

**ECO-RESTRUCTURING:
THE TRANSITION TO AN
ECOLOGICALLY SUSTAINABLE
ECONOMY**

by

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ECO-RESTRUCTURING: THE TRANSITION TO AN ECOLOGICALLY SUSTAINABLE ECONOMY

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Abstract

The term "sustainability" has been popularized in recent years, and there is some danger of it becoming a cliché. The chapter seeks to sort out the questions about sustainability on which there is substantial scientific agreement from those unresolved questions that are still subject to considerable controversy. In this context, several theses are proposed. The first thesis is that there *are* limits to the capacity of the natural environment to accommodate anthropogenic disturbances. The earth is finite. Second, there are also limits to the substitutability of conventional market goods and services for environmental services. Third, there are limits to the extent to which technology can repair or replace environmental resources that are irreversibly damaged. For instance, one cannot imagine undertaking to substitute engineering systems designed by humans to replace natural means of climate control and stabilization.

With respect to the controversial questions an agenda for urgently needed research is suggested. For instance, there is a possibility that nature may be exceedingly adaptable, resilient and resistant to anthropogenic disturbance. Or nature may not be so resilient. It is conceivable, too, that human ingenuity could invent engineering alternatives to natural processes being threatened, or that technology can offer ways of "adaptation" to ecological and climatic stress. However, the argument is that these possibilities are not probabilities. The limits of resilience are probably not very distant, and it is very difficult to justify a high degree of confidence that "business as usual" can continue without risk for even a few more decades.

In brief, the underlying problem is that many current demographic, economic and industrial trends currently seem to point unmistakably in the other direction. To achieve sustainability and minimize ecological risk I think it is necessary to reverse most of these trends. Indeed, some aggregated measures of material and energy use may have to be reduced by large factors (four to ten). Such a reversal will entail very fundamental changes in the economic system. The directions and magnitudes of these changes are assessed briefly, and various approaches to their implementation are analyzed.

Foreword

The paper which follows was originally prepared for, the United Nations University (UNU) as a background "white" paper in support of the development of UNU's long term research program.¹ As such, it was also the main background paper for the UNU Eco-Restructuring Conference, held in Tokyo, July 1993, at which most of the papers in this book were first presented.

For various reasons, the preparation of this book from those conference papers has been an unusually long and difficult process. The review and revision process has been very slow. A few of the original papers had to be dropped because the authors were too busy to undertake necessary revisions and submit revised versions. Some, which were topical at the time, have become a little dated. To fill gaps (some of which were evident from the start) several additional papers have been solicited and included. But, since these authors were not present at the conference, they lacked the common background and required more than the usual amount of "editorial guidance". I think, however, that the final result is useful and interesting, if not the "last word" on the subject (which, in any case, will never be written).

The objective of the 1993 Tokyo conference was to explore the technical and economic feasibility of long-term sustainability. The conference did not totally neglect the political and institutional issues, but they were deliberately given secondary status. Social and cultural issues were set aside altogether, as being outside our collective ken. The over-arching issue of population control was discussed only in my background paper, which follows, and only in terms of generalities. The bulk of the book deals with technological issues. Economics should have been given more attention than it was, but few economists are prepared to take on the practical aspects of long-range restructuring. This remains an open subject for future research.

Because of the background sketched above, I have since revised the paper only moderately to respond to reviewers' comments, while retaining much of its original logical structure. I recognize that the structure is not ideal for the intended audience of the book. (It is probably not ideal for any audience). But, as I say, the chapter which follows was essentially the "terms of reference" for all the other authors. To change it fundamentally would be a little unfair.

It must be acknowledged that, in many ways, the terms of the discussion have changed since the paper was written. In some ways, as on the problem of global climate change, there has been clear progress. One can only applaud this fact. On the other hand, thanks to the too-vague definition offered in the Brundtland Commission Report *Our Common Future*, the term "sustainability" has been popularized and virtually bowdlerized in recent years. It has been consistently misused, in particular, by the World Bank and other economic development agencies. These institutions are inclined to interpret "sustainable development" as "perpetual growth", which is an extreme perversion of the original sense of the phrase. But sustainability is also now an icon of generalized political correctness, where it is carelessly applied to a variety of attributes from culture to democracy.

Holding to the original sense of the word, the chapter seeks to sort out the questions about sustainability on which there is substantial scientific agreement from those unresolved questions that are still subject to considerable controversy. In this context, several testable theses are proposed. The first thesis is that there *are* limits to the capacity of the natural environment to accommodate anthropogenic disturbances. The earth is finite. Second, there are also limits to the substitutability of conventional market goods and services for

1. In fact, the UNU version was based on an earlier version that I prepared for a workshop held at IIASA, held in January 1991.

environmental services. Third, there are limits to the extent to which technology can repair or replace environmental resources that are irreversibly damaged. For instance, only the most naive technological optimist can imagine undertaking to substitute positive engineering control systems, designed by humans, to replace natural means of climate control and stabilization.

With respect to some controversial questions we cannot expect firm answers. For instance, there is a possibility that nature may be exceedingly adaptable, resilient and resistant to anthropogenic disturbance. Or, nature may not be so resilient. It is conceivable, too, that human ingenuity could invent engineering alternatives to natural processes being threatened, or that technology can offer ways of "adaptation" to ecological and climatic stress. However, the argument is that these possibilities are not probabilities. The limits of resilience are probably not very distant, and it is very difficult to justify a high degree of confidence that "business as usual" can continue without risk for even a few more decades.

In brief, the underlying problem is that many current demographic, economic and industrial trends currently seem to point unmistakably in the wrong direction, i.e. away from sustainability. To achieve sustainability, and to minimize ecological risk, it will be necessary to reverse most of these trends. Indeed, some aggregated measures of material and energy use may have to be reduced by large factors (four to ten). Such a reversal will entail very fundamental changes in the economic system. The directions and magnitudes of these changes are assessed briefly, and various approaches to their implementation are analyzed.

1. Introduction: On Sustainability

Before the beginning of the industrial revolution, some two centuries ago, human activities — on the average — were not really incompatible with a healthy and sustainable biosphere. The vast majority of humans lived and worked on farms. Land was the primary source of wealth. Horses and other animals, supplemented by windmills, sails and waterwheels provided virtually all power for plowing, milling, mining and transport. The sun, either directly or through products of photosynthesis, provided virtually all energy except in a few coal-mining regions. Metals were mined and smelted (primarily by means of charcoal), but their uses were almost exclusively metallic rather than chemical. Recycling was normal. Precisely because wealth was derived exclusively from the land, Thomas Malthus worried at the end of the eighteenth century about the propensity of human population to grow exponentially, in view of the limited amount of potentially arable land available for human cultivation.

As we approach the end of the 20th century, humans are far more numerous and also wealthier (on average) than they were two centuries ago when Malthus wrote. In particular, those countries that industrialized first, are now comparatively rich. In the rich countries most people live in cities. Land is no longer the primary source of wealth. Energy (except food) is largely derived from the combustion of fossil fuels (coal, oil, gas). Power for machines is obtained mainly from engines driven by heat from (internal or external) combustion of fossil fuels. (Nuclear and hydro-electric power, together, account for a relatively small percentage of the total). However one key attribute of our recent rise to wealth is critical for the future of Man: what we have achieved so far has been done by exploiting an endowment of natural capital, especially topsoil and minerals. For some material resources, technology can offer viable substitutes. For other resources in the natural endowment — notably the biosphere and its functions — no substitute is likely.

The report of the UN's World Commission on Environment and Development (WCED) — known as the Brundtland Commission — was published in 1987 under the title *Our*

Common Future. This triggered the Global Environmental Summit at Rio de Janeiro in June 1992, and its major product *Agenda 21*. Since that time it has been widely recognized that there is a very real conflict between meeting the needs and desires of the five billion people now alive and the possibility of satisfying the ten billion or so people expected by the middle of the next century. It will be exceedingly difficult to simultaneously satisfy the objectives of environmental preservation, on the one hand, and accelerated economic development of the Third World, based on current population trends and energy/material intensive technologies, on the other. The implications of this conflict have been delineated eloquently in the Commission's report [Brundtland *et al* 1987; McNeill 1989]. They need not be spelled out in detail again here.

Experts can and do disagree on the probabilities and timing of environmental threats relative to other problems facing the human race. Some ideologues have even argued that the threats are figments of the fevered imaginations of the "Greens". I think not. Arguments on these matters will probably continue for some time to come. But there is increasing evidence to suggest that major changes in the global economic and industrial system may be needed if the world is to achieve a sustainable state before the middle of the next century. Even though there is not yet a scientific consensus on the extent of the needed changes, it is clear that they will involve significant technological elements, as well as major investments.

The population problem comes to mind first, especially in the context of the recent Cairo Conference. It is unlikely that the other problems of the global environment can be solved if the world's population is not stabilized. Experts now generally agree that education and the status of women are central issues here. This implies that a world of relatively stable population must be one in which social patterns are significantly different than those now encountered in many parts of the world.

The kinds of techno-economic changes envisaged as necessary conditions for long-term sustainability also include a sharp reduction in the use of fossil fuels (especially coal) to minimize the danger of global "greenhouse warming". Alternatives to increasing use of fossil fuels include a return to nuclear power, large-scale use of photovoltaics, intensive biomass cultivation, large-scale hydroelectric projects (in some regions) and major changes in patterns of energy consumption and conservation. Again, there are disputes over which of these energy alternatives is the most (least) desirable, feasible, etc. However, the future of energy, both from the supply (technology) and demand perspective, is a critical topic (to which several chapters of this book are devoted).

Again, the broad question addressed in this book is: how to shift from a techno-economic "trajectory" based on exploiting natural resources — soil, water, biodiversity, climate — that, once lost, can never be replaced, to one that could lead to a future society that preserves and conserves these resources. To facilitate this search, it approaches the problem in three stages. First, it attempts to identify the most pressing questions, especially with regard to the severity of the threat and the technical feasibility of solutions. Next, it attempts to distinguish between those questions on which there is little or no scientific disagreement from those on which the evidence itself is disputed. Thirdly, it raises the most fundamental question of all: how to get from "where we are" to "where we need to be".

However, before plunging into the argument, some subsidiary topics are worthy of brief mention. These are discussed in the next two sections.

2. Need for holistic systems analysis

Since the early 1970s, the environmental movement has become increasingly profession-

alized and bureaucratized. As a consequence, largely, of the latter development, the "environment" is no longer seen in a holistic sense, but in terms of a number of specific, essentially independent issues. Nowadays, the "causes" of pollution are attributed, for the most part, to narrowly defined actions (or failures to act) of equally narrowly defined "polluters". The responsibilities for abatement or cleanup are correspondingly narrow. Solid wastes, hazardous or toxic wastes, liquid wastes and airborne wastes are likely to be allocated to different government departments, ranging from public health agencies to water/sewer authorities. Their regulatory powers are controlled by different kinds of legislation framed under different circumstances, sometimes based on quite different regulatory philosophies. "The right hand does not know what the left hand is doing", and *vice versa*.

Activities of different arms of the same agency can interfere with each other. (For instance, incineration can reduce the solid waste disposal problem and even produce useful energy as a by-product, but it creates an air pollution problem. On the other hand, to reduce the emissions of particulates and sulfur oxides from power plants creates solid wastes that must be disposed of somewhere on land. There is nobody with a global view of the problem to mediate among the parochial interests. There is nobody with the responsibility or the authority to induce competing offices, departments and bureaus to co-operate.

Yet the environment is, by its very nature, unsuited to incremental control strategies. It is equally unsuited for reductionist "bottom up" modes of analysis. The problem is that man's scientific insights are now, and will continue to be, insufficient for predicting the detailed environmental consequences of any change or perturbation. To take a concrete instance, nobody can predict the exact physiological effects of ingesting any chemical, from knowledge of its structure. Still less can the genetic or ecological consequences of its dispersion be predicted. This uncertainty is multiplied by the enormous number of different chemicals, materials, and mixtures simultaneously manufactured and used by man (natural and synthetic alike), not to mention the variety (type and intensity) of possible reaction modes, and interaction effects.

