources).

Criterion (II), ending cumulative environmental acidification, means ending the imbalance between natural rates of soil weathering and current levels of acid deposition.[6] This depends on the rate of emissions of sulfur and nitrogen oxides (SO_X and NO_X) into the atmosphere. These gases tend to oxidize further in the atmosphere and react with water to produce the corresponding sulfuric and nitric acids, especially in regions where soils have little or no buffering capacity (i.e. natural alkalinity). Again, it is possible to measure acidity (pH) in rainwater, and in lakes, by straightforward physical means. Thus the trends are easily documented, and there is a wealth of physical data with which to calibrate physical models.

6. Actually, what is measured is hydrogen-ion (H+) concentration.

By the same token, the rate of emission of sulfur oxides into the atmosphere is mostly proportional to the quantity of fossil fuel (especially coal) combustion, and the sulfur content of the fuel. These are well-known economic variables. There is also a modest contribution from other industrial activity, e.g. sulfuric acid production. In the case of nitrogen oxides, the relationship is slightly less straightforward, since nitrogen oxide is largely produced in the flame itself and depends on the combustion temperature and fuel-air mix. However, it is known that most NO_X arises from electric power generating plants and internal combustion engines. Again, these are familiar economic variables.

The economic implications of the above facts are not quite as clear as in the case of condition (I), since there is considerable scope for "end-of-pipe" treatment of the products of combustion, both SO_X and NO_X. In principle, sulfur dioxide can be removed from flue gases, and even recovered for industrial use as sulfuric acid, or as elemental sulfur (depending on the waste treatment and recovery process). Indeed, a large fraction of industrial sulfur is already obtained from natural gas processing or petroleum refining. It is a natural extension of this trend to recover sulfur from coal, either by coal gasification (and desulfurization) prior to combustion, or by post-combustion flue gas desulfurization (FGD). Corresponding measures of unsustainability might include (i) the fraction of total fuel sulfur that is *not* recovered for industrial use., and (ii) the total quantity of anthropogenic SO_X emissions in relation to total natural emissions of volatile sulfur-containing gases. In the case of NO_X it would be helpful to know (iii) the total quantity of anthropogenic emissions in relation to natural sources.[7]

Criterion (III) requires an end to environmental toxification. The buildup of toxics is the direct consequence of pollution and dissipative uses of toxic chemicals, especially heavy metals and some halocarbons, but also a number of other substances. Here the mode of environmental release — whether to air, water or land — is important, but in a very broad sense it is clear that release corresponds to use. Every material extracted from the environment is a future waste, and the period during which the material is actually performing a useful function in the economy tends to be rather short, except in the case of structural materials. The latter are generally not toxic.

Measures of unsustainability, in this case, would be toxic emissions (in environmentally mobile form) as compared with rates of mobilization of the same elements or compounds by natural processes. The environmental mobility of a toxic substance depends on the physico—chemical form in which it is emitted, and on the details of its subsequent metabolic history. This information is only partially available, and only for a few substances, so a general form of unsustainability measure for "toxification" cannot be stated. However, some special cases will be discussed hereafter.

As indicated above, the first three listed conditions for sustainability essentially require the curtailment, if not elimination, of most non-renewable energy sources[8] and many dissipative uses of toxic heavy metals and halogenated organic chemicals. Hence, the degree

7. Although there is some "fuel-bound" nitrogen in coal that can be converted to NO_X in a hot flame, in the presence of excess oxygen, this appears to be an insignificant overall source of NO_X. For the most part, it is the nitrogen in the air itself that is oxidized.

8. This restriction may, or may not, apply to fission-based nuclear power, due its dependence on highly toxic and hazardous heavy metals. It depends on whether the nuclear waste disposal problem can be solved in a satisfactory manner. The jury is still out on this question. The case of fusion power is difficult to evaluate at present.

of economic dependence on such materials is one key generic indicator of its "distance" from long-run sustainability. Another such measure is the efficiency with which the economic system recovers and reconditions used goods and recycles waste materials, especially those utilizing heavy metals and persistent, bio-accumulative halocarbons.

Criterion IV means ending the unsustainable use of fossil ground water. This use corresponds rather closely to irrigation from deep wells where there is no underground water flow. Unfortunately, a significant part of the western U.S., along with many other parts of the world, is not self sustaining with regard to water.

