Notes on Implementing Sustainable Development

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August 1999

Working Paper Series
Stern #IS-99-2

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March 3, 1998

ABSTRACT. "Sustainable Development" refers to a set of issues relating to two general questions: (1) Are the presently prevailing technologies and life-styles of economic development so destructive of the earth's natural resources and environment that the current pace of development cannot be maintained? (2) If so, what combinations of technology, life-style, and rate of growth are sustainable in the 'long-run,' and what mechanisms of cooperation and incentives can be devised to implement them? After providing some introductory background material for newcomers to the subject, and concluding that the answer to the first question is "yes," I sketch some challenges to economic theory implied by the second question. In particular, I argue that, for transnational issues like global warming, the 'standard' approaches of mechanism design theory are inadequate in the absence of a world government or equivalent institution for enforcing cooperative agreements. On the other hand, the typical large multiplicity of noncooperative equilibria of such global dynamic "games" creates a role for analysts to discover (invent?) equilibria that are superior to the status-quo equilibrium, if indeed the current situation can reasonably be interpreted as a (dynamic) equilibrium. I explore this idea in the context of an oversimplified model of the "Global Warming Game."

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1. BACKGROUND

The dramatic rise of the world's population in the last three centuries, coupled with an even more dramatic acceleration of economic development in some parts of the world, has led to a transformation of the natural environment by humans that is unprecedented in its scale. The magnitude and rate of this transformation have led many experts to question whether the present rate of economic development can be sustained for much longer without very significant global changes in technology, and even in the life style of economically developed societies. The group of issues arising out of these questions has come to be called the problem of "sustainable development" (SD).

There is no generally acceptable definition of the concept of SD. A much-quoted definition was formulated by the World Commission on Environment and Development (Bruntland, 1987, p.43): "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." So-called "strong" versions of SD require that certain specified resources or characteristics of the environment (e.g., ecosystems, atmospheric carbon dioxide) be maintained within specified limits. "Weak" forms of SD require that some measure of social well-being (e.g., GNP per capita) not decline over time.

At this stage of my exposition, it is not necessary to fix upon a particular definition of SD. Instead, I shall mention a number of more specific problems that, if not solved in some manner, may pose a threat to SD, however defined:

1. global warming,
2. depletion of cheap energy sources,
3. depletion of the ozone layer,
4. exhaustion of arable land,
5. loss of vital ecosystems (e.g., watersheds, wetlands, food chains),
6. reduction of biodiversity,
7. smog, acid rain, other air pollution,
8. buildup of toxic wastes,
9. pollution of water supplies.

Many of these problems are interrelated, often in complex ways. For example, deforestation contributes to global warming (see below) and the loss of ecosystems, e.g., watersheds. The latter contributes to the pollution of water supplies by destroying natural water-purification systems. Deforestation may also result in increased erosion, which in turn reduces the supply of arable land, and may result in the destruction of natural habitats, which in turn reduces biodiversity.

Finally, I must mention:

10. population growth,

which need not be a problem in itself, but contributes to the causes of the preceding problems. Figure 1 shows the growth of human population in broad historical perspective. According to Deevey (1960), there were three "spurts," associated with the tool-making, agricultural, and industrial "revolutions," respectively. In recent times, growth rates have been falling gradually, with approximately zero growth rates in many developed countries. The current world human population is about 5 1/2 billion. Figure 2 shows various forecasts of the world population between now and 2150. For example, the World Bank forecasts that the population will approximately double by 2150. The UN "medium" forecast is of a leveling off at about 10 billion by 2100, with a range of major projections from 8 to 15 billion. A doubling of the world population in this period would certainly aggravate most or all of the problems listed above, unless there were important changes in technology and/or life styles.

In what follows I shall focus primarily on the problem of global warming. This problem poses interesting theoretical challenges for several reasons:

(1) It is international is scope, and will require international, or at least transnational, cooperation for its solution; [Note: I shall use the term "transnational" to refer to groups of more than one country, but not necessarily all countries.]

(2) Its dynamics are long-lasting, and reversibility, even if possible, is very slow;

(3) Because of the long time scale (point 2 above), the issues of intergenerational equity are significant;

(4) Because of significant international differences in population, rates of population growth, levels of economic development, and cultural attitudes, issues of international equity are also significant; and

(5) Although the scientific basis of global warming is qualitatively established, there is considerable quantitative uncertainty (and disagreement) about its dynamics and its consequences.

There have, of course, been dramatic fluctuations in the Earth's climate during its history. For example, on a geological time scale the last ice age ended only recently. However, the threat of "global warming" (GW) is that, under "business as usual," the temperature of the atmosphere near ground level may increase by almost 6 degrees C. by the year 2100. (See Cline, 1992, pp. 4 ff., for the sources of this and other estimates, some of which are lower. See also Bruce et al, 1996, and Thomson, 1997.) The mechanism of this warming trend is the so-called *greenhouse effect.* "Carbon dioxide and [certain] trace gases (methane, CFCs, nitrous oxide, ozone) are transparent to incoming shortwave solar radiation but opaque to outgoing longwave (infrared) radiation from the earth. Their natural levels raise the earth's average temperature by some 33 degrees C. (from -18 degrees to +15 degrees)." [Cline, 1992, p. 4.]

Carbon dioxide (CO_2) is by far the most important of the "greenhouse gases," at least for the time frame we are considering, and I shall focus on it. (In what follows, I shall talk about "CO_2 equivalents," when it is important to make the distinction. (On the problems of "emissions accounting" for greenhouse gases, see Grubler and Fijii, 1992.)

Carbon dioxide is produced by the metabolism of living organisms, and by other activities of humans. On the other hand, CO_2 is broken down by photosynthesis in plants. We can think of this as a "negative emission." (Photosynthetic plants break down CO_2 during the day, and produce it at night.) Also, as the concentration of CO_2 in the atmosphere increases, the oceans recapture some of it, but very slowly. The net result of these activities is a net emission rate of CO_2. Currently, the burning of fossil fuels accounts for most of the carbon emissions actually produced by humans. However, the destruction of forests and other changes in land use have reduced the rate of global photosynthesis. This, in turn, reduces the rate at which CO_2 is removed from the atmosphere, thus increasing the net emission of CO_2. Figure 3 shows the history of net CO_2 emissions from fossil-fuel use, changes in forest and soil, and cement production from 1800 to 1987. We see that fossil-fuel use currently accounts for more than two-thirds of the (net) emissions, with changes in forest and land use accounting for most of the rest.

Almost all of the burning of fossil fuels is done for the purpose of producing energy. Figure 4 shows the shares of different regions in current and past energy-related carbon emissions. Note that North America currently produces about 27 percent of such emissions, with the bulk of this coming from the U.S. Note, too, that the current share of Asia (not including Japan) is double its cumulative share since 1800, reflecting its recent spurt in economic development. Of the regions listed, the share of Asia ranks second. On the other hand, the current and cumulative shares of North America are about equal. If we look at per capita carbon emissions from fossil-fuel use (Figure 5), the picture is somewhat different. North America still ranks first in both current and cumulative emissions (per capita), whereas Asia is about at the bottom. A notable feature of Fig. 5 is that in all regions these per-capita emissions have increased substantially, reflecting the pace of economic development. Furthermore, given the large population of Asia, and its rate of population growth, if per capita carbon emissions in Asia were to increase to North American and Western European levels, the total emissions from Asia would increase enormously.

In recent times, almost all of our energy has been derived from the burning of fossil fuels, with some contribution from moving water, and very recently, from atomic power (the combined contribution of "solar energy," geothermal sources, and windmills is still negligible). Nevertheless, the world is becoming more "efficient" in its use of carbon. One way to see this is provided by Figure 6, which shows, for a selection of countries, the relationship between (1) the ratio of carbon emissions to Gross Domestic Product (GDP), on the vertical axis, and (2) per-capita GDP, on the horizontal axis, over periods of time for which data are available. In almost all of the countries, carbon/GDP has declined with an increase in per-capita GDP Another view is provided by Figure 7, which shows recent time trends in carbon emissions per unit of energy, for five countries. Note that for the most recent available year, India and China use roughly fifty percent more carbon per unit of energy than do France, Japan, and the U.S.

The potential for the reduction of carbon emissions associated with the use of energy has three potential sources: increased efficiency in the production of energy, increased efficiency in the use of energy, and changes in the consumption of the services of energy.

In part, the progressive "decarbonization" of energy production is associated with the movement from coal to oil and natural gas.

“Carbon matters because it burns; combustion releases energy.....Carbon enters the energy economy in the hydrocarbon fuels, coal, oil, and gas, as well as wood. In fact, the truly desirable element in these fuels for energy generation is not their carbon (C) but their hydrogen (H). Wood weighs in heavily at ten effective Cs for each H. Coal approaches parity with one or two Cs per H, while oil improves to two H per C, and a molecule of natural gas (methane) is a carbon-trim CH4......Physical scientists can measure decarbonization in its elemental form, as the evolution of the atomic ratio of hydrogen to carbon in the world fuel mix. This analysis reveals the unrelenting though slow ascendance of hydrogen in the energy market." (Ausubel, 1996, pp. 3,4.)

Energy from hydrogen fusion reactors would represent the ultimate in decarbonization. Unfortunately, it appears that formidable technical problems remain to be solved before this method becomes practical. Other, similarly "decarbonized" technologies for energy production are nuclear, hydroelectric, solar, geothermal, and wind.