Setting aside carcinogens and highly toxic or radioactive substances,¹ only one important environmental problem has as yet been predicted in advance from the creation or displacement of any particular material stream. This single exception was Rowland's chance recognition of the reactive potential of the CFCs in the stratosphere, and the resulting possibility of stratospheric ozone depletion. This potential hazard, derided by chemical industry spokesmen in the 1970s as "speculative", has turned out to be real.

In speaking of the environment it is literally true that "everything depends upon everything else". A holistic "top down" perspective is essential to identifying the most important underlying factors and relationships. It is equally important to adopt a very broad perspective for seeking and — hopefully — finding effective global strategies to save the planet.

3. Environmental threats and (un)sustainability indicators

There has been a good deal of academic debate in recent years on the exact meaning that should be ascribed to the term "sustainability". For instance, Repetto states that "current decisions should not impair the prospects for maintaining or improving future living standards" [Repetto 1985 p. 16]. WCED paraphrased the same general idea; sustainable development "meets the needs of the present without compromising the ability of future generations to meet their own needs" [Brundtland op cit]. Tietenberg phrases it in utility terms, and defines sustainability as non-declining utility [Tietenberg 1984 p. 33]. Pezzey goes

further and insists that it is the discounted present value of utility that should not decline [Pezzey 1989]. Mainstream economists have concerned themselves with replacing depleted natural resource stocks. For instance, Nobel Laureate Robert Solow proposed that "an appropriate stock of capital — including the initial endowment of resources — [be] maintained intact" [Solow 1986]. More recently Solow said: "If 'sustainability' is anything more than a slogan or an expression of emotion, it must amount to an injunction to preserve productive capacity for the indefinite future. That is compatible with the use of non-renewable resources only if society as a whole replaces used-up resources with something else" [Solow 1992].

All of these definitions (and others) essentially agree on a single economic measure of welfare (GNP). They fundamentally assume unlimited substitutability between conventional economic goods and services that are traded in the marketplace, and unpriced environmental services, from the stratospheric ozone to the carbon cycle. However, virtually all environmentalists and an increasing number of economists explicitly reject the unlimited substitutability view as simplistic [e.g. Boulding 1966; Ayres & Kneese 1971; Ayres 1978; Daly 1990]. Similar critiques have been articulated recently by David Pearce and his colleagues [Pearce 1988; Pearce *et al* 1989].

The "ecological" criterion for sustainability admits the likelihood that some of the important functions of the natural world cannot be replaced within any realistic time frame — if ever — by human technology, however sophisticated. The need for arable land, water and a benign climate for agriculture is an example; the role of reducing bacteria in recycling nutrient elements in the biosphere is another. The ozone layer of the stratosphere is a third. The ecological criterion for long-run sustainability implicitly allows for some technological intervention: for example, methods of artificially accelerating tree growth may compensate for some net decrease in the area devoted to forests. But, absent any plausible technological "fixes", this definition does *not* admit the acceptability of major climate changes, widespread desertification, deforestation of the tropics, accumulation of toxic heavy metals and non-biodegradable halogenated organics in soils and sediments, or sharp reductions in biodiversity, for instance.

Having said this, it is obviously easier to find indicators of unsustainability than of sustainability. In work for the Advisory Council for Research on Nature and the Environment (Netherlands), preparing for the UNCED Conference in Rio de Janeiro, 1992, Dutch researchers proposed a taxonomy of sustainability indicators [Weterings & Opschoor 1992]. Their taxonomy has three dimensions, viz.

- (i) Pollution of natural systems with xenobiotic substances or natural substances in unnatural concentrations. The results include acidification and "toxification" of the environment.
- (ii) Depletion of natural resources: renewable, non-renewable (and semi-renewable). In fact, biodiversity can be regarded as a depletable resource, though not one that is commonly thought of as such. Of course, it also differs from other depletable resources that are exchanged (in, and priced by) well-developed markets. There is no such market for biodiversity, or for its complement, genetic information. Nevertheless, I regard this as a market failure and argue that loss of biodiversity is an aspect of depletion.
- (iii). Encroachment (human intervention) affecting natural systems e.g. loss of ground water or soil erosion.

Based on this taxonomy, Weterings and Opschoor prepared the following summary table of quantifiable sustainability indicators (*Table I*). The notion of "sustainable level" in regard to pollution, toxification, acidification, greenhouse gas buildup and so on is predicated on the idea that natural processes will compensate for some of the damage. For instance, natural weathering of rocks generates some alkaline materials that can neutralize acid. (Increased acidity will, however, increase the rate of weathering). Similarly, it is assumed that some of the excess carbon dioxide produced by combustion processes may be absorbed in the oceans or taken up by accelerated photosynthetic activity in northern forests. (This process is called "CO₂ fertilization").

Regarding depletion, it is assumed that some minerals (like aluminum) can be mined more or less indefinitely, even though the highest quality ores will be exhausted first. Other depletable ores could be effectively exhausted, in the sense that recovery from minable ores would be too expensive to be worthwhile except for very specialized and limited uses. Copper might be an example of this kind (though many geologists are more optimistic than Weterings & Opschoor). As regards renewable resources such as fisheries and ground water, it has long been known that there is a level of exploitation that can be sustained indefinitely by scientific management, but that beyond that level harvesting pressures can drive populations down to the point where recovery may take decades, or may never occur at all. Many fisheries appear to be in this situation at present, notwithstanding the fact that sustainable levels are not very precisely known. Granted some uncertainty, it is nevertheless clear that in all three dimensions, "sustainability" would require significant reductions in current levels of impact.

In recognition of the fact that both soil erosion and ground water loss overlap considerably with the "depletion" category, the later version of their work substituted "loss of naturalness" viz. loss of integrity, diversity, absence of disturbance [Weterings & Opschoor 1994]. What remains in category (iii) is the notion of "disturbance of natural systems", as such. Most environmentalists think of "systems" in terms of ecosystems and biomes. The sum total of such disturbances is indeed a significant environmental problem, though individual cases tend to be geographically localized. However there are also global systems that are being dangerously disturbed by anthropogenic activity. Examples of global systems include the hydrological cycle, ocean currents, the climate, the global radiation balance (including the ozone layer which protects the earth's surface from lethal ultra-violet radiation), the carbon/oxygen cycle, the nitrogen cycle and the sulfur cycle.² This problem is discussed in detail later.

Holistic analysis presupposes that it is possible to classify variables by degree of importance and derive significant and defensible results by judicious simplification. A universal measure to estimate and compare the relative environmental impact of different activities, goods, services and regulatory policies would be of great value.

Such a measure should satisfy the following conditions:

- It should be based on measurable quantities;
- It should relate to the most significant environmental impact potentials of human activities;
- It should allow transparent, cost-efficient and reproducible estimates of the environmental impact potentials of all kinds of plans, processes, goods, and services;
- It must be applicable on the global level as well as regional and local levels.

Choosing a single indicator to compare the environmental impact intensities of all kinds of present and future processes, goods, and services might seem to be a daring step, precisely because it constitutes a vast reduction of complexity. Simplification cannot be proven to be

"correct" in scientific terms.³ Only its plausibility in a variety of circumstances can be established.

For several reasons it can be argued that aggregate *resource productivity*, the ratio of GNP (or a better unit of economic welfare) to an index of total renewable-but-unrenewed or nonrenewable resource inputs, in physical units, might be a plausible measure of sustainability. At least, the two are correlated: the greater the resource productivity, the nearer to long-term sustainability. Obviously, the inverse of resource productivity — non-renewable or non-renewed resource use per unit of welfare output — is a measure of unsustainability.

Regrettably, neither this measure nor anything similar is currently computed at the national level by statistical agencies, and the required data is not readily available even to them, still less to non-government organizations. However, note that the corresponding measure can be computed in principle for a sector (industry), a firm, a region with well defined boundaries, or even a single product. Something like the inverse of resource productivity, *materials intensity per unit service* (MIPS) has been calculated for a number of specific cases at the Wuppertal Institute.⁴

4. Sharpening the debate

It is important now to confront three basic questions. The first two central questions are: (1) Is continued economic growth (appropriately defined) compatible *in principle* with long-run ecological sustainability? If so, (2) is our current mix of technologies and economic instruments consistent *in practice* with this goal? The final question is: (3) If not, what is the "least cost" (and "least pain") political/institutional path from where we are now to a sustainable world economy? Will it be very expensive, as claimed by many conservatives, or are there enough opportunities for energy and material savings by intelligent use of "clean technology" to compensate for many of the costs?

This trio of central questions, as stated, currently elicits passionately opposed positions. Fortunately, several of these questions can be restated in a way that leads toward an answer. The first question above can be restated: (1') Bearing in mind that most economists have been trained to believe that substitution of capital and/or technology for natural resources is virtually always possible, one can ask: is there any class of environmental assets or services that is *both* essential to human life (or to the biosphere) and for which there are no plausible substitutes? If substitutability (e.g. of capital for environmental resources) is more or less without limit, or if the limits are very remote, then it can be argued that present trends are sustainable, or could become sustainable (depending on one's exact definition of sustainability) with a few marginal changes in policy.

A majority of business and political leaders appear to assume that only minor changes in current technology and/or regulatory policy would suffice to overcome and environmental threat. In fact, even most so-called "environmentalists" appear to believe that the most serious environmental threats we face are direct threats to human health (contaminated water or food, skin cancer) or loss of amenity (forest die-back, oil spills, dirty beaches, litter, haze, bad smells, etc.) No doubt ex-president Bush truly saw himself as an "environmentalist" because of his long-standing love of hunting, boating and fishing. It has to be said, at the outset, that the problems that appear on most lists of "priority concerns" are localized, not global, problems. Even the rising public concern about loss of "endangered species" is limited to birds, fish, whales and mammals — especially large mammals like pandas and tigers. These are *NOT* the environmental problems of greatest concern from the standpoint of long-term survival of the earth as a habitable planet.

The second question can also be restated: (2') If there are environmental assets and services that are both essential and non-substitutable (i.e. the answer to the first question is 'yes') — as I believe — a second question follows: are any of these environmental assets or services now threatened by irreversible and/or irreparable damage? Is there a credible — not necessarily probable — threat to long-term survival of life on this planet?

The answer to this question is obviously critical for what follows. It can be further broken down into several subsidiary questions, for example:

(2.1) Is continued global population growth compatible with long-run eco-sustainability? Can the most densely populated countries (China, India, Indonesia, Bangladesh) continue to feed themselves as they increase in numbers? If not, what is the relationship between demographic variables and economic growth potential in various regions (notably China, India and Africa)?

(2.2) Does industrial activity and its associated demand for raw materials and depletion of high quality deposits of natural mineral or other environmental resources constitute a major constraint on continued environmentally sustainable economic growth? If so, how and why?

(2.3) Does waste and pollution (including acidification and environmental accumulation of toxic elements) constitute a direct threat to human welfare or to the habitability of the planet? For example, does it constitute a constraint on food production? If so, does it constitute a constraint on economic growth? If so, how and why?

(2.4) Does anthropogenic disturbance of balanced environmental systems (including ecosystems) constitute a major threat in the above sense? If so, how and why?

A brief digression is appropriate in connection with (2.4): the earth system depends on several balanced, biologically controlled recycling systems for nutrient elements that are required by living organisms in forms or amounts greater than they would be found in the earth's crust or the prebiotic atmosphere or hydrosphere. Nitrogen, for instance, constitutes the major part of the atmosphere, but molecular nitrogen (N_2) is so stable that it is virtually unusable by plants or animals. It is only when this strong nitrogen bond is split by some external agency (yielding nitrogen compounds like ammonia, ammonium, nitrates or nitrogen oxides) that the nitrogen becomes a nutrient element. Free oxygen would not exist at all without living organisms; it would all be combined with other elements as water, carbonates, silicates, sulfates, etc. Carbon, too, would be tied up (mostly as insoluble carbonates) and unavailable. Thus, a truly "dead" planet (like Mars or Venus) is literally uninhabitable.