Criterion V, ending topsoil loss (beyond the natural replacement rate), by erosion or salination, is one of the most difficult to meet, and to measure directly. The silt loads of large rivers and the rate of siltation of man-made reservoirs constitute perhaps the most direct measure of topsoil loss. However, if the soil no-loss condition were met there would be no reason (other than water scarcity) for arable land to be abandoned. Thus, a possible indirect surrogate measure would be the amount of formerly arable land that has been removed from cultivation. (Land used for highway construction or housing is also permanently lost to cultivation, and should be recorded independently in the statistics.)

3. Measures for climatic sustainability (criterion I)

As noted already in the previous section, the condition for maintaining climatic stability implies stability of the carbon cycle and the nitrogen cycle. The first of these is closely related to energy consumption and fuel use; the second is related to agricultural activity, and the use of synthetic fertilizers in particular.

Consider possible energy-related measures, in greater detail. The starting point is the gross energy consumption data for non-renewable hydrocarbon-based fuels (X_{hc}). These are coal, lignite, petroleum, gas) plus nuclear fuel. Data on fuel production and use is normally compiled by governments in terms of standard energy units, which are the product of total quantity produced (or consumed) multiplied by the measured heat-of-combustion of each type of fuel. For our purposes. it is also useful to know the carbon-content and (for later use) the sulfur content of each fuel. Thus the total carbon emissions (as CO_2) from burning carbonaceous fuels is the total quantity of fuel consumed, by type, times the total carbon content of each type. Exactly the same sort of calculation can be done to estimate sulfur emissions (as SO_2).

For renewable carbon-based fuels, the problem is slightly more complicated by problems of incomparability. First of all, data on biomass (e.g. wood) burned for heating, cooking or electric power generation (e.g. in the paper industry) are not normally obtainable through the same administrative channels as data on commercial fossil fuels. It must be obtained from special surveys or by indirect means.[9] The energy content of renewables X_c is presented in terms of potential heat of combustion, as is the case with other fuels. Second, the carbon-content of renewables may — or may not — be actually compensated by natural growth of replacement biomass. The term "renewable" implies only that when biomass is burned, releasing carbon dioxide into the atmosphere, the carbon *may* be taken up by photosynthesis

9. In the case of the U.S. renewable sources of energy were not separately included in official statistics between 1960 and 1975.

and reconverted back into biomass by other growing plants. On the other hand, the high rate of deforestation in the world implies that this is not actually happening.

For the special case of nuclear fuel, only electric power actually generated is directly measured. To compare with heat of combustion of fuels, it is usual to calculate the nuclear heat generated in the reactors, based on steam temperature in the generators. The sum total of all non-carbon thermal inputs (X_{nc}) is the sum of the combustion and nuclear components. In the case of hydro-electricity, as with nuclear electricity, only the electrical output is normally published. However, for consistency and comparability the potential energy theoretically available from the falling or moving water should be given. This can be done, at least approximately, by working back from outputs to inputs on the basis of known or estimated conversion efficiency data. In practice, however, it is more usual to assume that hydraulic energy conversion efficiency is the same as thermal energy conversion efficiency, and impute a hydraulic "equivalent" on that basis. The same thing can be done for wind power plants or geothermal power plants. The analogous procedure can also be used for photovoltaic cells, when the latter become a significant source of energy for society.

The sum of all of these energy inputs

$$X_{hc} + X_c + X_{nc} = T$$

is the total thermal energy produced (and consumed) by the country, T. Let the renewable inputs R be defined as

$$X_c + X_{nc} = R$$

From the same underlying data, by a similar calculation summing over fuels, one can estimate (quite accurately) the total potential carbon (C) and sulfur (S) emissions, viz.

$$\sum a_c X_{hc} = C$$
$$\sum a_c X_{hc} = S$$

where a_c is a coefficients reflecting the actual carbon content of fuels. The composite coefficient a_s is the product of sulfur content times the fraction not recovered for use, or for permanent disposal. The total carbon emissions C must be adjusted slightly downward to allow for the fact that some fuel carbon (e.g. in asphalt or plastics) is sequestered for a period of time in use, whence current emissions arise from material sequestered in the past when total production levels were lower than they are now. An upward adjustment is needed, on the other hand, because there are several chemical processes, notably the manufacture of lime and cement, that release carbon dioxide from carbonates. These corrections are both quantitatively small. The total sulfur emissions S (as SO_X) must also be adjusted upward to reflect a few other processes, notably the production of sulfuric acid from elemental sulfur and the burning of tires (which are about 1% sulfur). However, the corrections here, too, are small.