Another source of decarbonization is increased efficiency in the utilization of energy, coming from improvements in the design of electric generation and transmission systems, electric motors, combustion engines, manufacturing systems, heating and cooling systems, etc. Recall that a "good stove did not emerge until 1744 AD. Benjamin Franklin's invention proved to be a momentous event for the forests and woodpiles of America." (Ausubel, 1996, p. 4.) A review of this topic is beyond the scope of these Notes. However, it may be significant that, whereas the generation and transmission of electricity is a "public utility" in most countries, and the production of many fossil fuels, especially coal, is subsidized by the state, the utilization of most energy is in private hands, and improvements in the efficiency of utilization can usually be appropriated by the developers.

The costs and benefits of global warming are subject to considerable uncertainty and debate. My discussion here is primarily qualitative, and is only intended to illustrate the points (1) - (5) above that make the problem theoretically challenging. (In my description of the costs and benefits, I have relied heavily on (Cline, 1992).) Roughly speaking, the costs and benefits of GW are themselves the results of two primary effects: (1) a rise in the sea level, and (2) climate changes. The rise in the sea level is caused by melting of glacial ice, especially at the poles, and to some extent by the thermal expansion of the sea water. The rise in the sea level would damage, and even eliminate, many coastlines, and would be particularly costly to low-lying areas, such as Bangladesh, the Netherlands, and the eastern seaboard of the U.S. (for example). Climate changes are more complex. In some parts of the world, like the northern latitudes of North America, the warming would be accompanied by higher rainfall. This, with the lengthening of the summer growing period, would increase the agricultural productivity of such areas, benefiting Canada, the U.S., and Russia. (It is also thought by some that higher CO_2 concentrations in the atmosphere would stimulate plant growth.) Other parts of the world, such as Sub-Saharan Africa, would probably become more arid and less productive agriculturally. Other effects would include:

a. Increased energy requirements for air-conditioning, only partially offset by reduced heating costs.

b. Lesser runoff in water basins, curtailing water supplies.

c. Increased urban air pollution (tropospheric ozone).

d. Damage to human health, e.g., resulting from increased heat stress, and from the increased incidence of malaria.

e. Forest loss.

f. Increased hurricane and fire damage.

g. Costly increased immigration.

Damages are likely to be nonlinear in the amount of warming. For example, "in the initial range, the Antarctic does not contribute to sea-level rise, because temperature in is a low range where increased melting is more than offset by increased snow carried by air with more moisture. On the scale of 10 degrees warming, however, the Antarctic would likely become a major source of sea-level rise, especially if the West Antarctic ice shelf should disintegrate. Similarly for agriculture, heat stress could be expected to impose nonlinear damage." (Cline, 1992, p. 6.) Such a nonlinearity, coupled with uncertainty, has an effect analogous to that of risk aversion. [Thus, if the marginal cost of GW is increasing with the degree of GW, and the degree of GW is uncertain, then the expected cost of GW will be greater than the cost of the expected value of the GW.]

The efforts to avoid GW will, of course, be costly. Immediate costs would be incurred if economies were forced to substitute more expensive but less carbon intensive technologies for producing energy. Cutbacks in energy use would also be costly in terms of lower levels of output of goods and services, including "amenities" such as household cooling. On the other hand: "...There is another body of literature that suggests that some initial ... cutback can be obtained for free. The engineering tradition cites several avenues (such as compact fluorescent lights) by which energy needs may be reduced at zero or even negative cost. Market imperfections such as utility pricing rules that do not reward energy saved may contribute to this situation.... [S]tudies by the U.S. National Academy of Sciences and others suggest that this initial tranche of zero-cost energy reduction may be on the order of 20 percent." (Cline, 1992, p. 7.) Perhaps most important, significant long-term reductions or even stabilization of carbon emissions would require significant research and development efforts, whose outcomes would also be uncertain. As usual, many of the outputs of such R&D efforts are likely to have the character of public goods, and hence require some form of governmental or social intervention.

It is tempting to apply cost-benefit analysis to the evaluation of GW polices.

Of course, for this one needs quantitative, not merely qualitative, assessments of the effects of GW. A conclusion of Cline's study (1992), which is among the more ambitious is this regard, is that, with "central values of key parameters, ... the ratio of the present discounted value of benefits to that of costs [of GW damage avoidance] is approximately 3:4," from which the reader would probably conclude that the avoidance of GW is not economically justified. However, a consideration of risk-aversion leads Cline to revise his estimate of the ratio of expected benefits to expected costs, obtaining a new ratio of 1.3 to 1. Cline is, of course, aware of the uncertainty that surrounds his estimates. (Cf. also [Nordhaus and Yang, 1996].)

Estimates of the net benefit of actions taken to prevent or abate GW depend heavily on the cost-benefit methodology that is used. For one thing, the long time period involved in the calculations make the choice of a discount rate (or rates) important. Second, as is typical in the case of most environmental issues, it is important to include all of the (sometimes hidden) costs and benefits, and to get the prices right, which is especially difficult for goods and services for which markets are imperfect or nonexistent. (See Ahmad, et al, 1989; Pearce, et al, 1989; Dasgupta and Mitra, 1997; Weitzman, 1995.) Third, the international (and even intranational) distribution of costs and benefits is highly non-uniform, as noted above with respect to changes in the sea-level and in agricultural productivity. For example, how would Bangladesh, whose per-capita income is significantly less than that of Canada, be induced to compensate the latter for the expense of abating GW, just because Canada would be a hypothetical beneficiary of GW through higher agricultural productivity? Or, for that matter, what would be the politics of getting the Eastern Seaboard states of the U.S. to compensate the upper Midwestern states, for the same reason? Finally, there is the question of how to account for risk, and especially "catastrophic" risks!

2. THEORETICAL PROBLEMS

2.1. National and Transnational Issues. We should distinguish between issues that are national from those that are transnational. Even for small countries, depletion of cheap energy sources, exhaustion of arable land, loss of vital ecosystems, smog and other local air pollution, local buildup of toxic wastes, and pollution of water supplies will typically be national issues. (Cf. the list in Sec. 1.) For national issues, one can imagine that the national government can pass laws and/or issue regulations that determine the "rules of the game" for participants (e.g., individuals, corporations, local governments), and enforce these rules. Here we have a standard mechanism design situation, in which one predicts that the outcome will be a Nash equilibrium (NE) of the game (possibly subject to certain refinements, with or without complete information, etc.). The task is to design a mechanism that implements (uniquely or otherwise) a given concept of sustainable development (SD). But there is also the task of getting the mechanism enacted into law (see below). For transnational issues, such as global warming, depletion of the ozone layer, oceanic pollution, depletion of food species in international waters, acid rain, and the buildup of other toxic wastes that cross national borders, there is no capability for higher-level enforcement, e.g., no world government to enforce the rules of a game. Exceptions might include the European Community and (to some extent) the United Nations, but thus far the UN has not shown itself willing to enforce environmental policies. In this case, the "rules of the game" are determined by the powers of the individual governments and the laws of Nature. If there is more than one NE of this game, then the problem of mechanism design is replaced by the problem of identifying the best equilibria, according to some global criterion. The analyst can contribute to the solution of this problem. However, a further task is to move the participants from the status quo to an optimal or superior NE.

2.2. National Issues and Mechanism Design. Most of my remarks in this talk will be directed towards transnational issues. However, even in the national case, the particular form of the national (or local) government will implicitly determine a game whose outcome is the mechanism that is adopted. For example, in the U.S. the adoption of national legislation to regulate toxic emissions is the outcome of a complicated legislative game whose players include the members of Congress, the Administration, and lobbyists and contributors to political campaign funds. Furthermore, as the U.S. experience with Prohibition (of alcoholic beverages) illustrates, the government's ability to enforce the rules of some "games" may be limited. This suggests that some further serious theoretical work is needed to bridge the gap between the "classical" formulation of the mechanism design problem and the theory of political action at the national and local level. This problem has not, of course, been neglected by political scientists and "political economists." (For thought-provoking discussions of these issues from a game-theoretic point of view, see Schotter, 1986, and Hurwicz, 1993, 1996.)

2.3. Transnational Issues. Transnational issues present a more difficult challenge to the theory of "mechanism design" than do national issues. In fact, as I have suggested above, because of the absence of a world government or equivalent authority in the environmental arena, the standard mechanism design paradigm is not applicable to transnational issues. Instead, from a game-theoretic point of view, the problem would appear to be one of moving the community of national governments from one dynamic (sequential) Nash equilibrium (NE) to another that one hopes is superior.

A good example to have in mind is the threat of global warming, described at some length in the previous section. Recall that, roughly speaking, on the relevant time scale, the evolution of global warming is a complicated function of the initial condition of the atmosphere (at some given date) and the subsequent history of global levels of "greenhouse gases," primarily carbon dioxide. These levels depend, in turn, on the history of global emissions of greenhouse gases by the burning of fossil fuels, the amount of forestation and other flora, etc. In addition, the local effects of global warming depend on the evolution of sea levels and temperatures, the melting of polar ice, weather patterns, and a number of other variables.