Destruction of the earth's nutrient recycling systems would probably be the surest way of destroying all life on Earth. To be sure, human intervention at present can better be characterized as "eutrophication", in the sense of sharply increasing the availability of these nutrients. Yet eutrophication in a lake or stream can be disastrous if it leads to an unbalanced and explosive growth of a few species, which exhaust the supply of some other nutrient (e.g. oxygen) resulting in a "crash" that destroys the whole food web. What we do not (and probably cannot) predict is the probability or imminence of such a threat at the global level. (I do suspect that it is more likely than being struck by a comet!)

Now, turning to the third major question, which concerns strategies for change, and their cost, here also a breakdown into subsidiary questions is helpful. For example:

(3.1) Are there any feasible strategies, and implementable means, of bringing population growth to an end without government coercion, war or epidemic? Which of them would involve the least economic cost and/or the least conflict with deeply held religious beliefs?

(3.2) Is there any fundamental reason technological limit (other than the second law of thermodynamics) to the energy and materials productivities that can be achieved in the long run? Is there any fundamental limit to the long-run efficiency of materials recycling? To put it another way, is there a plausible set of technological "fixes"? We seek, in effect, an

"existence proof" that solutions are possible.

(3.3) Among the technological "fixes" postulated above, is there one (or more) that is inexpensive, even profitable? Can the needed technology be harnessed at modest, or even negative, cost? From the macro-economic perspective, the question is: Can continued economic growth be achieved simultaneously with environmental improvement by increasing resource productivity — thereby reducing the need for resource inputs and the generation of wastes — *without* significantly decreasing labor and capital productivity? To put it another way, is it feasible to find ways to increase *all* factor productivities simultaneously, i.e. without substituting energy or material resources for labor? In simpler words, is there a mother-lode of "win-win" possibilities — "free lunches" — for reducing pollution and increasing the value of output at the same time?

It is interesting to note that affirmative answers to (3.2) and, especially, (3.3) — the existence of possible technological "fixes" at low (or no) cost — imply a high degree of technological optimism. Curiously, most economists adopt an extremely optimistic stance in regard to questions of resource availability (2.2) but become pessimists when it comes to eliminating or repairing damages caused by pollution (3.3). It would seem logical that a Malthusian pessimist would be entitled to be pessimistic about the existence of "win-win" opportunities, but an opponent of the neo-Malthusian position should also be optimistic with regard to finding low cost or profitable solutions to the growth problem. Simple consistency would seem to require that both questions (2.2) (resource substitutability) and (3.3) (technological "fixes") be answered the same way: either "yes" to both or "no" to both.

5. Non-controversial issues: population, resources and technology

There has been, and still is, great controversy with regard to question #1 as regards the essentiality (non-substitutability) of certain environmental resources. However, the controversy is largely over definitions and details, not fundamentals. Possibly this confusion has arisen because the issues were not formulated sharply enough, until recently. I think there is a reasonable consensus among experts on the fact that some environmental services are essential to long-run human survival on this planet. The existence of "critical" environmental resources is not seriously doubted by most people. The doubters are mostly conservative libertarians with a deep faith in the ability of markets to allocate scarce resources and to call forth technological (or other) substitutes in response to any perceived scarcity.

The weakness of this position is that markets for environmental services are virtually non-existent. Markets must function through price signals. Clearly we need food, sunshine, clean air and fresh water. We also need the waste disposal services of bacteria, fungi, and insects. All are, at bottom, gifts of nature. Because they are not "commodities" that can be owned and possessed or physically exchanged, they have no prices. Moreover, since these services are not produced by human activity, price signals could not induce an increase in the supply. What is still doubted by many scientists, on the other hand, is the answer to the second half of the question: whether or not these essential environmental resources are truly vulnerable to human interference and possibly subject to irreversible damage.

One example of an essential environmental resource that appears to be subject to irreversible damage is the ozone layer of the stratosphere. The cause of damage, it is now agreed, is atomic chlorine, which originates from the inert chlorofluorocarbons (CFCs) that do not break down in the lower atmosphere and gradually diffuse into the stratosphere where they are broken up by high energy ultraviolet radiation (UV-B). The chlorine atoms, in turn, react with and destroy ozone molecules, thus depleting the protective ozone layer. This

phenomenon was very controversial twenty years ago, but the controversy has largely subsided, thanks to the discovery of annual "ozone holes" in the polar stratosphere, which were first seen in the mid 1980s.

Another example of increasing consensus is that of climate change. The climate is certainly an environmental resource. Even a decade ago there were still a number of scientists expressing serious doubts as to whether the problem was "real". The major source of doubt had to do with the reliability of the large-scale general circulation models of the atmosphere that had to be used to forecast the temperature effects of a buildup of greenhouse gases (e.g. carbon dioxide, methane, nitrous oxide, CFCs). Since then, the models have been improved significantly and it has been established fairly definitely that climate warming has been "masked" up to now by a parallel buildup in the atmosphere of sulfate aerosol particles (due to sulfur dioxide emissions) that reflect solar heat and cool the earth. The two effects have tended to compensate for each other. However, the greenhouse gases are accumulating (they have long lifetimes) whereas the sulfate aerosols are quickly washed out by rain. In other words, the greenhouse gas concentration will continue to increase geometrically, whereas the sulfate problem may increase only arithmetically or not at all (if sulfur dioxide emissions are controlled). In any case, the Intergovernmental Panel on Climate Change (IPCC) has now agreed that the greenhouse problem is indeed "real". The controversy continues, however, with regard to likely economic damages and optimal policy responses.

There is already a near-consensus among experts that continued human population growth is not consistent with long-run sustainability (question #2.1) and that some natural resources must eventually be depleted (question #2.2). On the other hand, there is less agreement as to whether increasing waste and pollution would constitute a limit on growth (question #2.3) or whether the balanced natural systems such as the carbon, nitrogen and sulfur cycles are at risk (question #2.4). These questions are considered subsequently.

The unacceptability of continued population growth (question #2.1) is a matter on which there is reasonably wide consensus. Malthus foresaw that population growth would eventually outrun the carrying capacity of the earth. Colonization of new lands in the Western Hemisphere, together with dramatic improvements in agricultural technology forestalled the crisis for two centuries. Some conservative economists regard this as sufficient evidence that "Malthus was wrong" and that today's neo-Malthusians are unnecessarily alarmist. Nevertheless, the alarm has been raised once again, perhaps on better grounds: there are no more "new lands" waiting for cultivation, and the potential increases in yield available from fertilizers and plant-breeding have already been largely exhausted.

Technological optimists — notably Herman Kahn and his colleagues [Kahn *et al* 1976] — have unhesitatingly projected that early 20th century rates of increase in agricultural productivity can and will continue into the indefinite future. However, agricultural experts are much less sanguine. The potential gains from further uses of chemicals by traditional methods are definitely limited. Ground water is already becoming seriously depleted and/or contaminated in many regions of the U.S. and Western Europe where intensive irrigation cum chemical agriculture have been practiced for a few decades. Such problems are now also becoming acute in places like Northern China. A decade ago Bernard Gilland wrote:

"Since the onset of the rapid rise in the world population growth rate over 30 years ago, there has been speculation on the human carrying capacity of the planet. Most writers on the problem either hold, on technological grounds, that the earth can support several (or even many) times its present population, or warn, on ecological grounds, that the Earth is already overpopulated and that human numbers should be reduced. I shall try to show that neither of these views is realistic, and that a

plausible assessment of carrying capacity leads to the view that the world is not yet overpopulated but will be so in the second decade of the twenty-first century, when the population will be 60 percent larger than at present". [Gilland 1983 p.203]

Gilland goes on to conclude:

"Estimates for global carrying capacity and long-range demographic projections are admittedly subject to wide margins of error, but the consequences of relying on an excessively optimistic assessment of the future population-food supply balance would be so serious that a conservative assessment is justified" [ibid. p 209]

Admittedly, Gilland's assessment was based on conventional agriculture using land now classified as "arable". Julian Simon argues in rebuttal that this is not a fixed quantity, and that so-called arable land had actually been increasing at a rate of about 0.7% per annum (from 1960 to 1974) [Simon 1980 p.1432]. This is one of the reasons food shortages projected earlier did not occur. But most of the "new" cropland was formerly tropical forest. (The rest was grasslands, such as, for instance, the vast and ill-conceived "new lands" projects of Soviet central Asia). Deforestation has now become an acute problem throughout the tropics, and most tropical forest soils are not very fertile to begin with and are rapidly exhausted of its nutrients by cropping. There is no basis for supposing that the amount of arable land can continue to increase much longer, if indeed it has not begun to decrease already for the reasons noted above. In any case, erosion and salination are taking a constant toll of the lands already in production.

With regard to the possibility of continuing to increase the productivity (yield) of existing arable land, there is a continuing push to develop improved varieties and higher photosynthetic efficiencies. Biotechnology is now beginning to be harnessed to increase food production. There is optimistic talk of a "second green revolution". For some years past, global grain production *per capita* has actually been declining. Thus, incremental improvements will be needed just to keep up with population growth.

Gilland also did not take into account several theoretical possibilities, including such "high tech" schemes as genetically engineered bacteria capable of digestion of cellulose or crude oil, large-scale hydroponics, and massive irrigation of tropical deserts such as the Sahara using desalinated seawater. Certainly, these possibilities must be taken seriously, and some of them may play an important role before the end of the next century. On the other hand, there is no chance that any of them could make a difference within the next twenty or thirty years. In short, there are strong indications that agricultural technology cannot continue to outpace population growth in the Third World for more than another few decades. For these reasons, the majority of demographers, and most economists, now take it for granted that population growth must be brought to an end as soon as possible if sustainability is to be achieved [e.g. Keyfitz 1990, 1991].

As regards concerns about resource exhaustion (question #2.2) the "neo-Malthusian" position was taken very seriously by some alarmists, such as Paul Ehrlich, in the 1970s. The argument was made that economic growth is inherently limited by the limited availability of exhaustible natural resources [e.g. Meadows *et al* 1972]. However, it is now widely agreed among both economists and physical scientists that energy or mineral resource scarcity is *not* likely to be a growth-limiting factor, at least for the next half century or so. The Malthusian "limits to growth" position adopted by some environmentalists in the 1960's and 1970's has been largely discredited, both by empirical research [e.g. Barnett & Morse 1962; Barnett

1979] and by many theorists. The main reason for the change of perspective is that the neo-Malthusian view was naive in two respects.

First, the neo-Malthusians neglected the fact (well known to the fuel and mineral industries) that there is no incentive for a mining or drilling enterprise to search for new resources as long as it has reserves for thirty years or so. This is a simple consequence of discounting behavior. It explains why "known reserves" of many resources tend to hover around twenty to thirty years of current demand, despite continuously rising demand. Secondly, they gave too little credit to the power of market-driven economies to call forth technological alternatives to emergent scarcities [e.g. Cole *et al* 1973; Goeller & Weinberg 1976].⁵ However, as it turns out, it is over-used "renewable" resources, like arable land, fish, fresh water, forests, biodiversity and climate that are more likely to be limiting factors [Hammond 1997].

The existence of feasible strategies to achieve population stability (question #3.1) is now generally accepted. The subsidiary question of most appropriate *means* remains murky. This optimism is based partly on evidence of recent slowdown in global population growth in recent decades. However it is admittedly unclear whether the observed slowdown (mostly in China, so far) can be extrapolated to other countries, particularly in the Muslim world. Still, the majority of experts seem to believe that the required "demographic transition" is economically and institutionally feasible, in principle. Here the central problem is seen to be to achieve near universal literacy, equal rights and legal standing for women, a social security net for the poor, and real economic growth to finance all of this, at a rate fast enough to reach that "middle class" standard within a few generations⁶.