It is possible to derive several measures of interest from these statistics alone. The first is the ratio of renewable primary energy sources R to total thermal energy consumed T, year by year. The greater the ratio R/T, the less energy inputs are obtained from non-renewable sources, the more nearly sustainable the society is likely to be. If the trend is increasing, the society is becoming more sustainable (in energy terms) and conversely. In a fully sustainable economy, in the very long run, one would expect $R/T = 1$.

Another interesting measure is the fraction f_E of primary thermal energy resources being used to generate electricity. Let primary inputs to electricity production be denoted P and electricity output (in energy units) be denoted E. In symbolic form:

$$f_E = P/T$$

If this fraction is growing over time, it implies that electricity accounts for an increasing proportion of final energy use, whereas direct fuel usage (for space heating or for powering prime movers) accounts for a decreasing proportion. Since electricity is the most convenient form of energy, as well as being "non-polluting" (at the point of use) it is generally expected that this fraction will gradually increase over time in the future, as it has already done for a number of decades. Thus, in the long run, electric heat pumps are expected to replace most forms of direct heating (also in industry), while electric vehicles and electric trams or trains may claim an increasing share of urban transportation (as urbanization, itself, increases). It is not absolutely clear *a priori* that these trends coincide with increasing sustainability. But they are certainly consistent with reduced dependence on fossil fuel combustion, except under the most efficient and controllable conditions.

A final energy-related measure is the efficiency e_E of thermal electric power generation, where

$$e_E = E/P$$

The ratio of E/P is the average efficiency of electricity production, in physical terms. But it is also a surrogate measure of the productivity of fuel resources. This measure rose rapidly in the early years of this century, but it has levelled off in recent decades. This probably reflects the fact that thermal electric power generation is a mature technology, approaching its physical limits.[10]

As it happens, T, E and e_E are all well-known quantities (and e_E is relatively constant) whereas P is seldom given explicitly. However, from the foregoing relationships it follows that

$$P = E/e_E$$

and, therefore,

$$f_E = E/(e_E T)$$

Table I below shows U.S. energy data organized to produce the above non-global measures. *Table II* exhibits the three derived measures. Thermal efficiency (E/P) is actually given in *Table I*, while R/T and P/T are calculated from the R, T and P rows of *Table I*. The various trends from *Table II* are plotted in *Figure 1*.

10. The apparent average efficiency of thermal electric power generation (around 34%) underestimates the actual thermodynamic efficiency currently being obtained, since it also reflects mechanical losses in the turbo-generators and resistance losses in the electric poser distribution system. State of the art steam generators today achieve around 48% thermodynamic efficiency, which is very close to the theoretical maximum that can be achieved without raising the temperature of the steam. The latter would require new turbine blade materials that are not currently practicable. In short, further improvements in efficiency will be very costly.

4. Measures of acidification and toxification (criteria II & III)

Based on the discussion in Section 1, there are two obvious, and one less than obvious economic measure of distance from sustainability condition (II), viz. zero increase in acid deposition due to anthropogenic activities at the national level. The two obvious conditions are direct emissions of SO_2 and NO_X. Both of these have been estimated for the U.S. since 1900, and are shown in *Table III*. The sulfur dioxide emissions were estimated based on fuel consumption and sulfur content, as described above. The NO_X emissions were estimated on the basis of measured emission rates for specific fuel types and combustion processes (e.g. thermal power plants, internal combustion engines).

The historical emission trends are plotted in *Figure 2*. It is interesting to note that sulfur dioxide emissions peaked around 1970 and are now declining (albeit slowly) whereas nitrogen oxide emissions continued to increase until 1980 and constitute an increasing proportion of the acidification problem. The decline in sulfur emissions is mostly attributable to coal washing, and substitution of natural gas for coal. The use of fuel-gas desulfurization (FGD) technology has not been a major factor up to now: it accounted for only 6% of coal burned in U.S. electric power plants up to 1988. Thus FGD use has had little impact on sulfur emissions to date.