To the extent that the evolution of global warming depends on global (i.e., total world) emissions of greenhouse gasses, global forestation, etc., the situation is formally analogous to the "problem of the commons," as in the cases of fishing from a common population, or grazing on a common pasture. Thus we might expect to learn something about the structure of the set of NEs from the literature on the problem of the commons, although the law of motion in this case will be different. It is well known that such games typically have many NEs, some of which are Pareto superior to others. The situation here is analogous to the simpler case of "repeated games," but richer because of the presence of state variables that evolve through time, and hence the results of the theory of repeated games cannot be blindly applied to such dynamic games. A typical situation is that there is a set of NEs in which, at any date, the actions of the players depend only on the state variable(s), but not directly on the past actions of the other players. Such NEs are called Markovian; they correspond in some rough sense to the equilibria of repeated games in which players repeatedly play equilibrium strategies of the one-stage game. Other NEs may involve strategies in which players react directly to past actions of the other players; these NEs can often be interpreted in the language of "retaliation against departures from cooperative behavior." Although I am not aware of any general theorem to this effect, it would appear that Markovian NEs typically display "competitive" behavior that is inefficient in a "commons" context, whereas NEs that involve threats of retaliation can be used to sustain more cooperative and globally efficient behavior. (See, e.g., Benhabib and Radner, 1992; Dutta and Sundaram, 1996; Radner, 1991.) This phenomenon is illustrated in Section 3, in the context of a simple model of a "global warming game."

For example, in a plausible model of two nations fishing in a common fishing-ground, the total discounted quantity of jointly harvested fish is maximized by doing no fishing until the fish population reaches some critical level, and then (jointly) harvesting at a rate that just maintains the fish population at that level. (For example, the two nations may each harvest at one half the optimal rate, once the critical level has been reached.) However, one NE may involve "overfishing" to the extent that the population of fish tends asymptotically to zero. In another pair of strategies (sometimes called "trigger strategies), each nation observes the other's fishing rate, and reverts to the "overfishing NE" rate if the other ever departs from the jointly optimal rate. The second pair of strategies will be a NE if the players' discount rates are not too large, relative to the other data of the problem, in which case it will sustain a jointly optimal total rate of fishing. (See Benhabib and Radner, 1992, for a related model and references to other literature.) Note that, if the dynamics of the fish population are stochastic, it will not be possible to infer with certainty from the observation of the current fish population alone whether the other nation has followed the jointly optimal fishing policy. Hence, in order to implement the second (jointly optimal) NE, it will be necessary for each nation to observe the other's fishing rate, not just the evolution of the fish population. In this sense, the "overfishing NE" will be Markovian, whereas the second, jointly optimal, NE will not.

We may interpret the negotiation of a treaty or other (nonbinding) transnational agreement as the process of moving to a new NE. [Note: Victor and Skolnikoff (1997) describe "how governments, industry, and nongovernmental organizations put [transnational] environmental agreements into practice" in a way that lends itself to this interpretation, although they do not use the language of game theory.] However, we don't have a good theory of how this is done, or at least a good theory that is compatible with game theory (although the general situation is reminiscent of the theory of "renegotiation-proofness). If the status quo were a NE, then we could imagine a bargaining "metagame" in which the players negotiate a move to a new NE. For example, suppose that (1) the status quo will have a very bad outcome for all players after some specific date (call this date the "deadline"); (2) the target NE has been specified in advance (i.e., there is no process of negotiating the specific terms of the agreement): (3) each player signals a commitment to the agreement by taking some irreversible action (like incurring a sunk cost); (3) certain subsets of players are sufficient to "initiate" the new NE; then we might interpret the situation as a "war of attrition with a deadline." [Note: This observation is due to Giuseppe Lopomo, in a private communication.]

In modeling such games, we may ask which simplifications are least harmful, and which are to be avoided. For example, in the area of global warming, scientific and technological uncertainty will typically be important, whereas the relevant scientific information will typically be widely available (at least to scientists), so that it may be relatively safe to assume that the available scientific information is common knowledge (although the *preferences* for costs and benefits may be private). On the other hand, there will typically be dramatic asymmetries in the situations of the players (e.g., size, capital stocks, stage of industrial development, per capita income, education, etc.), so that the common practice of game theorists of analyzing symmetric games will usually be seriously inappropriate.

[Note: Nordhaus and Yang (1996) use a model with a diversity of country types to contrast "cooperative" and "noncooperative" policies. However, their "noncooperative" equilibrium is a Nash equilibrium in so-called "open-loop policies," i.e., each country is able to commit to a time path of actions that is adhered to whatever the subsequent states of the system or actions of the other countries. It is difficult to justify the realism of such commitments, and in particular the corresponding equilibria do not in general satisfy the requirement of subgame perfection, although it is not known to me in what respect they would differ from any of the equilibria described above in this particular application.]

2.4. Intertemporal and Distributional Preferences. Issues in sustainable development usually (but not always) concern significant and persistent costs and benefits in the fairly distant future, say 50 to 200 years from now. It is therefore important to give a good deal of thought to the representation of the intertemporal preferences of the relevant players. Here we can observe an apparent paradox. On the one hand, if future benefits are discounted at plausible "market" rates, their present value at relevant time horizons will be very small, and the net present value of environmental projects will typically be negative. (See the remarks on global warming in the previous section.) For example, if the discount rate is 8 percent, the discounted present value of one dollar 50 years from now is less than two cents. Even at a discount rate of 2 percent, the present value of one dollar 50 years from now is 37 cents, and the present value at year 200 is 0.18 cents. On the other hand, significant groups in many countries appear to be in favor of such projects with negative present value.

Some authors have proposed that, on ethical grounds, the standard procedures of discounting should not be applied to environmental projects. Others, citing experimental evidence, have argued that discounted present value does not adequately represent the preferences of "ordinary" economic agents (see the references cited in Chichilnisky, 1966b). Chichilnisky (1996a) has proposed a criterion that is a weighted average of a present discounted value and a "purely asymptotic" value. With this criterion, projects whose benefits and costs extend over only a finite period of time will be compared by their discounted present values, whereas a project whose benefits and costs are "infinitely long-lived" will have an additional value. Of course, the concept of "infinitely long-lived" benefits and/or costs must be taken with a grain of salt (at least in the material rather than spiritual realm), but may still be useful as an approximation when thinking about the "very long run."

Environmental projects also have diverse distributional consequences, among as well as within, nations and regions. Citizens and governments reveal by their actions that they are not entirely insensitive to these distributional issues, although this sensitivity may decrease with greater geographical and/or cultural remoteness. I have alluded to such distributional issues in the case of global warming, at the end of Section 1. At a national level, richer citizens of many countries are willing to be taxed progressively in order to provide poorer citizens (of the same country) with food, medical care, housing, and education. It is more difficult, however, to persuade these richer citizens to provide comparable benefits to the poorer citizens of other countries. [There is, of course, some question as to how much of these "welfare" programs are seen as "social insurance" rather than as "redistributive justice."] At an international level, countries may be more willing to aid "culturally similar" countries than "culturally distant" ones.

Both of these "non-neoclassical" types of preference - for asymptotic consequences and for distributional consequences - may present additional challenges for the game-theoretic analysis of sustainable development. It is also possible that the revealed intertemporal and distributional preferences of citizens and governments are not strictly self-consistent. [See (Schelling, 1995) for a thoughtful discussion of the relation between intertemporal and distributional preferences, and (Bradford, 1997) for a further discussion of the use of benefit-cost analysis of global warming.]

From a game-theoretic point of view, it is essential to try to represent realistically the preferences of the players as they are, rather than as the theorist thinks they "ought to be." As noted above, the evidence about the actual preferences of nations (if the concept is meaningful) may be mixed, but on the whole economists and game theorists tend to represent nations as largely impatient and selfish. Nevertheless, it would be interesting to examine the NEs of environmental games in which the players have "non-neoclassical" preferences, such as proposed by Chichilnisky (1996a).

2.5. Bounded Rationality. Nations, as well individuals, are boundedly rational, and one may question whether they play their games according to fully worked-out strategies, much less Nash Equilibrium profiles of strategies. If this caveat is significant, then one needs an alternative theory to predict the behavior of players in environmental games. In this case, one may also question the relevance of game-theoretic mechanism design, or its cousin, equilibrium selection, for the elucidation of social policy (see Radner, 1996), since mechanism design theory postulates that outcomes are NEs.

When we leave the strict confines of complete rationality and game theory, we enter the territory of "organizational behavior." Here we have to deal with elusive concepts such as "leadership" and "management style." At the individual level, the perceptions of different facets of SD may be distorted, not merely by ignorance and obsolete information, but also by various psychological mechanisms (see, e.g., Gladwin, et al, 1997). Whether there is a satisfactory way to bridge the gap between economics and game theory on the one hand, and the fields of individual and organizational psychology on the other, remains to be seen.

In spite of these caveats, it would seem to be a potentially useful exercise for the analyst to identify heretofore unrecognized dynamic self-enforcing profiles (sequential NEs) of international behavior that are superior to the status quo. In fact, if individuals and nations are boundedly rational, then the analysts have even more scope for influencing international behavior by exercising "leadership" or educating those who do. If one is not entirely to abandon the game-theoretic paradigm, a major challenge for the theorist is to model in a useful way how players move from one sequential equilibrium to another.

3. A SIMPLE GLOBAL WARMING GAME

3.1. The Model. In this section I contrast a Markov Nash Equilibrium (MNE) with the global Pareto optima (GPOs) for a greatly simplified model of a "global warming game." We shall see that the MNE emission rate for each country is higher than it is in any GPO. I shall also discuss the possible existence of equilibria that are Pareto superior to this MNE. Finally, in the context of a simple production-function model, I shall examine the effects on welfare and emission rates of changing the emission-producing technology.