Demographers and social scientists generally agree that these are the preconditions for radically reduced birth rates. A few years ago Jessica Matthews of WRI had the following comment:

"The answer is emphatically that there is a realistic path to global population control. The demographers measure what they call unmet needs for contraceptives. That's the place where action has to begin — with women and couples who express a desire to use contraceptives, but who currently have no access to them. The cost is about \$10 per couple per year. The need is several times world spending on contraception — a trivial, almost infinitesimal sum, compared to defense spending. I dare say it would probably be covered by the cost of one B-2 bomber, about \$500 million. ... The second most important realistic, feasible, direct intervention is through women's education. For reasons that are not entirely understood, even primary school education makes a huge difference in women's fertility rates. Therefore education of women in developing countries, and expansion of that opportunity, will have a huge effect ..." [Matthews 1990; pp 27-28]

The 1994 Cairo Conference on Population and the Status of Women echoed most of Matthews' themes. While there were passionate objections to the conference itself, and to the manifesto signed by most attendees, they scarcely challenged the cause-effect relationships set forth by Matthews. On these issues, there is a wide consensus among experts. The most passionate debates with regard to population policy center on moral (and, of course, political) questions centering on methods of birth control and, especially, the legitimacy of abortion. These arguments are *not* within the realm of science or scientific debate.

6. Controversial issues: pollution, productivity and biospheric stability

The existence of plausible threats to biospheric stability, even survival, (questions #2.3 and #2.4 above) is by no means obvious. The question as to whether pollution constitutes a possible limiting factor for economic growth (question #2.3) is perhaps the one most debated at present. It is highly controversial. If there is any consensus on this issue it is merely that "toxification" — in the sense of "toxic wastes anywhere near my neighborhood" — is unacceptable (i.e. must be prohibited regardless of cost). The next section (#7) discusses this further. But, the extent to which pollution constitutes a limitation on growth itself, or on the welfare generated by economic activity, remains an open question.

The problem of climate warming has been extensively studied and debated (as mentioned above), though there are still significant areas of disagreement among experts with regard to the economic damages and appropriate response strategies. On the other hand, the issue of environmental acidification and/or toxification has never been considered seriously as a global threat to human survival. However, concerns are beginning to arise, especially in regard to cancer and human reproductive capacity. The link between various chemical agents and biological impacts remains largely speculative, however, and is likely to remain so for many years. Damage mechanisms and thresholds are known in some cases, but not in others. However, it is fairly easy to construct a simple catalog of measures of materials flux and consequent waste generation that self-evidently cannot continue to increase indefinitely.

The issue of whether there is a threat to biospheric stability itself (question #2.4) is rather deep. There are two aspects. The first has to do with phenomenology. The second aspect has to do with the essential indeterminacy of the risk. Not only is there no consensus on either of these points, there has been almost no discussion up to now. I return to this question at greater length below.

As regards the third main question, concerning the least-cost (or "least pain") transition to a sustainable trajectory, the problem of slowing population growth (question 3.1) has already been mentioned. The existence of plausible technological "fixes" (question 3.2) and the possible existence of large numbers of "win-win" opportunities, or "free lunches" (question 3.3) are much more controversial. There is also no consensus as yet. These questions are discussed after the two digressions — on toxicity and on biospheric stability — which follow.

7. On toxicity

There is no doubt that widespread fear of exposure to toxic chemicals is one of the major driving forces behind the environmental movement. The near hysterical media coverage of the "Love Canal" episode, and the proliferation of "Superfund" sites, certainly support this contention. Yet, as a basis for discussing environmental threats half a century hence, one needs a different kind of evidence. Unfortunately, methodological problems proliferate even faster than superfund sites.

First, the number of industrial chemicals produced in annual quantities greater than 1 metric ton is estimated at 60,000. The number grows by thousands each year. Only a tiny percentage of these has been tested for the whole range of toxic effects. In fact, it could be argued that none has, since new effects are being discovered all the time, often by accident, or from epidemiological evidence long after the fact. For instance, mercury was not known to be harmful in the environment until the mysterious outbreak of "Minimata disease", a severe and sometimes lethal neurological disorder among cats, seabirds and fishermen living

near Minimata bay, in Japan. It took several years before public health workers were able to trace the problem to organic mercury compounds (mainly methyl mercury) in fish from the bay. The ultimate source turned out to be inorganic mercury from spent catalysts discharged by a nearby chemical plant. The toxic effects of cadmium ("itai-itai disease") were discovered in a similar way.

Second, quantitative production and consumption data for chemicals are not published consistently even on a national basis, still less on a worldwide basis. Data can be obtained only with great difficulty, from indirect sources (such as market studies) and only for the top 200 or so chemicals. In the U.S. and virtually all countries with a central statistical office (or census), production and shipments data are collected, but the data are withheld for "proprietary" reasons if the number of producers is three or fewer. In Europe, the largest producer of most chemicals, all quantitative production and trade data are suppressed. Data are published only in terms of "ranges" so wide (e.g. between 100 tonnes and 10,000 tonnes) that the official published numbers are useless for analysis.

Data on toxic chemical emissions is extremely scarce. EPA's Office of Toxic Wastes is the only official primary source of such data in the world, and its major tool is the so-called Toxic Release Inventory (TRI), which is an annual survey that has been in effect since 1987. The survey must be filled out by U.S. manufacturing firms (SIC 20-39) with 10 or more employees and that produce, import, process or use more than a threshold amount of any of 300 listed chemicals. The reporting threshold as regards production or processing for each chemical was initially (1987) 75,000 pounds; since 1989 it has been 25,000 pounds (roughly 12 metric tons), while for use the reporting threshold is now set at 10,000 pounds (roughly 4.5 metric tons) per year. Releases are reported by medium (air, water, land) and transfers for disposal purposes to other sites are also reported. There is serious doubt as to both the completeness and the accuracy of the TRI reports, since published data are very difficult to reconcile with materials balance estimates, as discussed elsewhere [Ayres & Ayres 1996].

Third, a large number of manufactured chemicals — probably the vast majority, in terms of numbers, if not tonnages — are not produced because they are really needed as such, but because they are available as by-products of other chemical processes. This is particularly true of products of chlorination and ammonylation reactions, which require repeated separation (e.g. distillation) and recycling stages to obtain reasonably pure final products. For instance, it has been estimated that 400 chlorinated compounds are used for their own sake, but at least 4000 are listed in the directories [Braungart 1992]. This is because it is easier to treat them as "products" than as wastes. Many such chemicals are found in products like pesticides, paint thinners and paint removers, dry-cleaning agents, plasticizing agents, etc.

Fourth, many of the most dangerous toxic chemicals are known to be produced by side reactions in the manufacturing process, or "downstream" reactions in the environment. Perhaps the most infamous toxic/carcinogenic chemicals are the so-called "dioxins", which are not produced for their own sake, but appear to be minor contaminants of some chlorinated benzene compounds that are used for herbicide manufacturing. Thus dioxins were accidental contaminants in the well-known herbicide 2-4-D that became known as "Agent Orange" during the Vietnam war. They are also probably produced by incinerators and other non-industrial combustion processes, depending on what is burned. As regards downstream processes, the example of methyl mercury — produced by anaerobic bacteria in sediments — was mentioned earlier. Exactly the same problem arises in the case of dimethyl and trimethyl arsine, extremely toxic volatile compounds that are generated by bacterial action on arsenical pesticide (or other) residues left in the soil. Still other examples would be the dangerous carcinogens such as Benz(a)pyrene (BAP) and per-acyl nitrate (PAN) produced by reactions between unburned hydrocarbons, especially aromatics, nitrogen oxides (NO_x) and

ozone. (This occurs in Los Angeles "smog", for instance). In fact, oxides of nitrogen themselves are toxic. Not only is NO_x produced by most high temperature combustion processes, but also by atmospheric electrical discharges.

An even more indirect downstream effect is exemplified by the *Waldsterben* in central Europe. The conifer trees of the Black Forest and much of the Alps are now being weakened and many are dying. This appears to be the result of a complex sequence of effects starting with increased acidity of the soil. As the pH drops below 6 there is a sharply increased mobilization of aluminum ions, which are toxic to plants. There is also an increased mobilization of heavy metals hitherto fixed in insoluble complexes with clay particles. Many toxic heavy metals — from pesticides, or from deposition of fly ash from coal burning — have long been immobilized by adherence to clay particles, at relatively high pH levels (thanks, in part, to liming of agricultural soils). However, as the topsoil erodes due to intensive agriculture, it is being washed into streams and rivers and, eventually, into estuaries, bays such as the Chesapeake, or enclosed seas (such as the Baltic, the Adriatic, the Aegean or the Black Sea), where it accumulates.

This sedimentary material is "relatively" harmless as long as the local environment is anaerobic, except for the localized risk of bacterial methylation of mercury, arsenic and cadmium mentioned earlier. But this accumulated sedimentary stock of heavy metals (and other persistent toxic chemicals too) would become much more dangerous in the event of a sudden exposure to oxygen. For instance, sediments dredged from rivers and harbors may be rapidly acidified and could become "toxic time bombs" [Stigliani 1988].

Fifth, many toxic compounds are produced naturally by plants and animals, largely as protection against predators, or as means of immobilizing prey. Nicotine, rotenone (from pyrethrum), heroin and morphine (from opium), cocaine, curare, digitalis, belladonna and other alkaloids are well-known examples from the plant world. Recent research suggests that natural (i.e. biologically produced) compounds have about the same probability of being toxic or carcinogenic as synthetic compounds. The widespread idea that "natural" products are *ipso facto* safer than synthetic ones is apparently false. In fact, Bruce Ames (inventor of the "Ames test") has argued with considerable force that the use of synthetic pesticides is less dangerous, to humans, than reliance on "non-chemical" methods of agricultural production, because plants produce greater quantities of natural toxins when they are under stress. However, probably even less is known about the range of toxic effects from natural chemicals than from industrial chemicals.

In fact, there is no general theory of toxicity. It comes in many colors and varieties. The notion includes mutagenic effects only visible after generations, effects on the reproductive cycle, and carcinogenic effects (e.g. asbestos, dioxins, vinyl chloride), or chronic but minor degradation of physiological function. At the other extreme are acute effects resulting in rapid or even instantaneous death. Methyl isocyanate (MIC), the cause of the Bhopal disaster, is an example of the latter. Chlorinated pesticides and PCB's were not even thought to be dangerous to humans until long after they had been in widespread use. It was belatedly discovered that these chemicals tend to accumulate in fatty animal tissues and to be concentrated as they move higher in the food chain. Eagles, Falcons and Ospreys were nearly wiped out in some areas by DDT because their eggshells were weakened to the point of non-viability.

As noted above, soil acidification resulting from anthropogenic emissions of SO_2 and NO_x to the atmosphere is also releasing toxic metals (and other compounds) that were formerly immobilized in the soil. Large accumulations of toxic metals reside in the soils and sediments in some areas. For many decades lead arsenate was used as an insecticide, especially in apple orchards. Copper sulfate and mercury compounds (among others) were widely used to control

fungal diseases of plants. Mercury was also used to prevent felt hats from being attacked by decay organisms. Chromium was, and still is, used for the same purpose to protect leather from decay. Copper, lead, nickel and zinc ores were roasted in air to drive off the sulfur (and the arsenic and cadmium). Lead paint was used for more than a century, for both exterior and interior surfaces. For half a century TEL and TML were used as gasoline octane additives (they still are so used in much of the world). Soft coal has been burned profusely in urban areas; usually the bottom ash was used as land fill for airports and roads. Coal ash contains trace quantities of virtually every toxic metal, from arsenic to mercury to vanadium. For decades, phosphate fertilizers have been spread on farmlands without removing the cadmium contaminants. In all of these cases, increasing acidity means increased mobilization of toxic metals. These metals eventually enter the human food chain, via crops or cows milk.

It is clear that toxicity is not simply a problem associated with production and use of industrial chemicals, or heavy metals. It is intimately linked to a number of other anthropogenic processes, not least of which is global acidification. To take another example, it is well-known that CFCs emitted to the atmosphere are responsible for depleting the ozone layer in the stratosphere. The major consequence on the earth's surface is an increase in the intensity of harmful UV radiation reaching the surface. Spawning zooplankton and fish in shallow surface waters are likely to be adversely affected. This is, in effect, a form of eco-toxicity.

Is there any common factor among all these types of toxicity? It can be argued that all human toxins are, in effect, causes of physiological disturbance. All interfere with some biological process. Mutagens interfere with the replication of the DNA molecule itself. Carcinogens interfere with the immune system; neurotoxins (e.g. cyanide) interfere with the ability of the nerves to convey messages. Many toxins cause problems for the organism because they closely resemble other compounds that perform an essential function. Thus carbon monoxide causes suffocation because it binds to the hemoglobin in the blood, like oxygen does. But, when the hemoglobin carrier arrives at a cell in need of oxygen, the potential recipient only "sees" a carbon atom where an oxygen atom should be.