The third indicator is, at best, a partial one but interesting nevertheless: It is the fraction of total sulfur consumed by industry that is extracted from secondary sources. On reflection, it is clear that this is *not* a sufficient measure of either sustainability or distance from sustainability, except under restricted circumstances. On one hand, it is true that a high value of the sulfur recovery index (meaning that very little industrial sulfur is recovered from primary sources) strongly implies a low value of acid deposition. On the other hand, there is no physical necessity that unrecovered sulfur be emitted to the air. Indeed, the current technology for flue gas desulfurization (FGD) results in a waste product that is disposed of on land. Thus a low value of the sulfur recovery index does not *necessarily* imply a high level of acid deposition; it might imply a high level of penetration of conventional FGD technology. However, in the long run, it seems likely that coal will have to be gasified prior to combustion, whence elemental sulfur or sulfuric acid will eventually be economically recoverable. In this case, the correlation between sulfur recovery and low acid deposition would be quite strong, at least in the short run.

Data on sulfur recovery from secondary sources (mainly gas and oil refineries) is available for most, if not all, OECD countries and some others. In the case of the U.S. the relevant data, from the U.S. Bureau of Mines, is displayed in *Table IV* (since 1968). However, while secondary sources now account for more than half of all industrial uses of sulfur, it should be pointed out that none is currently recovered from coal, and sulfur emissions from coal-burning (*Table IV*) have scarcely declined at all.[11]

While nitric acid accounts for a significant fraction of acidification (about one third), there is no obvious counterpart to the sulfur recovery index, in the case of nitrogen. In other words, primary nitrogen-based chemicals cannot be obtained as by-products of other extractive processes.

It is important to note that sulfur recovery from secondary sources is not to be confused with sulfur recycling. In fact, sulfur used in industry is scarcely recycled at all. If one traces

11. Significant amounts of SO_2 are also emitted by some industrial processes. It is estimated that 19% of SO_2 emitted in Europe is attributable to industrial processes (other than fuel combustion), mostly from the chemical industry [IIASA]. This obviously contributes to acidification.

the uses of materials from source to final sink, it can be seen that virtually all the elemental sulfur that is produced is ultimately dissipated in use (e.g. as fertilizers or pigments) or discarded, as waste acid or as ferric or calcium sulfites or sulfates.

There is only one `long lived' structural material embodying sulfur: plaster-of-Paris (hydrated calcium sulfate) which is normally made directly from the natural mineral gypsum. Globally, about 55.6 million metric tons of sulfur *qua* sulfur — not including gypsum — was produced in 1991, mostly for sulfuric acid production. Of this, less than 2 million tonnes was recycled (mainly acid used by U.S. petroleum refineries). However, the forms in which produced sulfur is lost to the environment are mostly sodium or calcium salts, disposed of into waterways.

The third sustainability condition (Criterion III) is that the buildup of toxic metals in the environment should be brought to an end. In principle, changes over time might be measured in terms of the ratio of aggregate anthropogenic flux to natural flux. If the anthropogenic flux is much larger than the natural flux (as shown in *Table V* below) *ipso facto* the level of anthropogenic disturbance must be correspondingly high. This argument is very convincing.

Unfortunately, physical measures such as this are still very uncertain, even at the global level. Two different published sources are illustrated in *Table V.* (They do not refer to different years of measurement). While the second estimate, being more recent, is presumably more reliable, the differences between the two are disturbingly large. It would be natural to conclude that if we don't know the natural fluxes any better than this table suggests, the value of the measure itself must be somewhat doubtful. Beyond this problem, is the fact that the estimates of natural fluxes and reservoirs at the global level are largely model-based. Within national boundaries a much greater level of local detail would be needed, requiring geological information detail available in general only to oil companies and mining companies.

This does not absolutely preclude the use of such statistics, at least in countries with an adequate national geological survey. However, I do not know how many countries would qualify at present.

Another approach to developing indicators of Condition II is to look at the mechanisms underlying the mobilization of toxic metals and chemicals. Suffice it say that mining and ore processing, fly ash from coal combustion, and particulates from cement production and metallurgical processes accounted for most of the buildup in the past. Industrial processes are becoming cleaner, or at least their emissions are being controlled better, so this source is much less important today.