There are I countries. The emission of (a scalar index of) greenhouse gases during period t by country i is denoted by $a_i(t)$. [Time is discrete, with $t = 0, 1, 2, ...$, ad inf., and the $a_i(t)$ are nonegative.] Let $A(t)$ denote the global (total) emission during period t;

$$A(t) = \sum_{i=1}^{I} a_i(t). \tag{1}$$

The total (global) stock of greenhouse gases (GHGs) at the beginning of period t is denoted by $g(t)+g_0$, where g_0 is what the "normal" steady-state stock of GHGs would be if there were negligible emissions from human sources (e.g., the level of GHGs in the year 1800). We might call $g(t)$ the *excess GHG*, but I shall usually suppress the word "excess." The law of motion for the GHG is

$$g(t+1) = A(t) + \sigma g(t), \tag{2}$$

where σ is a given parameter ($0 < \sigma < 1$). We may interpret $(1-\sigma)$ as the fraction of the beginning-of-period stock of GHG that is dissipated from the atmosphere during the period. The "surviving" stock, $\sigma g(t)$, is augmented by the quantity of global emissions, $A(t)$, during the same period. [Note: A realistic model of GHG dynamics would be more complicated; see (Thomson, 1997).]

Suppose that the utility of country i in period t is

$$v_i(t) = h_i[a_i(t)] - c_i g(t). \tag{3}$$

The function h_i represents, for example, what country i's gross national product would be at different levels of its own emissions, holding the global level of GHG constant. This function reflects the costs and benefits of producing and using energy from alternative sources, including fossil fuels. For a given population there will be an optimal level of energy use, and hence an optimal level of emissions, *not taking account of the costs of the stock of GHG*; call this the *myopically optimal* level of emissions. It therefore seems natural to assume that h_i is a strictly concave C^2 function that reaches a maximum at the myopically optimal level of emissions (finite) and then decreases thereafter. The parameter $c_i > 0$ represents the marginal cost to the country of increasing the global stock of GHG. Of course, it is not the stock of GHG itself that is costly, but the associated climatic conditions. In a more general model, the cost would be nonlinear. The total payoff (utility) for country i s

$$v_i = \sum_{t=0}^{\infty} \delta^t v_i(t) dt. \tag{4}$$

For the sake of simplicity, I have taken the discount factor, δ, to be the same for all countries. [Note: It has implicitly been assumed here that each country's population is constant in time. See Section 4 for comments on this issue. See also (Dutta and Radner, 1998).]

A *strategy* for a country determines for each period the country's emission level as a funtion of the entire past history of the system, including the past actions of all the countries. A *stationary strategy* for country i is function that maps the current state, g, into a current action, a_i. As usual, a *Nash Equilibrium* is a profile of strategies such that no individual country can increase its payoff by *unilaterally* changing its strategy. A *Markov Nash Equilibrium (MNE)* is a Nash Equilibrium in which every country's strategy is stationary.

[Note: The model described above is what Sobel (1990) calls an "affine dynamic model." The results in Sections 3.2 and 3.3 below follow from Sobel's paper, but I provide proofs here for the convenience of the reader. For a more complete characterization of the equilibria of this game, not covered in Sobel (1990), see (Dutta and Radner, 1998).]

3.2. The Global Pareto Optimum. Let $x = (x_i)$ be a vector of positive numbers, one for each country. A *Global Pareto Optimum (GPO)* corresponding to x is a profile of strategies that maximizes the weighted sum of country payoffs,

$$v = \sum_i x_i v_i, \tag{5}$$

which I shall call the *global welfare*. Without loss of generality, we may take the weights, x_i, to sum to I.

Theorem 1. *Let $\hat{V}(g)$ be the maximum attainable global welfare starting with an initial GHG stock equal to g; then*

$$\hat{V}(g) = u - wg, \tag{6}$$

$$w = \frac{1}{1-\delta\sigma} \sum_i x_i c_i,$$

$$u = \frac{1}{1-\delta} \left[\sum_i x_i h_i(\hat{a}_i) - \delta w \hat{A} \right],$$

$$\hat{A} = \sum_i \hat{a}_i,$$

where $\hat{a}_i$ is determined by

$$x_i h_i'(\hat{a}_i) = \delta w. \tag{7}$$

(It is assumed that this last equation has a solution.) Furthermore, country i's GPO strategy is to use a constant emission equal to $\hat{a}_i$ in all periods.

Proof. The proof uses a standard dynamic programming argument. Let $a = (a_i)$. It is sufficient to show that the value function, $\hat{V}$, given above satisfies the functional equation

$$\hat{V}(g) = \max_a \left\{ \sum_j x_j \left[h_j(a_j) - c_j g \right] + \delta \hat{V} \left[\sum_j a_j + \sigma g \right] \right\}. \tag{8}$$

The first-order condition for a maximum is that, for each i,

$$x_j h_j'(a_j) + \delta \hat{V}' \left[\sum_j a_j + \sigma g \right] = 0.$$

But $\hat{V} = -w$, so the optimal emission is independent of g, and is given by (7). The values of u and w are now determined by the equation

$$\hat{V}(g) = \sum_j x_j \left[h_j(\hat{a}_j) - c_j g \right] + \delta \hat{V} \left[\sum_j a_j + \sigma g \right],$$

which must be satisfied for all values of g.

3.3. A Markov-Nash Equilibrium. The next proposition describes a Markov Nash equilibrium. This MNE has the unusual feature that the equilibrium emission rate of each country is constant in time, and it is the unique MNE with this property. There are, however, other MNEs; see (Dutta and Radner, 1998).

Theorem 2. *Let g be the initial stock of GHG. For each country i, let $a_i{}^*$ be determined by*

$$h_i'(a_i{}^*) = \delta w_i, \tag{9}$$

$$w_i = \frac{c_i}{1-\delta\sigma},$$

and let its strategy be to use a constant emission equal to $a_i{}^*$ *in each period; then this strategy profile is a MNE, and country* i*'s corresponding payoff is*

$$\begin{aligned} V_i{}^*(g) &= u_i - w_i g, \\ u_i &= \frac{1}{1-\delta}\left[h_i(a_i{}^*) - \delta w_i A^*\right], \\ A^* &= \sum_j a_j{}^*. \end{aligned} \tag{10}$$

Note that

$$\sum_i w_i = w,$$

where w *is defined in (6).*

Proof. The proof uses an argument similar to that of Theorem 1. If the emissions of all countries other than i are constant, say a_j for country j, then country i faces a standard dynamic programming problem. It is sufficient to show that the value function $V_i{}^*$ satisfies the functional equation,

$$V_i{}^* = \max_{a_i}\left\{h_i(a_i) - c_i g + \delta V_i{}^*\left(\sum_j a_j + \sigma g\right).\right\}$$

The argument now proceeds as in the proof of Theorem 1.

Recall that both the globally optimal and MNE emission rates are constant in time. Let A be any constant global (total) emissions rate. The difference equation governing the evolution of the GHG stock is

$$g(t+1) = A + \sigma g(t). \tag{11}$$

This can be solved to give

$$g(t) = \sigma^t g + (1-\sigma^t)\tilde{g}, \tag{12}$$

where

$$\begin{aligned} g &= g(0), \\ \tilde{g} &= \frac{A}{1-\sigma}. \end{aligned} \tag{13}$$

The last quantity, $\tilde{g}$, is of course the steady-state GHG stock.

If the cost of the stock of GHG were nonlinear, then one would expect the GPO and MNE emissions to vary with the stock, and in fact one would expect higher stocks to lead to lower emissions.

3.4. Comparison of the GPO and the MNE. The preceding results enable us to compare the emissions in the GPO with those in the MNE:

$$\begin{aligned} \text{GPO} &: \qquad h_i'(\hat{a}_i) = \frac{\delta \sum_j x_j c_j}{x_i(1-\delta\sigma)}, \\ \text{MNE} &: \qquad h_i'(a_i{*}) = \frac{\delta c_i}{1-\delta\sigma}. \end{aligned} \tag{14}$$

From

$$x_i c_i < \sum_j x_j c_j,$$

it follows that

$$\frac{\delta c_i}{1-\delta\sigma} < \frac{\delta \sum_j x_j c_j}{x_i(1-\delta\sigma)}.$$

Since h_i is concave, it follows that

$$a_i{*} > \hat{a}_i. \tag{15}$$

Note that this inequality holds for all vectors of strictly positive weights (x_i). [I conjecture that this inequality would hold in a variety of models. Indeed, one can show in a quite general model that a GPO cannot be a MNE, or even that, starting from a GPO, each country will want to increase it emissions unilaterally by a small amount. However, to get the inequality (15) one probably needs more specific assumptions.]

It follows from these results that there is an open set of strictly positive weights (x_i) such that the corresponding GPO is strictly Pareto superior to the MNE. We are therefore led to search for (non-Markovian) Nash equilibria of the dynamic game that sustain a GPO, or at least are superior to the MNE. Such a program is beyond the scope of this paper, but related research (e.g., Benhabib and Radner, 1992) suggests that such a search might succeed.