The point of this example is that *toxicity*, to an organism, is just another word for *imbalance*, or *disturbance*. A toxin is an agent that causes some metabolic or biological process to go awry. Every organism has a metabolism. Metabolic processes are cyclic self-organizing systems far away from thermodynamic equilibrium. The same statement can be made of the metabolic processes — the "grand nutrient cycles" such as the carbon and nitrogen cycles — that regulate the whole biosphere. Any disturbance to the latter is "toxic", in principle.

8. The stability of the biosphere: impossibility of computing the odds

The fundamental question as to whether the stability of the biosphere is at risk, was deferred. This is a very deep question indeed.

First, a quick review of the case for believing there may be a real threat to survival. Most people who have never thought deeply about the matter tend to assume that life is a passive "free rider" on the earth. In other words, most people suppose (or were taught) that life exists on earth simply because earth happened to offer a suitable environment for life to evolve. They imagine that earth was much like it is now (except for more volcanic activity) before life came along, and that if life were to be snuffed out by some cosmic accident — say a massive solar flare — the animals and plants would disappear, but the inanimate rivers, lakes, oceans and oxygen-nitrogen atmosphere would still remain much as they are today.

The above quasi-biblical vision is not in accord with the scientific evidence. It is true that

life probably originated on earth (though some scientists speculate that the basic chemical components of all living systems may actually have originated in a cold interstellar cloud [Hoyle & Wickramasinghe 1978]). However life certainly evolved on earth. The earliest living organisms appear to have been capable of metabolizing organic compounds (such as sugars) by fermentation, to yield energy and waste products such as alcohols. The organic (but non-living) "food" for these simple organisms was created by still-unknown processes in a reducing environment. The composition of the atmosphere of the early earth cannot be reconstructed with great accuracy, but it undoubtedly contained ammonia, hydrogen sulfide and carbon-dioxide, plus water vapor. There was certainly no free oxygen. It is less certain, but possible that no free nitrogen present. Life would have disappeared as soon as the supply of "food" was exhausted, if it had not been for the evolutionary "invention" of photosynthesis.⁷

The first photosynthetic organisms converted carbon-dioxide and water vapor into sugars, thus replenishing the food supply. But they also generated free oxygen as a waste product. For a billion years, or so, the free oxygen produced by photosynthesis was immediately combined with soluble ferrous iron ions dissolved in the oceans, yielding insoluble ferric iron. Similarly hydrogen sulfide and soluble sulfites were oxidized to insoluble sulfates. These were deposited on the ocean floors. Thanks to tectonic activity, some of them eventually rose above sea level and became land. (Virtually all commercial iron ores, and gypsum, now being mined by humans are of biological origin). When the dissolved oxygen acceptors were used up, oxygen began to build up in the atmosphere. As a metabolic waste product, oxygen was toxic to the anaerobic organisms that produced it. Again, there was a threat of self-extinction.

Once again, an evolutionary "invention" came to the rescue. This was the advent of aerobic respiration, which utilized the former waste product (oxygen) and also increased the efficiency of energy production seven-fold over the earlier fermentation process. Aerobic photosynthesis followed, thus closing the carbon cycle (more or less) for the first time. This occurred less than one billion years ago, though life has existed on the earth for at least 3.5 billion years. But the carbon cycle and the earth's atmosphere did not stabilize for several hundred million more years. The free oxygen in the atmosphere exists only because large quantities of carbon, with which it was originally combined, have been *sequestered* in two forms: (1) as calcium carbonate, in the shells of tiny marine organisms (where they later reappear as chalk, diatomaceous earth, or limestone) or (2) as coal or shale. The carbon sequestering process took place over several hundred million years — a period culminating in the so-called *carboniferous era* — during which the carbon-dioxide content of the atmosphere declined to its present very low level. In addition, sulfur has been sequestered, primarily as sulfates. Similarly, though somewhat less certainly, the free nitrogen in the earth's atmosphere was probably originally combined with hydrogen, in the form of ammonia of volcanic origin. Whereas the carbon has mostly been buried, the missing hydrogen has probably recombined with oxygen as water vapor.

The early atmosphere and hydrosphere of the earth were quite alkaline compared to the present, because of the ammonia. The hydrogen-rich *reducing* atmosphere of the early earth has been replaced by an *oxygenating* atmosphere; the hydrosphere is correspondingly more acid than it once was before life appeared. The biosphere has stabilized the atmosphere (and the climate), at least for the last several hundred million years. If all life disappeared suddenly today, the oxygen in the atmosphere would gradually but inexorably recombine with atmospheric nitrogen and buried hydrocarbons and sulfides (converting them eventually to carbon dioxide, nitric acid, nitrates, sulfuric acid and sulfates). Water would be mostly bound into solid minerals, such as gypsum (hydrated calcium sulfate). This oxygenation process would also further increase the acidity of the environment.

Suppose all possible chemical reactions among carbon, nitrogen and sulfur compounds — including those currently sequestered in sediments and sedimentary rocks — proceed to thermodynamic equilibrium. The atmosphere would consist mainly of carbon dioxide. The final state of thermodynamic equilibrium would be totally inhospitable to life. (For one thing, the temperature would rise to around 300 degrees Celsius). Once dead, the planet could never be revived [Lovelock 1979]. *Table II* displays some of these "ideal" effects.

The point of the capsule history of the earth shown in *Table II* is that our planet is, in reality, an extraordinarily complex interactive system in which the biosphere is not just a passive passenger but an active element. It is important to establish that the earth (atmosphere, hydrosphere, geosphere, biosphere) is a **self-organizing system** (in the sense popularized by Prigogine and his colleagues, e.g. [Prigogine & Stengers 1984]), in a stable state far from thermodynamic equilibrium. This system maintains its orderly character by capturing and utilizing a stream of high quality radiant energy from the sun. Living organisms perform this function, along with other essential functions such as the closure of the carbon cycle and the nitrogen cycle [Schlesinger 1991].

Complex systems stabilized by feedback loops are essentially non-linear. An important characteristic of the dynamic behavior of some non-linear systems is the phenomenon known as **chaos**. Such systems are characterized by trajectories that move unpredictably around regions of phase-space known as **strange attractors**. "Stability", for such a system means that the trajectory tends to remain within a relatively well-defined envelope. However, a further characteristic of non-linear multi-stable dynamic systems is that they can "jump" — also unpredictably — from one attractor to another. (Such jumps have been called "catastrophes" by the French mathematician René Thom, who has classified the various theoretical possibilities for continuous systems). The **resilience** of a non-linear dynamic system — its tendency to remain within the domain of its original attractor — is not determinable by any known scientific theory or measurement. In fact, since the motion of a non-linear system along its trajectory is inherently unpredictable (though deterministic), the resilience of the earth-system is probably unknowable with any degree of confidence. It is like a rubber band whose strength and elasticity we have no way of measuring.

The climate of the earth, with its feedback linkages to the biosphere, is a non-linear complex system. It has been stable for a long time. However, there is no scientific way to predict just how far the system can be driven away from its stable quasi-equilibrium by anthropogenic perturbing forces before it will jump suddenly to another stable quasi-equilibrium. Nor is there any way to predict how far the equilibrium will move if it does jump. The earth's climate, and the environment as a whole, may indeed be very resilient and capable of absorbing a lot of punishment. Then again, it may not.

What can be gained by more research? Probably we can learn a lot about the nature of the earth-climate-biosphere interaction. We will learn a lot about the specific mechanisms. We will learn how to model the behavior of the system, at least in simplified form. We will learn something about the stability of the models. We may, or may not, learn anything definitive about the stability of the real system. The real system is too complex, and too non-linear, for exact calculations. There is no prospect at all of "knowing the odds" and making a rational calculation of risk. The problem we face is that the odds cannot be calculated, even in principle. In the circumstances, prudence would seem to dictate buying some insurance. The question on which reasonable people can still differ is: how much insurance is it worthwhile to buy? The answer depends, in part on the technological alternatives

9. Technical pre-conditions for sustainability

Given the previous discussion, one can identify the following hypothetical necessary (but not sufficient) conditions for long-term sustainability:

- No increase in the atmospheric concentration of "greenhouse gases" (beyond some limit yet to be determined).
- No increase in environmental acidification (hydrogen ion concentration) in surface waters and soils (beyond some limit).
- No increase in toxic heavy metal concentrations in soils and sediments (beyond some limit).
- No further topsoil erosion, beyond the rate of natural soil formation.
- No further degradation of groundwater with nitrates and nitrites; no further drawdown of "fossil" (non-replaceable) groundwater.
- Preservation of (most of) the remaining tropical rain-forests, estuarine zones, coral reefs, and other ecologically important habitats. No further disappearance of species.

A shorter list that is substantially equivalent to the above has been set forth by Holmberg, Robèrt and Eriksson [Holmberg *et al* 1995]. Their list (paraphrased) is as follows:

- No accumulation of substances taken from the earth's crust in 'nature' i.e. the biosphere or its supporting physical systems (atmosphere, oceans, topsoil).
- No accumulation of synthetic materials produced by man in natural systems.
- No interference by man in the conditions for biospheric diversity and stability.
- Natural resources should be utilized as efficiently as possible.

To satisfy these conditions, several straightforward implications can be drawn. Among them are the following:

- (i) Use of fossil fuels must stop increasing and must drop to very low (and declining) levels by the middle of the next century;
- (ii) Agricultural, forestry and fishery practices must be radically overhauled and improved, with much less dependence on chemicals and mechanization;
- (iii) Net emissions to the environment of long-lived toxic chemical compounds (especially compounds of the toxic heavy metals and halogenated organics) must drop to near zero levels by the middle of the next century, or so.

To simplify even further, one can argue that the average materials-intensity per unit service (MIPS) must be decreased radically for society as a whole [Schmidt-Bleek 1992;

1994]. Putting it another way, which is perhaps more acceptable to economists, I think that sustainability in the long-run requires a very sharp increase — by at least a factor of four and perhaps a factor of ten — in the *materials productivity* of our society.⁸ While such a radical productivity increase may seem utopian at first, it is well to recall that labor productivity in the western world has increased by much larger factors, perhaps a hundred-fold or more, since the beginning of the Industrial Revolution, largely by substituting capital goods and energy from fossil fuels for human and animal labor. What I am suggesting now amounts to a minor (but necessary) reversal of that historical substitution trend. In short, the time has come to substitute a modest additional amount of human labor to achieve a radical decrease in the extraction, mobilization and discard of physical materials and fuels.

10. Do technically feasible solutions exist?

The last question (#3.2) was: Is there a range of plausible technological possibilities that would be compatible with long-run eco-sustainability? Paraphrased in less abstract language, the question is whether sustainability is *technically feasible* for a stable population of 10 to 12 billion people living with "middle class" (or higher) standards of living in the very long run (say, by the end of the next century)? This question, as such, is hardly new. The negative position has been strongly and somewhat dogmatically asserted in the past by some environmentalists of the "no growth" school, notably Paul Ehrlich [Ehrlich 1968; Ehrlich & Ehrlich 1970], and Barry Commoner [Commoner 1971, 1976]. Most economists, however, did not and do not subscribe to this view, at least in its original (somewhat simplistic) form.

The main counter-argument adduced by economists like Beckerman, Nordhaus and Solow against the neo-Malthusians (e.g. Meadows *et al*) was, and is, that, given the right incentives — prices — and time enough, technology is capable of finding a way to avoid essentially *any* physical resource bottleneck, as long as the product or service in question is produced and exchanged within the competitive market system. However, this answer is much too theoretical to be satisfying. It really avoids the question; it does not answer it.

To attempt an "existence proof" of at least one plausible long-run solution (setting aside the question of cost, for the moment) the technical implications of eco-sustainability must be spelled out more precisely. As noted already, agricultural and industrial activity today is almost entirely dependent on fossil fuels (and also on dissipative uses of toxic chemicals and heavy metals) whose extraction and use harm the environment. This pattern is clearly incompatible with long-term sustainability.