However dissipative uses of toxic metals are becoming the primary source of the problem for many metals. This is especially true for arsenic, cadmium, chromium, copper, lead, mercury and zinc. The second biggest source of emissions of several toxic metals (such as arsenic, cadmium, and mercury) is fly ash from coal combustion. Another major source of some toxic trace elements is secondary recovery (e.g. for lead, copper and zinc). Minor sources include phosphate fertilizer; other minor ones, are cement production and iron/steel production.

Short term indicators of these sources are obvious, namely production and consumption of the metals themselves, as well as coal, phosphates, cement, and steel respectively. However, these are cases where end-of-pipe emissions controls are feasible and necessary. For instance, electrostatic precipitators can recover over 99% of the particulate emissions from coal-burning power plants, cement plants and metallurgical operations. In the case of phosphate rock processing, there are chemical means of removing the toxic trace elements (which would also make it possible to utilize the phospho-gypsum wastes from the process more safely), although such means are not currently in use.

Emissions from manufacturing processes are gradually being reduced. In the long run, it can be foreseen that such processes will produce no significant airborne or water-borne emissions. Increasingly, however, it is the dissipative end-uses that must be controlled or brought to an end. In this regard, it is important to distinguish between the three cases: (i) end uses that are routinely recycled, (ii) end-uses that could be recycled but are not, and (iii) end-uses that are inherently dissipative. Generally speaking, it is arguable that most structural metals and industrial catalysts are in the first category; other structural and packaging materials, as well as most refrigerants and solvents, fall into the second category. This leaves coatings, pigments, pesticides, herbicides, germicides, preservatives, flocculants, anti-freezes, explosives, propellants, fire retardants, reagents, detergents, fertilizers, fuels and lubricants in the third category. In fact, it is easy to verify that most chemical products belong in the third category, except those physically embodied in plastics, synthetic rubber or synthetic fibers. An initial attempt along these lines has been carried out by the U.S. Bureau of Mines [Rogich *et al* 1992]. A partial list (metals only) is shown in *Table VI.*

The numbers in *Table VI* are "best estimates" by USBM commodity specialists. It is obvious that they used a very restrictive definition of "dissipative use", and that there are serious inconsistencies. For instance, in the case of copper, it is clear that only agro-chemical uses (e.g. copper sulfate) were regarded as dissipative; in the case of arsenic most uses (e.g. as wood preservatives) were apparently considered not to be dissipative, and in the case of chromium, none of the uses — even for leather tanning and pigments — were so considered. I would have counted essentially all chemical uses except catalysts as dissipative, in all three of these cases (and in the case of most other metals), as well as most uses for metal plating and a number of others. As an example, the metals in nails, bottle caps, aluminum foil, staples, paper clips, tungsten filaments in light bulbs, the phosphors in TV tubes and the semiconductors embodied in computer chips are essentially impossible to recover. These uses therefore should be regarded as dissipative. Admittedly there is some fuzziness in these classifications, but it should be possible for a group of international experts to arrive at some reconciliation.

The case of sulfur has already been mentioned. Following similar logic, it is easy to demonstrate that most chemicals derived from ammonia (fertilizers, explosives, acrylic fibers), and from phosphorus (fertilizers, pesticides, detergents, fire retardants) are dissipated in use. In the case of chlorine, there is a division between potentially recyclables (solvents, PVC) and inherently dissipatives (hydrochloric acid, chlorine used in water treatment, etc.). Chlorofluorocarbon refrigerants and solvents are long lived and non-reactive. In fact, this is the reason they pose an environmental problem. Given an appropriate system for recovering and reconditioning old refrigerators and air-conditioners, the bulk of the refrigerants now in use could be recovered, either for re-use or destruction. However CFC's used for foam-blowing are not recoverable.

With regard to materials that are potentially recyclable (classes 1 and 2) the fraction actually recycled is a useful measure of the approach toward (or away from) sustainability. A reasonable proxy for this, in the case of non-ferrous metals, is the ratio of "old scrap" supply to total supply of final materials. This data is not often published, because "old scrap" and "new scrap" are often lumped together and the "recycling" ratio is normally calculated from the sum of the two, to make it look larger.) However, the data is available for the U.S. as shown in *Table VII*, but only since 1987. The table shows, incidentally, that old scrap recycling has been rising consistently in recent years only for the cases of aluminum, lead and zinc.