3.5. Effects of Reducing Emission Factors. It is generally agreed that it will not be possible to achieve an acceptable level of global emissions of GHG without considerable research and development effort. If one expands the strategy spaces of the countries to include research and development, and technology transfers among countries, it may be possible to improve the MNE itself. From the second line of (14) we see that MNE emissions of a country would be reduced if the slope of the function h_i - call it the *technology function* - were reduced in the appropriate range. Recall that this function is maximized at a "myopically optimal" level of emissions. The MNE level is smaller than this (since at the MNE the slope of the technology function is strictly positive). The slope of the technology function to the left of the myopic optimum reflects the cost of reducing emissions below the myopic optimum;

the greater the marginal cost of doing this the steeper the slope. Technological innovations may reduce this marginal cost. If the costs to advanced countries of developing such innovations, and transferring them to other (presumably poorer), countries are not too high, it may be part of a MNE in such an "expanded" game for such activities to take place, thus moving the global economy along a path of declining emissions.

I shall illustrate this point in the context of a special case. Suppose that the emission of GHG is entirely caused by the production and consumption of energy (which is, of course, an exaggeration). Imagine that energy is an input in the production function of each country, along with other inputs like capital, labor, etc. Assume that, as a function of the input of energy, e_i, in country i, it's net output in a given period is $Y_i(e_i)$. Assume further that the country's emission of GHG during the period is proportional to the input of energy, say

$$a_i = f_i e_i. \tag{16}$$

I shall call the coefficient f_i the emission factor of country i. Thus the technology function is given by

$$h_i(a_i) = Y_i\left(\frac{a_i}{f_i}\right). \tag{17}$$

However, instead of directly applying Theorem 2 to characterize the MNE, it is slightly more transparent to take the energy inputs as the control variables. In this case, the law of motion (2) becomes:

$$\begin{aligned} g(t+1) &= A(t) + \sigma g(t), \\ A(t) &\equiv \sum_i f_i e_i(t). \end{aligned} \tag{18}$$

Note that $A(t)$ is a linear function of the energy inputs of the several countries, with coefficients equal to their respective emission factors. The MNE energy inputs, $e_i{*}$, are the solutions of the equations:

$$\begin{aligned} Y_i'(e_i{*}) &= f_i \delta w_i, \\ w_i &= \frac{c_i}{1-\delta\sigma}. \end{aligned} \tag{19}$$

The value function for country i is:

$$V_i{*}(g) = u_i - w_i g,$$

$$u_i = \frac{1}{1-\delta}\left[Y_i(e_i{*}) - \delta w_i A{*}\right], \tag{20}$$

$$A* \equiv \sum_j f_j e_j * .$$

Research and development that "decarbonizes" energy inputs without increasing the price of energy would have the effect of decreasing the emission factors. Somewhat paradoxically, *this need not lead to a decrease in emissions for that country.* From equation (17),

$$\frac{\partial a_i{*}}{\partial f_i} = e_i{*} + f_i \frac{\partial e_i{*}}{\partial f_i}. \tag{21}$$

Of course, if the energy input were held constant, then a decrease in the emission factor would result in a decrease in the emissions. However, from equation (20) and the strict concavity of the function Y_i, it is clear that

$$\frac{\partial e_i{*}}{\partial f_i} < 0, \tag{22}$$

Hence a *decrease* in the emission factor for a given country would result in an *increase* in its MNE energy input, thus having the effect of *increasing* its emissions. From (20),

$$\frac{\partial a_i{*}}{\partial f_i} > 0 \tag{23}$$

if and only if

$$\left(\frac{\partial \log e_i{*}}{\partial \log f_i}\right) = \left(\frac{\partial e_i{*}}{\partial f_i}\right)\left(\frac{f_i}{e_i}\right) > -1. \tag{24}$$

Note that the absolute value of the left-hand-side of (22) is what economists call the *elasticity* of $e_i{*}$ with respect to f_i. [See also (28) below, and the discussion leading up to it, for a special case.]

On the other hand, that country's welfare in the MNE will nevertheless be increased. To see this, first note that the coefficient w_i in the value function does not depend on the emission factor. Hence the value function is increasing in the emission factor if and only if the constant term, u_i, is increasing. From (20),

$$\begin{aligned}
(1-\delta)\frac{\partial u_i{*}}{\partial f_i} &= Y_i'(e_i{*})\frac{\partial e_i{*}}{\partial f_i} - \delta w_i \frac{\partial A{*}}{\partial f_i}; \\
\frac{\partial A{*}}{\partial f_i} &= \frac{\partial (f_i e_i{*})}{\partial f_i} = f_i \frac{\partial e_i{*}}{\partial f_i} + e_i{*}, \\
(1-\delta)\frac{\partial u_i{*}}{\partial f_i} &= Y_i'(e_i{*})\frac{\partial e_i{*}}{\partial f_i} - \delta w_i \left(f_i \frac{\partial e_i{*}}{\partial f_i} + e_i{*}\right) \\
&= \left(Y_i'(e_i{*}) - f_i \delta w_i\right)\frac{\partial e_i{*}}{\partial f_i} - f_i \delta e_i{*} \\
&= -f_i \delta e_i{*} < 0
\end{aligned}$$

(the last step following from the first-order condition (19). Hence I have proved:

Theorem 3. *For all g and i,*

$$V_i{}^*(g) \text{ is decreasing in the emission factor } f_i \text{ of country } i.$$

The effect on one country's MNE welfare of a change in another country's emission factor is not so unambiguous. From (20), for $j \neq i$,

$$(1-\delta)\frac{\partial u_i{}^*}{\partial f_j} = \delta w_i \frac{\partial A^*}{\partial f_j} = \delta w_i \frac{\partial a_j{}^*}{\partial f_j}, \tag{25}$$

and we saw in (23)-(24) that the sign of the last term depends on the elasticity of $e_i{}^*$ with respect to f_j. It follows that, if the cost of the R&D were sufficiently small, it might pay for a small group of advanced countries, or even a single advanced country, to develop a technology for reducing emission factors and transfer that technology to other countries, provided that (24) were satisfied for enough of the latter countries. A formal analysis of such situations is beyond the scope of this paper.

I illustrate these results with a special case of the "production function" Y_i :

$$Y_i(e_i) = \pi_i e_i^{\theta_i} - p_i e_i \ , \tag{26}$$

where π_i and θ_i are positive parameters, with $\theta_i < 1$,and p_i is the price of energy for country i, also a positive parameter. Such a formulation is consistent with a "Cobb-Douglas" production function in which labor is fixed exogenously, and the other inputs (e.g., capital, but excluding energy) are optimized accordingly. (See below for a further discussion of this point.)

In this special case, the MNE energy inputs are given by

$$e_i{}^* = \left(\frac{\theta i \pi_i}{p_i + f_i \delta w_i}\right)^{1/(1-\theta_i)} . \tag{27}$$

It turns out that the net effect on emissions depends on the size of the emission factor. It is straighforward to verify that

$$\frac{\partial a_i{}^*}{\partial f_i} > 0 \text{ iff } f_i < \left(\frac{1-\delta\sigma}{\delta}\right)\left(\frac{1-\theta_i}{\theta_i}\right)\left(\frac{p_i}{c_i}\right). \tag{28}$$

Thus *if the emission factor is sufficiently large, a decrease in it will result in an increase in MNE emissions for that country.*

I now take a closer look at the "production function" model in (26). Suppose that there are 3 factors of production, say capital, labor, and energy, and that the (net) output of a country in any period is determined by a "Cobb-Douglas" producton (to simplify the notation, I temporarily suppress the country subscript):

$$Y = \phi K^k L^\lambda e^\in - rK - pe, \tag{29}$$

where K, L, and e denote the inpits of capital, labor, and energy, respectively, and $\phi, k, \lambda, \in, r$, and p are positive parameters. Capital and energy are to be chosen optimally by the country (in the MNE), whereas labor is given exogenously, and is constant in time. I assume constant returns to scale:

$$k + \lambda + \in = 1. \tag{30}$$

The amount of capital has no effect on emissions, so it will be chosen to maximize Y. It is straightforward to verify that the optimal input of capital is:

$$K = \left(\frac{k\phi}{r}\right)^{\left(\frac{1}{1-k}\right)} L^\Lambda e^\theta, \tag{31}$$

$$\Lambda \equiv \left(\frac{\lambda}{\lambda + \in}\right), \theta \equiv \left(\frac{\in}{\lambda + \in}\right). \tag{32}$$

The corresponding output is:

$$\begin{aligned} Y &= \Phi L^\Lambda e^\theta - pe, \\ \Phi &\equiv \phi^{\left(\frac{1}{1-k}\right)} \left(\frac{k}{r}\right)^{\left(\frac{k}{1-k}\right)} (1-k). \end{aligned} \tag{33}$$

Of course, Φ should have a country subscript i, as should all of the parameters and variables. From this last we see that the coefficient, π_i , in (16) is given by:

$$\pi_i = \Phi_i L_i^{\Lambda_i}. \tag{34}$$

Since $\Lambda_i + \theta_i = 1$, it follows from (21) that *each country's MNE input of energy is proportional to its labor input, and hence so is its MNE level of emissions.*

One can also examine the effect on a Global Pareto Optimum of changing the emission factors of one or more countries. One obtains similar results, using arguments similar to those leading up to Theorem 3 and equation (25), but I omit the details.

4. CONCLUDING REMKARKS

I have argued that, for transnational problems like global warming, there is currently no effective world government to enforce desirable changes in the "rules of the game."