It is obviously not possible to describe, in detail, technology based on discoveries and inventions that still lie in the future, perhaps a century hence. However, the constraints imposed by the definition of sustainability limit the range of possibilities worth exploring considerably. In addition, it is possible to carry out a major part of the analysis in terms of macro-scale indicators of technological performance that could be achieved in many different ways.

For example, it is clear that sustainability requires much more efficient use of energy in the future than we observe today. Some improvement will occur as a direct consequence of the fact that electricity is displacing other energy carriers, because of its convenience and cleanliness at the point-of-use. Electric space-heating can be quite economical (using heat pumps), especially in properly insulated buildings. (However, effective means of recycling refrigerant fluids will be necessary). Microwave cooking is so much faster and more efficient than its competitors (gas or electric ranges) that it is rapidly spreading anyhow.

Substitution of electric power for other fuels for space heating, hot water and cooking can

and will occur more or less quickly, assuming appropriate price incentives. There are no technological barriers. Most energy needs, except for transportation, can be supplied by electricity. Very long distance high voltage lines — or possibly superconducting lines — could distribute power around the globe, and even under the sea. Orbiting solar satellites, or lunar PV farms transmitting energy to earth via satellite are a possible variant.

Of course, there is little or no environmental advantage in using electricity if it is generated by burning fossil fuels. Fortunately, there are viable long-term alternatives on the supply side, including biomass and wind (near term), PV-electric and PV-hydrogen (longer term). Chapters in this book by Williams, Rogner and Frankl go into detail. Also, efficiency gains can reduce the need for more energy. Nuclear power (fission or fusion) cannot be ruled out of consideration. However both variants involve long term storage of radioactive wastes, not to mention other major costs that continue to escalate. Thus, nuclear options are less attractive in the very long run than the solar option.

Most mobile power sources at present (except for the few electric trams or trains) depend on liquid fuels derived from hydrocarbons. Up until the present time, centrally generated and wire-distributed electric power has not been economically attractive for mobile power, although it is technically feasible for local deliveries and commuting. Middle East petroleum will finally approach exhaustion around the middle of the next century (or sooner). It seems probable that electric vehicles (for short distances) will finally become economically competitive with any coal-based synthetic fuel, especially if coal is made to bear anything like its real environmental costs. There seems little doubt today that, sooner or later, the electric car will play a bigger role.

The fact that gasoline-burning vehicles are becoming increasingly intolerable in large cities suggests a plausible mechanism for this to come about: large cities plagued by traffic congestion, noise and smoggy air may begin to create "car-free" zones in their centers, permitting only small electric cars (as some lakes already permit only electric boats). At first, the electric cars will be found largely in these zones. But, these same central zones will also be accessed by high-speed electric (probably "mag-lev") intercity trains, which will finally begin to reverse the auto-induced suburban sprawl of recent decades. As time passes, the electric vehicles will get better and cheaper, the "electric" zones will spread to the suburbs, and eventually gasoline (or synfuel) powered ground vehicles will be essentially limited to rural use. By the second half of the next century electric vehicles may be able to extend their range by using automated mag-lev pallets along major intercity routes.

Electrification is only part of the solution. As suggested above, sustainability implies reliance mainly — if not entirely — on renewable sources of energy. In principle, the energy could easily be supplied by the sun, as combustible biomass, as direct heat for buildings, as heat to operate engines, or via photovoltaic cells. The latter, in turn, could generate hydrogen by electrolysis. (There are other possibilities too, including geothermal heat and nuclear fusion). The most likely solution seems to be a combination of wind power for irrigation water pumps, direct solar heating or "district heat-pumping" using waste heat from high temperature industrial processes to supply warm water for many buildings, and electrolytic hydrogen as a fuel for aircraft.

To reduce waste and pollution by converting it into raw materials is another technological and economic challenge of the next half century. To accomplish this structural change we need to create a whole new class of economic activities — the equivalent of decay organisms in an ecosystem — to capture useful components, compounds and elements and re-use them. In other words, the linear raw material-process-product chains characteristic of the present system must ultimately (within the next century, or so) be converted into closed cycles analogous to the nutrient cycles in the biosphere [Ayres 1989; Frosch & Gallopoulos 1989].

This new class of activities, called "industrial ecology", will gradually replace some of the extractive activities and associated waste disposal activities that are characteristic of the current system.⁹

The existence question can also be addressed theoretically by putting it in the negative sense: are there any fixed minimum materials/energy requirement to produce useful goods and services for humans? Or, are there fundamental limits to the amount of service (or welfare) that can be generated from a given energy and/or material input? If there is no such limit, then energy intensities and materials intensities can be reduced indefinitely; there can be no fixed relationship between primary energy or materials requirements and GNP.

In fact, if this condition is met there is, in principle, *no* theoretical maximum to the quantity of final services — i.e., economic welfare in the traditional sense — that can be produced within the market framework from a given physical resource input [Ayres & Kneese 1989]. It follows, too, that, there is *no* physical limit (except that imposed by the second law of thermodynamics) to the theoretical potential for energy conservation and materials recycling.

This restatement is actually critical to the fundamental case for optimism today. However, is not a "mainstream" view among engineers and "men of affairs", or even economists, at present. In common with the World Commission on Environment and Development (WCED), virtually all economists would regard continuing economic growth as both necessary and possible. However, the implication that economic growth can and must be permanently "delinked" from energy and materials use is far from universally accepted. (In short, most economists and business leaders have not thought through the consequences of their assumptions). In fact, something like an "existence proof" is needed, to demonstrate that there are feasible technologies which, if adopted, could end our current dependence on fossil fuels and substantially close the materials cycle.

This is still an area of sharp disagreement. The politically powerful extractive industry argues strongly for linkage:

"No doubt about it, we all need to be careful of the amount of energy we use. But as long as this nation's economy needs to grow, we are going to need energy to fuel that growth. ... For the foreseeable future, there are no viable alternatives to petroleum as the major source of energy ... Simply put, America is going to need more energy for all its people"

[Mobil Corp "Public Service" advertisement in the New York Times, April, 1991]

In other words, the conventional position is that economic growth cannot occur without more energy — i.e., a fixed relationship *does* exist.

In principle, any such fixed relationship between energy/materials use and economic activity would be quite inconsistent with fundamental axioms of economic theory, which assume general substitutability of all factors of production. Economists who are quick to attack neo-Malthusians for unjustified worry about natural resource scarcity should be equally optimistic about the potential for energy savings by increased conservation. Unfortunately, this is not the case, for reasons discussed later.

Optimism in regard to the potential for energy/materials conservation — or increasing energy/materials productivity — is also justified by recent history. The E/GNP ratio has been declining more or less continuously for many decades in the case of the advanced industrialized countries (*Figure 1*). Past experience suggests that this ratio tends to increase for countries that are in the early stages of industrialization, only to decrease later; this is the so-called "inverted U" phenomenon [World Bank 1992]. Moreover, countries industrializing

later have lower peaks than countries that industrialized earlier. Lower energy intensity reflects the shift from heavy industry to "high tech" and services. The trend would almost certainly continue in any case. It can probably be accelerated significantly by appropriate policy changes.

The Energy/GNP ratio is closely related to the thermodynamic efficiency with which the economy uses energy. For this purpose, it is convenient to define the so-called "second law" efficiency — or, in European parlance, the "exergy efficiency" — with which energy is converted from primary sources to final services¹⁰. Electricity is currently generated and delivered to homes with an overall efficiency of about 34% in the U.S. This figure has increased only slightly in recent years. Efficiency in LDCs is significantly lower, implying greater room for improvement. Energy experts generally agree that by the year 2050 this might increase to something like 55-60% for steam-electric plants, taking advantage of higher temperature (ceramic) turbines, combined cycles, co-generation, etc.

Energy is currently used very inefficiently to create final services, as compared to the first stage of energy conversion and distribution. The problem is that energy is lost and wasted at each step of the chain of successive conversions, from crude fuels to intermediates, to finished goods, to final services. For instance, incandescent lights (converting electricity to white light) are only 7% efficient (fluorescent lights are better). Moreover, lighting fixtures are typically deployed very inefficiently (c.10%) so that the final service (illumination where it is actually needed) is probably less than 1%. Electricity may be used less wastefully than fuel, although this is doubtful since many end-uses of electricity are extremely inefficient from a second-law perspective.

Second-law (exergy) end-use efficiency has been estimated at 2.5% for the U.S. as a whole [Ayres 1989]. This means that, in principle, the same final services (heat, light, transport, cooking, entertainment, etc.) could have been obtained by the expenditure of only 1/40 as much energy as was actually used. Western Europe and Japan are significantly more efficient (in the second-law sense defined above) than the U.S. Both regions are in the 4% range, while Eastern Europe, the Soviet Union, and the rest of the world are even less efficient than the U.S. — perhaps 1.5-2% [Schipper 1989; Nakicenovic *et al* 1990; Nakicenovic *et al* 1996]¹¹. For the world as a whole, it is likely that the overall efficiency with which fuel energy is used is currently no greater than 3-3.5%. But there is no fundamental technical reason why end-use efficiency could not be increased by several-fold (perhaps as much as a factor of 5) in the course of the next half century or so.

11. Finding the least-cost (least pain) path

To summarize, there are three technical elements to a program leading to long-term sustainability. The first is to reduce, and eventually eliminate, inherently dissipative uses of non-biodegradable materials, especially toxic ones (like heavy metals). This involves process change and what has come to be known as "clean technology". The second is to design products for easier disassembly and reuse, and for reduced environmental impact, known as "design for environment" or DFE. The third is to develop much more efficient technologies for recycling consumption waste materials, so as to eliminate the need to extract "virgin" materials that only make the problem worse in time.

There is also an important socio-economic and political dimension to the problem that we do not address sufficiently in this book. To state it very briefly, the strategies that maximize profits for an individual firm in the manufacturing sector of our competitive economic system tend to be the ones that exploit economies of scale and do so by

maximizing sales and production. The downstream consequences, in terms of energy consumption, pollution and final disposal of worn out goods is not the responsibility of the producer and is, therefore, not taken account of in either product design or pricing. Thus, competitive markets, as they currently function, tend to over-produce both goods and pollution, while simultaneously over-consuming natural resources. In short, there is an inherent dissonance — economists call it an externality — in the economic system that must be eliminated or compensated.

It does not follow that the resolution of this fundamental dissonance is to be found in public ownership. That "solution" clearly does not work. The next most obvious solution seems to be regulation. But the regulatory approach only works well when the regulations are simple and easy to enforce. It has worked well mainly in the case of outright bans on the production of certain products, such as DDT, PCBs and tetraethyl lead. But this strategy is also limited. It does not work well, for instance, when applied to widely used consumer products such as cigarettes, liquor, drugs, handguns or pornographic literature. "Green" taxes on resource consumption, or on pollution *per se*, are another possibility. But, there are at least two major drawbacks. One is that taxes on resource consumption — or pollution — tend to be regressive (hitting low-income consumers most heavily). The other drawback is that they would be complex to administer, because of the need to provide exceptions and exemptions e.g. for farmers, health workers, exporters *et al.* In practice, green taxes are probably not feasible at the national level. There would have to be major efforts at cross-border "harmonization" in order to maintain international competitiveness. Still other approaches are currently being explored, such as tradeable permits and quotas. However, there is very little experience of actual implementation for these newer ideas.

But, having said this much, the fundamental issue of compensating for externalities in the economic system is not addressed further in this or the following chapters.

It is not easy to discern a long term trend toward increasing recycling/re-use. Indeed, anecdotal evidence would suggest the contrary: poor societies recycle and re-use far more efficiently than rich ones. Also, the increasing complexity of both materials and products has made recycling and re-use more difficult in many cases. For instance, old wool clothes were once routinely collected by rag-merchants and recycled (after a complicated process of washing, unpicking, bleaching, re-spinning, re-weaving and re-dyeing) into blankets and pea-coats. Today, because of the prevalence of blends of natural and synthetic fibers, recycling is almost impossible. Much the same problem occurs in many other cases. To increase re-use and recycling, it may be necessary to induce manufacturers to sell services, rather than products, and/or to take back products they have previously made.