In the case of aluminum, the recovery of aluminum beverage cans is responsible for the increase. In the case of lead, the U.S. ban on using tetraethyl lead as a gasoline additive (an inherently dissipative use) is responsible. In the case of zinc, it is probably the introduction of an improved process to recover zinc from galvanized iron that accounts for the increase. These data are not comparable (or even available) in all countries for every metal, but it should not be too difficult to fill in the gaps from industry sources.

In summary, there are only two possible long-run fates for waste materials: recycling and re-use or dissipative loss[12]. (This is a straightforward implication of the law of conservation of mass). The more materials are recycled, the less will be dissipated into the environment, and vice versa. Dissipative losses must be made up by replacement from virgin sources. A long-term sustainable state would be characterized by near-total recycling of intrinsically toxic or hazardous materials, as well as a significant degree of recycling of plastics, paper and other materials whose disposal constitutes an environmental problem. Heavy metals are among the materials that would have to be almost totally recycled to satisfy the sustainability criteria. The fraction of current metal supply needed to replace dissipative losses (i.e. production from virgin ores needed to maintain a stable level of consumption) is thus a plausible static measure of the absolute "distance" from a condition of long run sustainability.

5. Measures of unsustainable agriculture (criteria IV & V)

As regards both the fourth and fifth criteria for sustainability, it is agricultural statistics that are relevant. With respect to pump irrigation with fossil water, the acreage of irrigated farmland is regularly tabulated by the US Department of Agriculture. Detailed information is certainly available for the U.S. on the type of irrigation and the source of water. The USDA could, without difficulty, compile time series statistics on the quantity and value of crops produced from each type of irrigated land.

At the global level, the FAO could probably make similar estimates based on information available from local sources. A key measure of unsustainability would be the fraction of total output produced by unsustainable means. If this fraction is growing (as it almost certainly is), the future outlook is very grim.

Soil erosion (Criterion V) is not easily measured on an aggregate basis, although reasonably good estimates can be made by measuring sediment loads in rivers and streams on a regular basis and allocating the sediments to their sources. The silt measurements *per se* are not expensive, but they must be fairly extensive. The translation of measured silt loads into inches of topsoil lost per year requires additional information, and modelling. This is done routinely by the USDA (Soil Conservation Service), however, and a time series for the U.S. could probably be compiled for recent decades, at least. Very sketchy evidence suggests that the trend is improving (i.e. erosion is being reduced). The rest of the world is much less well documented, at present, and such indicators as do exist are not encouraging. Erosion in Asia is extremely bad, and probably getting worse. In any case, the preparation of an annual soil erosion statistics would be an appropriate task for the FAO to undertake.

12. The special case of indefinite storage in deep underground mines, wells or caverns, currently being considered for nuclear wastes, is not really applicable to industrial or consumer wastes except in very special and rare circumstances. Surface landfills, no matter how well designed, are hardly permanent repositories although little consideration has been given to the long run disposal of leachates.

6. Global measures of unsustainability: the nutrient cycles

A concern that can only be addressed at the global level is the potential for disturbance of the global nutrient cycles: the carbon cycle, the nitrogen cycle and the sulfur cycle.

A measure of disturbance of the carbon cycle, at the global level, is the fraction of total atmospheric carbon dioxide generated each year from anthropogenic carbon emissions. See *Table VIII*. At present anthropogenic carbon dioxide emissions from all fossil fuels is estimated to be around 7 GT/y, compared to roughly 100 GT/y from natural sources (respiration). The latter figure is moderately uncertain, but presumably not changing much from year to year. The ratio is about 0.07, or 7%. This number appears not to be excessive, at first glance. However, the anthropogenic contribution is rising quite rapidly, whereas the biological output of CO_2 may actually be declining (due to land degredation following tropical deforestation). This trend is a possible cause for concern. The measure, in this case, is exactly proportional to anthropogenic CO_2 generation, which is — in turn — almost exactly proportional to the carbon content of total global fossil fuel consumption. There is enough global data on fuel consumption to prepare a time series of this measure. In fact, global CO_2 output is being estimated and published annually by the Institute for Energy Analysis, for the U.S. Department of Energy.