Hence the standard paradigm of "mechanism design" needs to be replaced by a search for Nash equilibria of an appropriately modeled global dynamic game that are Pareto superior to the current "business as usual" situation. I also suggested that is plausible that "business as usual" corresponds to a Markov-Nash equilibrium of the global dynamic game. This program poses a number of interesting challenges to the theorist, for a number of reasons:

1. The relevant "game" is not simply repeated; there are significant state variables that evolve through time.
2. There are dramatic asymmetries among the players.
3. Uncertainty is important.
4. There are significant problems of representing intertemporal and distributional preferences.
5. If one interprets a treaty as an articulation of a superior Nash equilibrium, then there is the question of how to move from the current equilibrium to the one described by the treaty.

I illustrated some of these ideas in the context of an oversimplified model of a "global warming game." In this "toy" model, I characterized a particular Markov-Nash equilibrium (MNE), and compared it to the set of global Pareto optimal outcomes (GPOs). In particular, the MNE emission level of greenhouse gases for each country turned out to be higher than its emission level in any GPO. I also showed how the MNE and GPOs would vary with changes in the technological coefficient ("emission factor") relating the level of a country's emissions to its use of energy. In particular, a decrease in one country's emission factor would increase its own MNE and GPO welfare. However, the effect on its emission rate cannot be determined without more information. In a special case derived from a "Cobb-Douglas" production function, I showed that a decrease in one country's emission factor would decrease it's own MNE emission rate, and hence increase the welfare of all other countries, provided it's emission factor was not "too large." In this special case, each country's MNE emission level is also proportional to the (exogenous) size of its labor input, after the levels of variable factors, such as capital, have been optimized.

Several further comments on the model of Section 3 are called for:

1. Attaining equilibria that are Pareto superior to the MNE would probably be facilitated by observation of the actions (emissions) of the individual countries. It is not clear how accurately this can be done using current technology. Similarly, it has been implicitly assumed above that the stock of GHG at any time can be measured without error. Measurement errors would make it more difficult to attain "trigger strategy equilibria" that sustain superior outcomes (moral hazard).
2. The above model implicitly assumes constant populations, levels of economic development, and technology. Any model that is even semi-realistic would have to take account of changes in these factors. [For an analysis of a model with changing

population, see (Dutta and Radner, 1998).

3. Moving to Pareto superior equilibria would probably require "side payments" from some countries to others. Because of moral hazard and related problems, it might be preferable to make such side payments in the form of technology that can be used only for the purpose of reducing emissions.(See Section 3.5 for a discussion of the effects on the MNE of reducing emission factors.)

4. More generally, moving to a superior equilibrium would be a process that takes time. Whether and how such a process could take place in a "self-enforcing" or "self-confirming' manner is a challenge for analysis.

5. ACKNOWLEDGEMENTS

These notes were prepared for the Woytinsky Lecture, University of Michigan, March 11, 1998. Previous versions were presented at a meeting of the Association of Southern European Economic Theorists, Marseille, Nov. 1, 1997, and the Bosphorus Workshop on Economic Design, XX, August, 1997. I would like to thank Graciela Chichilnisky, Prajit K. Dutta, Arnulf Grubler, Geoffrey Heal, Leonid Hurwicz, Jill Jaeger, Peter de Janosi, Paul Kleindorfer, Giuseppe Lopomo, Thomas Schelling, Tapan Mitra, Michael Toman for helpful discussions and references, and Andrew King, Charlotte V. Kuh, and Frank Sinden for comments on an earlier draft. In the case of the present enterprise, much of whose scope lies outside of my previous expertise, it is even more important than usual to emphasize that I am responsible for all errors.

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[Note: There is by now an enormous literature on the subject of sustainable development, and I have made no attempt to make this bibliography comprehensive.]

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Figure 3. World Population with Three Growth Pulses.

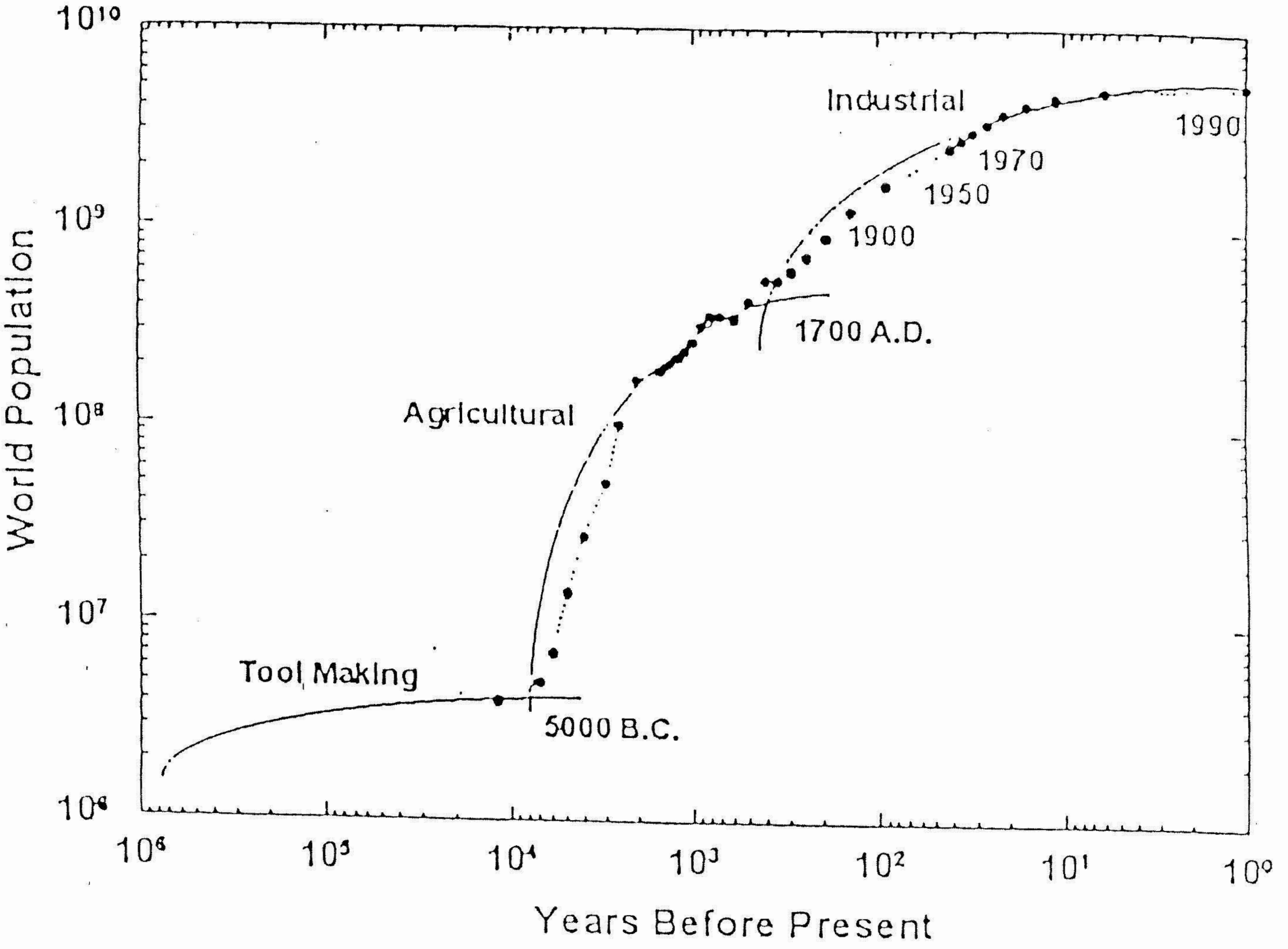

Fig. 1. Reproduced from (Kates, 1996), updated and redrawn from (Deevey, 1960).

Figure 7. World Population Projections.