Re-manufacturing avoids many of the problems of re-cycling. This is not an important economic activity at present. However, it may grow, especially as the shortage of landfill sites induces municipal authorities (or, perhaps original equipment manufacturers forced by law to accept trade-ins) to offer subsidies. Remanufactured refrigerators, cars (or engines), and other large appliances can offer a good low-priced alternative to low income workers in the rich countries, or they could fill an important economic niche in the developing countries. Actually, since re-manufacturing will always be more labor-intensive than original equipment manufacturing (OEM), it is inherently a suitable activity for border regions such as Mexico, Eastern Europe or North Africa. (As these countries develop, of course, the "border regions" will shift too).

In the case of municipal wastes (mostly paper products and containers), recycling is already increasing in importance. Again, the shortage of land for disposal is mainly responsible. More efficient technologies for separating materials will certainly be developed in coming decades. In any case, there is no technical reason why the recycling/re-use rate for

most types of materials should not be dramatically increased from the low levels of today. This will happen, eventually, when material prices better reflect the true environmental costs of both extraction and use.

It is not really necessary to know in detail how this will be accomplished. It is sufficient to know that it is technically and economically feasible. (It remains, still, for policy makers to create the appropriate incentives to harness market forces. But this is a separate topic). Of course, specific "scenarios" might be helpful in making such a conclusion more credible to doubters. However this would serve a communications purpose rather than an analytic one.

Assuming the existence of a collection of potential technological "fixes" the last question follows: Is there a *feasible political/ institutional pathway* to get from "here" to "there"? What, in particular, is the role of economics? This question can be re-phrased to make the underlying problem clearer. Assuming technical and economic feasibility, it is reasonable to assume political feasibility if (and only if) there exists a painless (or near-painless) development trajectory, such that each incremental socio-economic change leaves every politically powerful interested party better off — or, at least no worse off — than before. Along such a path there must be very few or no losers. Everybody gets richer more or less automatically. This is called a "win-win" strategy, in the language of game theory. In more literary terms, it might be termed a "Panglossian" path.

To restate the question then: is there a Panglossian Path? The fundamental problem is that an affirmative answer (i.e. that low cost "win-win" solutions, or "free lunches" do exist) is essentially inconsistent with most economists' fundamental belief in profit maximizing behavior and perfect information. Given these assumptions, the economy would always be in (or close to) equilibrium and this equilibrium would reflect the most efficient (i.e., least-cost) choices of technology. If this were true, energy and natural resource conservation should cost a lot more money ("there is no free lunch"). This view seems to be supported by econometric data, based on historical responses of energy demand to price changes. These data indicate that higher prices encourage lower consumption, and vice versa. Reduced physical consumption is commonly interpreted by economists as "anti-growth".

It happens to be convenient to incorporate this set of assumptions in long term forecasting models based on the assumption of a quasi-general equilibrium varying slowly along an optimal path, over time [e.g. Edmonds & Reilly 1985; Manne & Richels 1989, 1990, 1992; Jorgenson & Wilcoxon 1990, 1990-a; Nordhaus 1994].¹² However, such models do not — and cannot — reflect the endogenous nature of technological change. How can an optimal path be determined that takes into account unpredictable technological change? Nor do these models reflect the distortions due to institutional barriers and "wrong" prices.

To explain the dilemma in non-economic terms, if a lot of "win-win" opportunities really do exist, then somehow these opportunities must have been overlooked by entrepreneurs. Assuming entrepreneurs always do what is in their own best (economic) interest, any real opportunities to make profits would be instantly snapped up, consequently no more such opportunities can exist.

The obvious flaw in this reasoning is that entrepreneurs are constantly finding opportunities for making extraordinary profits. If no profitable opportunities existed, there would be no entrepreneurs. Since there are many entrepreneurs, it follows logically that many more such profit opportunities must exist. In recent years, since environmental concerns have become more pressing, surprisingly many profitable opportunities have been found to reduce environmental pollution. To explain this, it must be assumed that industry and consumers have *not* always chosen the optimal energy technologies, even at present (too low) prices. Entrenched oligopolies or monopolies, established regulatory bodies, institutional separation between technological decision-makers and final consumers who pay the costs, lack of

technical information are the most likely reasons. (See, for instance, [Sant 1979; Lovins *et al* 1981; Goldemberg *et al* 1987; Ayres 1990, 1994; Mills *et al* 1991]). Inappropriately low prices due to subsidies (e.g. to coal mining and nuclear power) compounds the problem.

Fortunately, there is a potential link between increasing resource productivity and reducing unemployment. Unemployment is becoming a very serious political issue in Europe. Conservative (business-oriented) economists tend to blame the problem equally on high wages and benefits and "labor market rigidity" (i.e. the network of taxpayer supported measures known as the "social safety net"). But there is growing recognition that the tax system itself may be more to blame than the size of the public sector. The problem is that the "safety net" in Europe is financed almost exclusively by taxes on labor, whereas the use of energy and materials by industry is virtually untaxed (except for motor fuel) and, in many countries, fossil energy is heavily subsidized.¹³

Up to now, environmentalists have approached the issue of environmental protection largely as a regulatory problem. Regulations in this field are now numerous, burdensome and — in many cases — inefficient. As an alternative, environmental economists have recommended schemes like effluent taxes, but this approach has not been strongly supported by the business community (which, surprisingly, is less opposed to regulation than its rhetoric would suggest). Environmental economists argue that revenue from effluent taxes and resource-based taxes could be used to reduce other unpopular taxes, such as taxes on savings or investment. Conservatives fear that "revenue neutrality" would not be adhered to in practice, and that any increase in government revenue would be used to finance more "spending".

In recent years another scheme, "tradeable permits" has received some support. The idea here is that "rights to pollute" would be issued, but in limited amounts corresponding to the total target level for a given pollutant. The initial allocation system could be either "free" to current polluters, or based on an auction (like offshore oil rights). Once allocated, these rights would be tradeable. Those firms able to reduce their emissions below their entitlements could sell the excess entitlement. This possibility would induce firms to innovate. The revenues would remain in the private sector and government revenues (after the initial auction, at least) would not be increased by such a system.

The tradeable permit is opposed by many environmentalists on moral grounds. It is argued that there should be no "right to pollute", and certainly it is repugnant that such a right should be purchased for money. But, to some extent, this issue is a matter of perception. For instance, consumers now have an implicit "right" to pollute by virtue of the fact that they have a right to consume. Thus, the right to consume gasoline, for instance, could be rationed equally. Those able and willing to consume less than their "share" could be allowed to sell the excess. This would actually provide a kind of minimum income for the poor and elderly (if they do not drive cars) and could serve as a partial substitute for existing and increasingly unaffordable social services provided by the government from taxes.

The main alternative to regulation is to use emission-based or resource-based taxes or exchangeable permits, as a method of internalization of environmental damage costs. For both regulation or standard-setting, and for the use of emissions taxes or permits, there is still a problem of enforcement and a role for government. On the one hand, bureaucrats must determine the standards; on the other hand, they must set the scale of fees or fix the allocation of permits, and regulate the operation of the market mechanism to minimize opportunities for fraud. In any case, government must also monitor the effects of the policy.

Unfortunately, a "win-win" path is not necessarily painless. Those now receiving subsidies will experience pain. Those who cannot reduce their pollution levels by innovation will have to pay more. This being acknowledged, the obvious implication is that a truly

painless pathway to an ecologically sustainable future may *not* exist! If a painless path does not exist, or cannot be found, it means that to get from our present techno-economic state to one capable of permanent sustainability — even by the "least pain" route — significant short-term adjustment costs must eventually be borne by some groups or institutions. This means, in turn, that some very hard decisions will have to be taken, and soon. Unfortunately, experience suggests reason to doubt that our chaotic world of nearly 200 sovereign nation states can make such a transition successfully. Nevertheless, if the human race is to have a long term future, we must make the attempt.

Notwithstanding the difficulties, I think there is a "win-win" path to sustainability, or at least a policy that could take us a good part of the way in the right direction. I have noted that, if a single "objective function" for societal sustainability were to be selected, it would probably have to be something like the following: *to sharply increase the productivity of natural resources, especially non-renewables*. The reason this could turn out to be a "win-win" strategy is that increasing resource productivity implies decreasing the use of natural resources as a substitute for human labor. This, in turn, implies increasing employment! Since high unemployment (together with increasing associated costs of social security) is one of our most persistent socio-economic problems in the West, it seems only logical to explore possibilities for solving both the sustainability problem and the unemployment problem with a single common policy approach. It may not be too much to hope that this approach will also be beneficial to the less developed countries and the developing countries.

At first glance, increasing employment seems to imply decreasing labor productivity, which is *not* consistent with continuing economic growth. In the short run, some measures to increase resource productivity — especially by using less energy — may temporarily have this effect. Recycling tends to be more labor intensive than manufacturing with virgin materials, for instance. However, in the longer run, the object is to increase *total factor productivity*, while using a lot less resources and a little more labor. This can be done, I believe, by reducing the cost of labor and increasing the cost of material resources while encouraging technological innovation and the development of new (but not resource-intensive) services.

At any rate, it seems clear that there are some promising possibilities to be explored. This exploration is critically important. Some will say that society must seek pathways to long-run eco-sustainability, regardless of what the cost in conventional economic terms turns out to be, whether high or negative (i.e. profitable). If the latter turns out to be the case, so much the better. However, society will be much slower to adopt a high cost path than a profitable one. Indeed, there is good reason to fear that, if the cost (or pain) appears too high, the difficult decisions will be delayed too long — perhaps until it is too late.

12. Concluding comments

For a pessimist (or, by his own estimation, a "realist"), the deeper question lying behind all of the foregoing is this: should we defer taking actions that might have economic costs (at least to some sectors) in the hope that further research will reveal that the threat is overstated or non-existent? Needless to say, those likely to be affected adversely by restructuring changes — especially the extractive industries — will tend to argue vociferously for delaying any serious action until more research is done. Scientists, too, are usually in favor of more research. Both these groups are influential. Hence, the argument for delay is likely to prevail indefinitely, or until there is "indisputable" evidence of the seriousness of the problems.

A case in point: the scientific predictions of ozone depletion between 1974 and 1984

were countered by protracted arguments for delay by the affected industries. It was only after the discovery of the "ozone hole" that the resistance crumbled and the Montreal Protocol was adopted.

Unfortunately, in some cases indisputable evidence may not be available until it is too late to reverse, or prevent, major damage. Indeed, the damage itself may *be* the only convincing evidence. For example, the skeptics about climate warming may not be convinced until the average temperature of the earth has risen by half a degree or so (with accompanying sea level rise). By that time, hundreds of thousands of hectares of low-lying land may have become unproductive or uninhabitable, and hundreds of thousands of peasants in Bangladesh or Indonesia may have been killed by floods. Thus it is particularly important to state clearly the case for not waiting until the evidence is "indisputable". It is also important to develop clear and defensible criteria for (1) when looking is better than leaping, and (2) when it is time to stop looking and leap, even into the dark.

It need hardly be said that most elected officials in most countries are committed (at least in public) not only to the existence of such a painless development trajectory, but to the idea that we are already moving along it, thanks to the "invisible hand" of the free market. According to this comforting view, (which, it must be said, is supported by many mainstream economists) market forces left to operate with minimal government intervention will automatically induce the necessary technological responses. These "techno-fixes" (it is assumed) will compensate for gradual resource exhaustion and environmental degradation.

I believe that the optimistic view that the free market will take care of the problem is false and unwarranted. The present path is one in which virtually all of the trends are clearly in the wrong direction, as I have taken some pains to explain above. Energy use, exhaustible resource use, erosion, toxic pollution and waste are all increasing globally.

It is not enough to establish a plausible case that technical solutions do exist. The institutional framework of society, as it is structured today, is not likely to allow these solutions to emerge spontaneously. If unregulated competitive markets were going to solve these problems, there should be some indication of it: the trends, at least, should be in the right direction. There is no such indication. The fact we must face is that competitive "free" markets are imperfect. Market forces do not function in some of the critical areas. Alternative approaches are going to be needed. Governments must intervene on several fronts. They must increase the level of R&D support in critical areas (notwithstanding the usual criticism that governments should not attempt to "pick winners").