A similar measure, at the global level, is the fraction of total atmospheric sulfur dioxide attributable to fossil fuel burning. Unfortunately, while the numerator of this fraction is moderately easy to estimate (from equation 4 above), the denominator is still somewhat uncertain (i.e. by at least 50% or so). However, as in the case of carbon dioxide above, the denominator can be assumed to be effectively constant over time. Thus, the anthropogenic fraction of global atmospheric sulfur dioxide is simply proportional to the numerator, which is very nearly proportional to global coal consumption (and production). This ratio can be regarded as a measure of anthropogenic disturbance of the global sulfur cycle.

A corresponding measure suggests itself for the global nitrogen cycle. This refers only to the cycling of biologically available forms of nitrogen, which are either oxidized or reduced forms, but do not include nitrogen gas (N_2) itself. In this case, the anthropogenic contribution to the nitrogen cycle includes both nitrogen oxides (NO_X), ammonia (NH_3) and ammonium compounds, especially synthetic fertilizers. In this case, however, there is a complication, since "natural" nitrogen fixation of atmospheric nitrogen (N_2) by bacteria living on the roots of legumes has increased significantly since pre-industrial times. Again, the fertilizer and NO_X contributions are moderately straightforward to estimate from industrial statistics, but the contribution from natural processes, including leguminous plants, is somewhat uncertain. To prepare a meaningful time series requires a significant effort, but at least two worthwhile attempts have been made [Smil 1991; Vitousek & Matson 1993].

7. Concluding thoughts

It would be very helpful, for purposes of environmental management, to have reliable measures of change both at the national and global levels. Evidently a time series of simple measures, such as ratios, based on readily available statistics, such as the ones discussed above, could serve such a purpose. It is not suggested that this list of simple measures would be sufficient, still less comprehensive. For instance, it is not impossible (though unlikely) that all of the measures suggested could point in the direction of environmental improvement, even though the earth system itself continues to deteriorate. On the other hand, it is hard to see why a set of simple measures, such as these, has never been prepared and published by any national or international statistical agency. The relatively low cost of such an effort, by international standards, makes the omission all the more incomprehensible.

Of course, further measures would be desirable. Some emphasis has been placed on the desirability of developing measures of energy and materials *productivity* (gross output, in value terms, per unit of physical input). Here it must be stressed that national aggregates, such as the inverse of the well-known *energy/GDP* ratio, are *not* reliable measures of progress. This is due to the inevitable confusion of technical improvements with structural changes.

Specifically, some of the most energy-intensive processes in the industrial economy tend to be associated with the early stages of ore beneficiation and reduction. But, for obvious reasons, there is a strong economic incentive to carry out these processing stages as near as possible to the source of the raw material. As the best quality resources are exhausted in the industrialized countries, there is a tendency for such energy-intensive activities as primary steel, copper and aluminum, as well as petrochemicals production, to migrate "south". From a statistical perspective, this results in an apparent reduction in energy inputs per unit output in the "north", with a corresponding increase in the "south". However a shift of this sort does not signify any overall improvement in resource productivity.

Increased output per unit input *within* a given industrial sector is much more significant than aggregate measures for the economy as a whole. While intrasectoral structural shifts can still confuse the interpretation, such shifts are considerably less significant in practice. Moreover, it is possible, with some effort, to derive measures of output per unit input using input-output methodology and underlying economic transactional data[13]. This approach deserves much greater attention than it has received to date.

To recapitulate the discussion above, one major objective of EUROSTAT and the new UN SEEA (or its satellites) should be to permit construction, at the national (or regional) level, of certain statistical measures of the long-term sustainability of sources of energy and metals, especially the toxic heavy metals. As was pointed out above, some of the measures in question can be constructed from data that is already readily available in most OECD countries, or can be easily developed from such data.

It is clear that other interesting and useful measures based on physical data are possible. Moreover, if similar data were collected and published at the sectoral level, it would be possible to undertake more ambitious engineering-economic systems analyses and forecasts — of the kind currently possible only for energy — in the entire domain of "industrial metabolism".

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13. This approach was pioneered by P. Becker. [See Becker 1975, 1976, 1977].

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