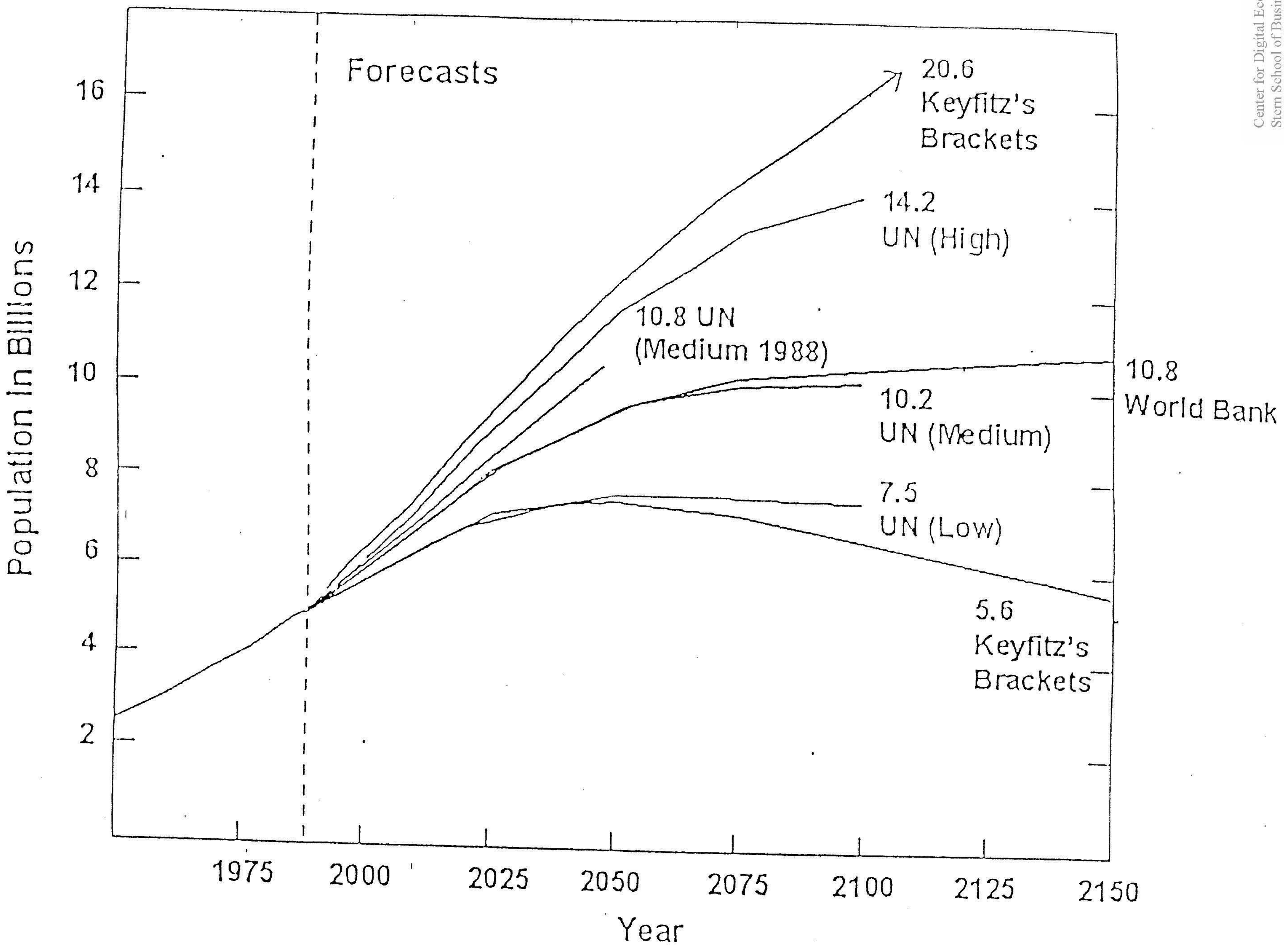

Fig. 2. Reproduced from (Kates, 1996), after (Lee, 1991, p. 59).

Fig. 3. Reproduced from (Grubler and Fujii, 1991).

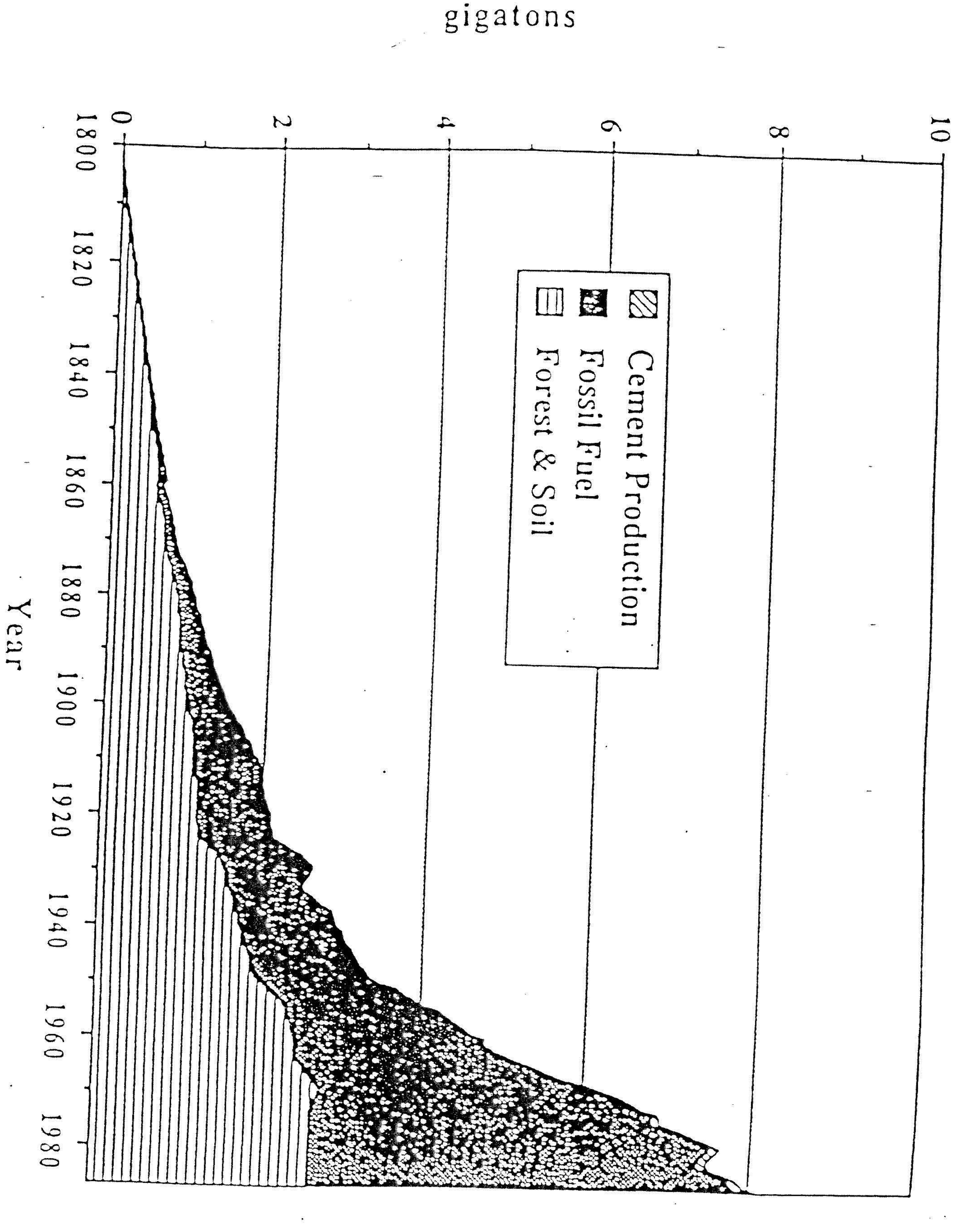

Fig. 2. Historical carbon emissions from fossil-fuel use,[25] cement production,[27] and forest and soil[3] gigatons for 1800–1987.

Fig. 4. Reproduced from (Grubler and Fujii, 1991).

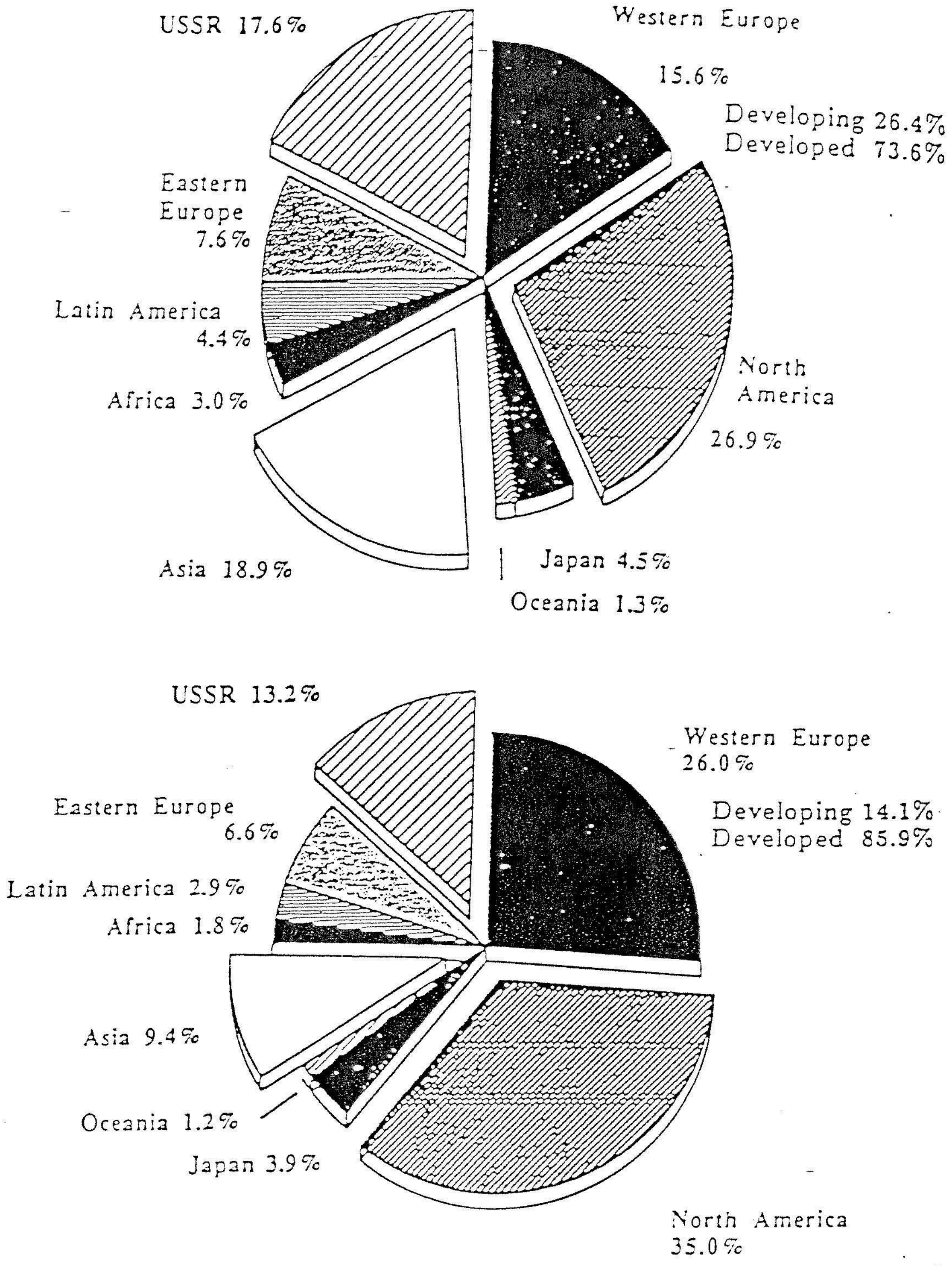

Fig. 5. Share of different regions in current (1987) energy-related carbon emissions (top) and in contribution to the increases in atmospheric concentration since 1800 (bottom), in percent.