Governments must also intervene to eliminate or compensate for externalities. Regulation is only part of the answer. "Green" taxes may be another part. The encouragement of voluntary agreements may be a part, also. Tradeable pollution permits, or tradeable consumption permits may be a part of the answer in the future. But all of these interventions will have the effect, separately and cumulatively, of increasing the cost of resources *vis a vis* labor and capital. This is the negative view. It has led many economists to conclude (with the assistance of so-called computable general equilibrium or CGE models) that environmental regulation, by driving up costs, must inevitably reduce the rate of growth of the economy.

The other side of this coin is that rising resource costs imply *ipso facto* that labor and some kinds of capital (especially knowledge-based capital) will be relatively less expensive, *vis a vis* resource inputs. The argument can be turned on its head. When one factor of production becomes less expensive than another, that factor will be more utilized. The factor that is to become less expensive is labor. This implies — or seems to imply — that the demand for labor can be expected to increase. In other words, costlier material resource inputs => more jobs, less unemployment.

Actually, this outcome would be a kind of "double dividend", if it can be achieved. But

theory is one thing, practice is another. The service sectors are growing, to be sure. If the costs of physical materials were to increase (to compensate for externalities) this trend should accelerate. But the "growing tip" of the service sector is "high tech". It is health services, biotechnologies, telecommunications and information technologies. Unemployed factory workers or miners cannot easily convert themselves into medical technologists or network systems managers. Since older, uneducated people are very difficult to retrain, the transition is limited by the rate at which skilled and educated young people can enter the labor force.

This, again, is an area requiring government intervention. In brief, governments must invest much more in human capital. This will be increasingly difficult to finance in an environment of extreme budgetary stringency that will have to be faced by virtually every industrialized western country in coming decades.

But the socio-economic and political dimensions of eco-restructuring are far more complex than even the last few paragraphs have suggested. As noted earlier, the socio-economic and political aspects of the "eco-restructuring" problem deserve — and must ultimately get — much more attention than they have yet received. Indeed, it is a subject for another book...

Endnotes

1. Toxics and carcinogens are considered dangerous from a human health point of view and are therefore commonly placed under strict control, irrespective of whether ecological consequences are likely or not.
2. Phosphorus is the other nutrient element that is required in amounts greater than the earth's crust normally contains. It is not recycled biologically, however, but accumulates on the ocean floors where it is recycled by ocean currents and by tectonic action. If the earth ever ceased to be tectonically active, the land surface would eventually run out of phosphorus.
3. Agreeing on the common use of simple and crude measure is nothing new. The gross domestic product (GDP) has been used for decades as a measure of "welfare" despite serious doubts that it really measures any such thing. It omits important sectors, including subsistence agriculture and unpaid household work (mostly by women), and it omits environmental services. On the other hand, it includes dubious items, like "defensive measures" to protect health and safety, despite the fact that the health and safety hazards result from human activity in the first place. Clearly defensive expenditures make no contribution to net social welfare. Nevertheless, GDP is still being used by macro-economists, almost universally, without any of the adjustments or corrections that numerous critics have advocated.
4. The Wuppertal calculations of mass moved, or mass disturbed, generally include more than material "inputs" in the strict sense. The difference may be quite significant in some cases.
5. For a more complete review of this controversy see [Ayres 1993].
6. It is unclear what should be meant by "middle class". To put a specific monetary equivalent on it seems futile. A more functional suggestion might be that the relevant criterion of middle-class-ness is that children do not contribute to the family income, but rather constitute a financial obligation.
7. Some scientists argue that organic synthesis of a sort may have been going on in the reducing atmosphere of the early earth by mechanisms as yet unknown.
8. The argument for "factor four" is set forth in a recent book (in German) by E. U. von Weizsäcker, A. B. Lovins & L. H. Lovins *Faktor Vier* (Droemer Knauer, München, 1995); the argument for "factor ten" is summarized in the *Carnoules Declaration*, Factor Ten Club, F. Schmidt-Bleek, Wuppertal Institute, 1994.

9. The phrase "closed cycle" should not be taken literally. Closure with respect to materials is possible, but the cycle cannot be closed with respect to exergy.
10. The "second law" efficiency of any process is defined as the ratio of the minimum amount of energy theoretically needed for the process to the energy actually used. It can be defined consistently, in principle, for any process (given a suitable convention on the treatment of co-inputs and by-products), although actual numerical determination can be difficult in some cases. It must be pointed out that there is another widely used definition of efficiency, namely the ratio of "useful" energy outputs to total energy inputs. In some cases, such as electric power generation, the two definitions are equivalent. However in other cases (such as heating units) there is a very big difference. Gas furnaces are often advertised as having "efficiencies" up to 90%, which merely means that 90% of the heat is "useful" and only 10% is lost up with the combustion products. However, it often happens that the same amount of final heating effect could have been achieved with much less energy expenditure (e.g. by means of a "heat pump"). In this sense, most heating systems are actually very inefficient.
11. Note that efficiency of use is quite independent of the amount of use. The U.S. uses by far more energy per capita than India, for instance, because it receives more energy services. But many energy using activities in India, from electric power generation to cooking, nevertheless tend to be considerably less efficient than their western counterparts.
12. For a more detailed review of this literature see [Ayres 1994].
13. This issue was highlighted in the 1994 "White Paper" *Growth, Competitiveness, Employment— The Challenges and Ways Forward into the 21st Century*: issued by Jacques Delors, then Chairman of the European Commission [EC 1994].

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Table I: Sustainable vs expected level of environmental impact for selected indicators

<i>Dimension/indicator of environmental impact</i>	<i>Sustainable level</i>	<i>Expected level 2040</i>	<i>Desired reduction</i>	<i>Scale</i>
DEPLETION OF FOSSIL FUELS:				
• oil	stock for 50 years	stock exhausted	85%	global
• natural gas	stock for 50 years	stock exhausted	70%	global
• coal	stock for 50 years	stock exhausted	20%	global
DEPLETION OF METALS:				
• aluminum	stock for 50 years	stock for >50 years	none	global
• copper	stock for 50 years	stock exhausted	80%	global
• uranium	stock for 50 years	depends on use of nuclear energy	not quantifiable	global
DEPLETION OF RENEWABLE RESOURCES:				
Biomass	20% terr. animal biomass	50% terr. animal biomass	60%	global
	20% terr. primary production	50% terr. primary production	60%	global
Diversity of species	extinction of 5 species per year	365 - 65,000 species per year	99%	global
POLLUTION:				
Emission of CO ₂	2.6 gigatonnes carbon per year	13.0 gigatonnes carbon per year	80%	global
Acid deposition	400 acid eq. per hectare per year	2400 - 3600 acid eq.	85%	continental
Deposition nutrients	P: 30 kg per hectare per year N: 267 kg per hectare per year	No quantitative data No quantitative data	not quantifiable not quantifiable	national national
Deposition of metals:				
• deposition of cadmium	2 tonnes per year	50 tonnes per year	95%	national
• deposition of copper	70 tonnes per year	830 tonnes per year	90%	national
• deposition of lead	58 tonnes per year	700 tonnes per year	90%	national
• deposition of zinc	215 tonnes per year	5190 tonnes per year	95%	national
ENCROACHMENT:				
Impairment through de-hydration	reference year 1950	no quantitative data	not quantifiable	national
soil loss through erosion	9.3 billion tonnes per year	45 to 60 million tonnes per year	85%	global

Source: [Weterings & Opschoor 1992: Table 6, page 25]

Table II: The stabilizing influence of the biosphere (Gaia)

<i>Reservoir</i>	<i>Substance</i>	<i>Actual world</i>	<i>Ideal world I</i>	<i>Ideal world II</i>
Atmosphere	Nitrogen	78%	0%	1.9%
	Oxygen	21%	0%	trace
	CO ₂	0.03%	99%	98%
	Argon	1%	1%	0.1%
Hydrosphere	Water	96%	85%	? Not much water
	NaCl	3.4%	13%	?
	NaNO ₃	—	1.7%	?
Temperature	Degrees Celsius	13	290 ± 50	290 ± 50
Pressure	Atmospheres	1	60	60

Note: Life is impossible if average temperature is too high for liquid water, or if salinity exceeds 6%.

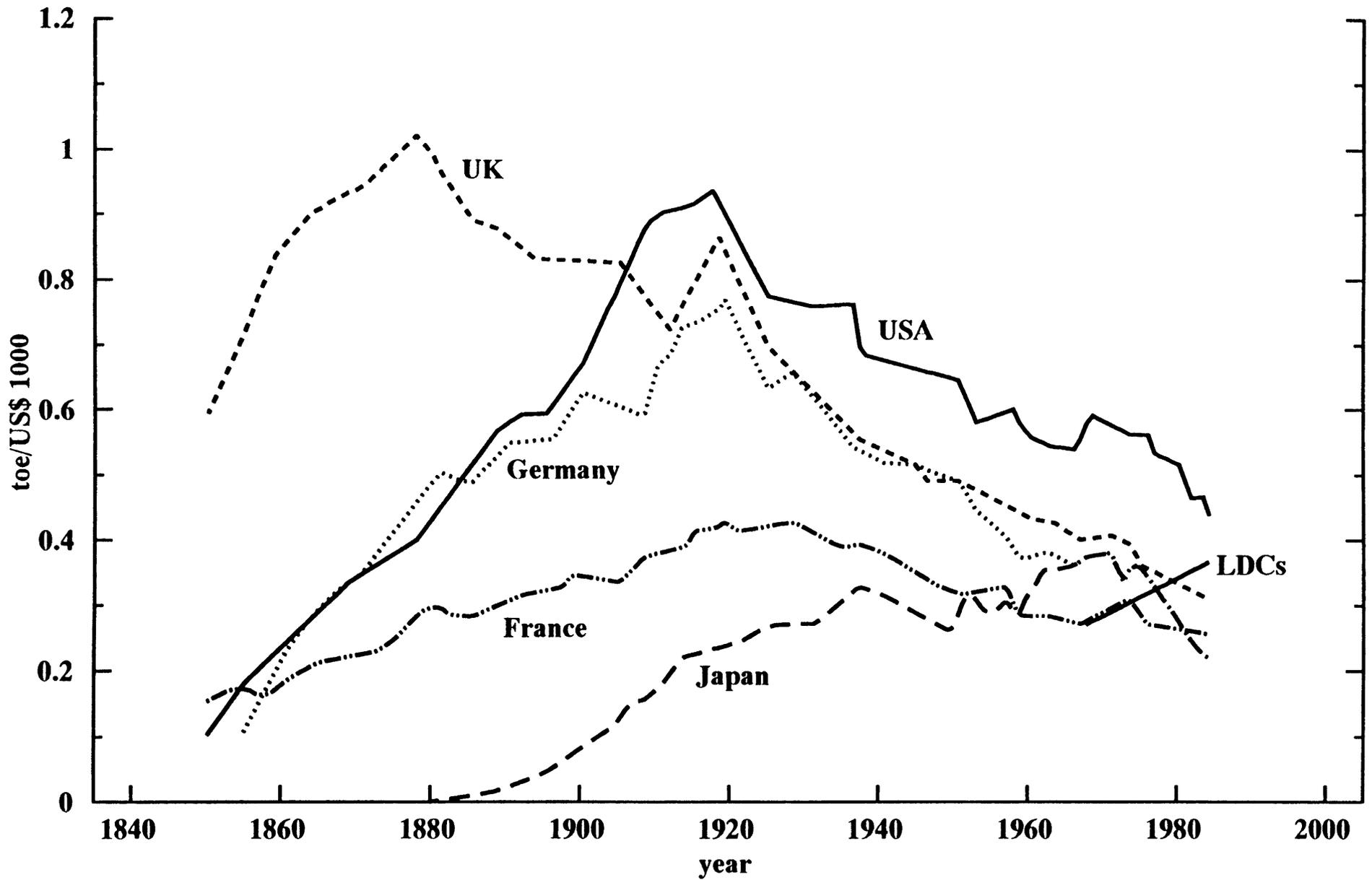


Figure 1: Long term trends in energy intensity