Fig. 5. Reproduced from (Grubler and Fujii, 1991).

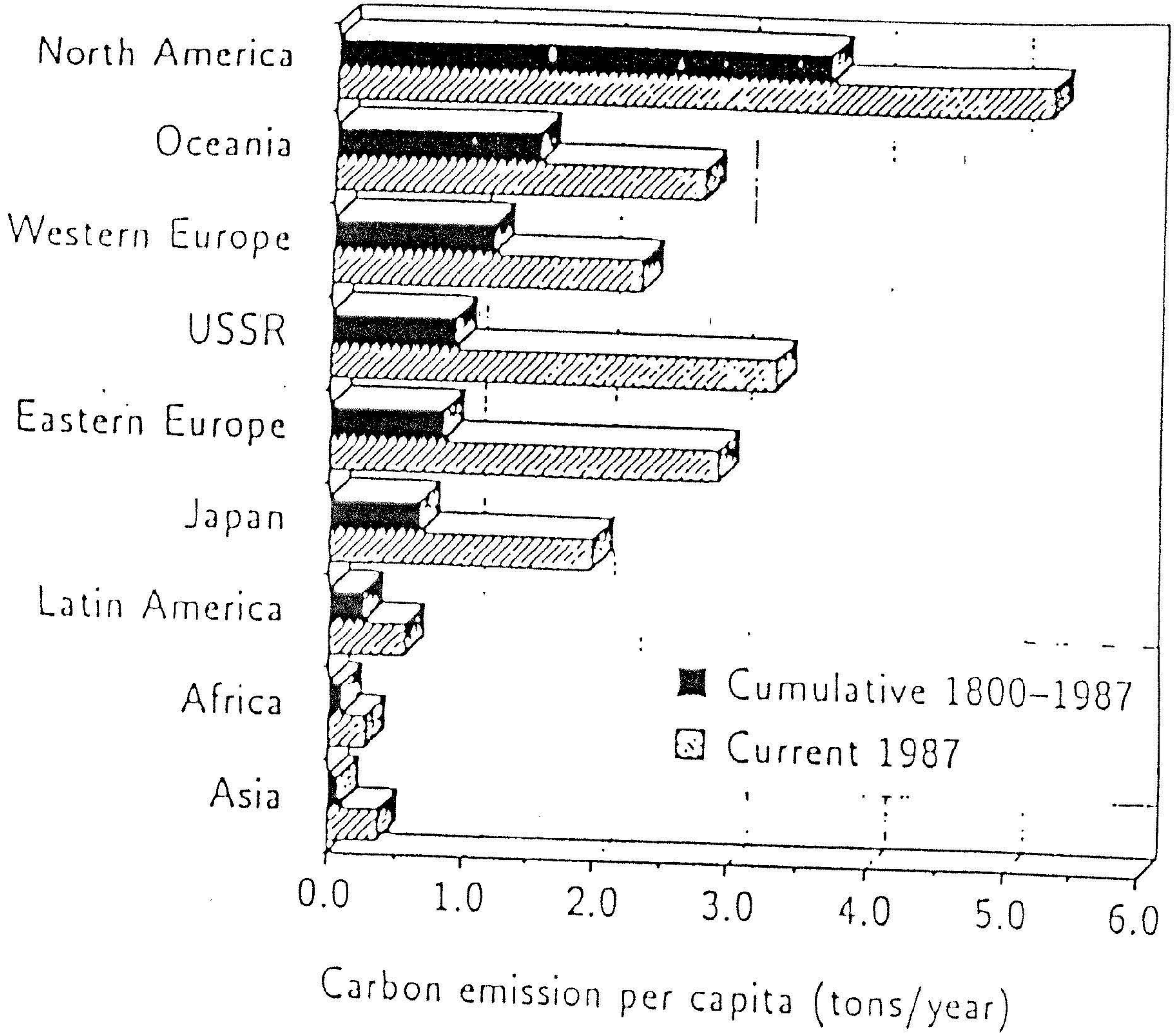

Fig. 6. Current (1987) and cumulative (1800–1987) per capita carbon emissions from fossil-fuel use b world region (in tons of carbon/yr per capita and person-yr).

Fig. 6. Reproduced from (Grubler and Fujii, 1991).

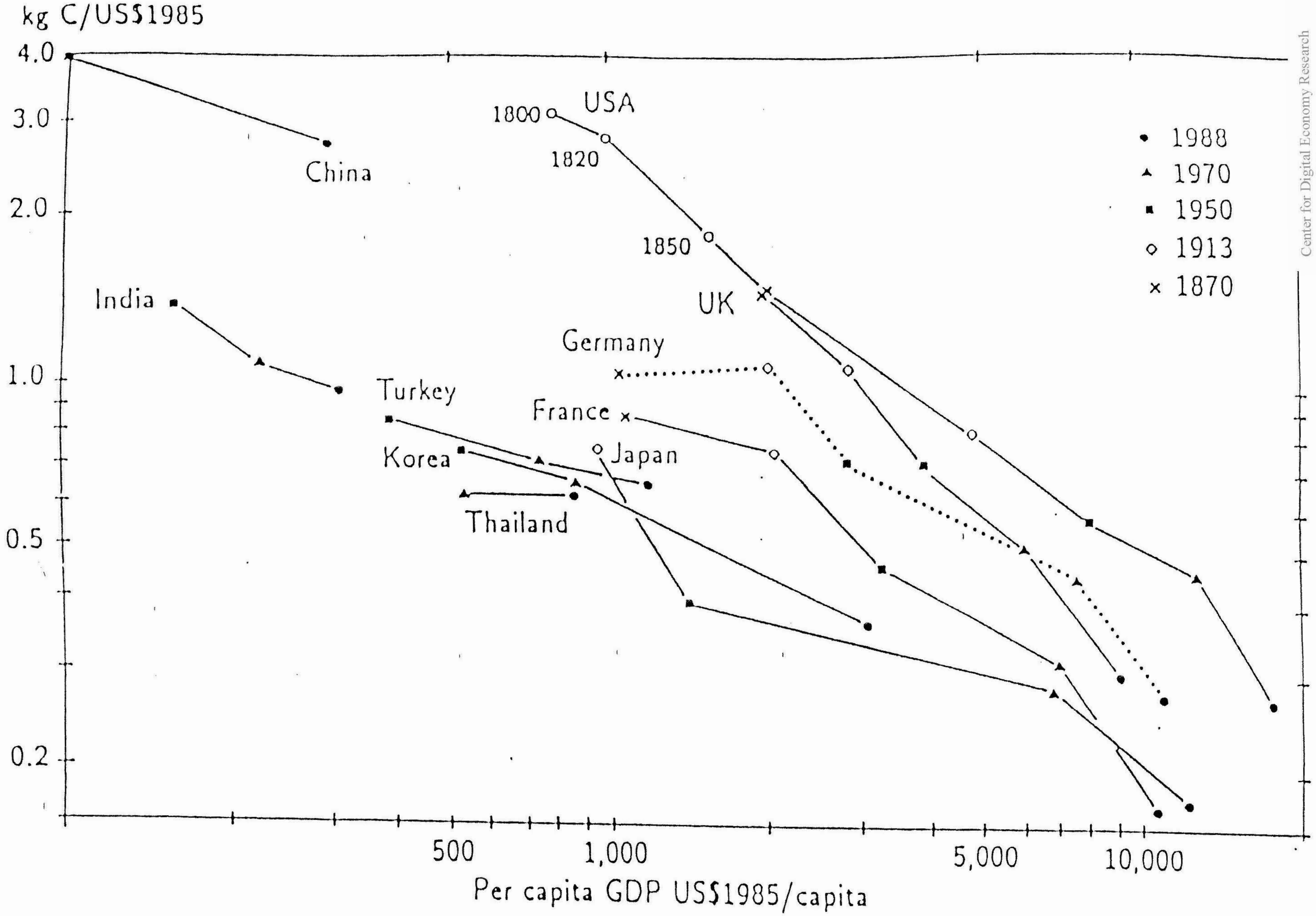

Fig. 1. Energy carbon intensity per constant GDP, in kg carbon per U.S.$ 1985 vs per capita GDP. Energy data include also non-commercial sources such as fuelwood. Note the improving carbon intensity of economic activities as a function of the degree of economic development and remaining decisive differences between countries for similar per capita GDP levels.

Figure 5. Carbon Intensities of Final Energy, expressed in tons of carbon per ton of oil equivalent energy (tC/toe).

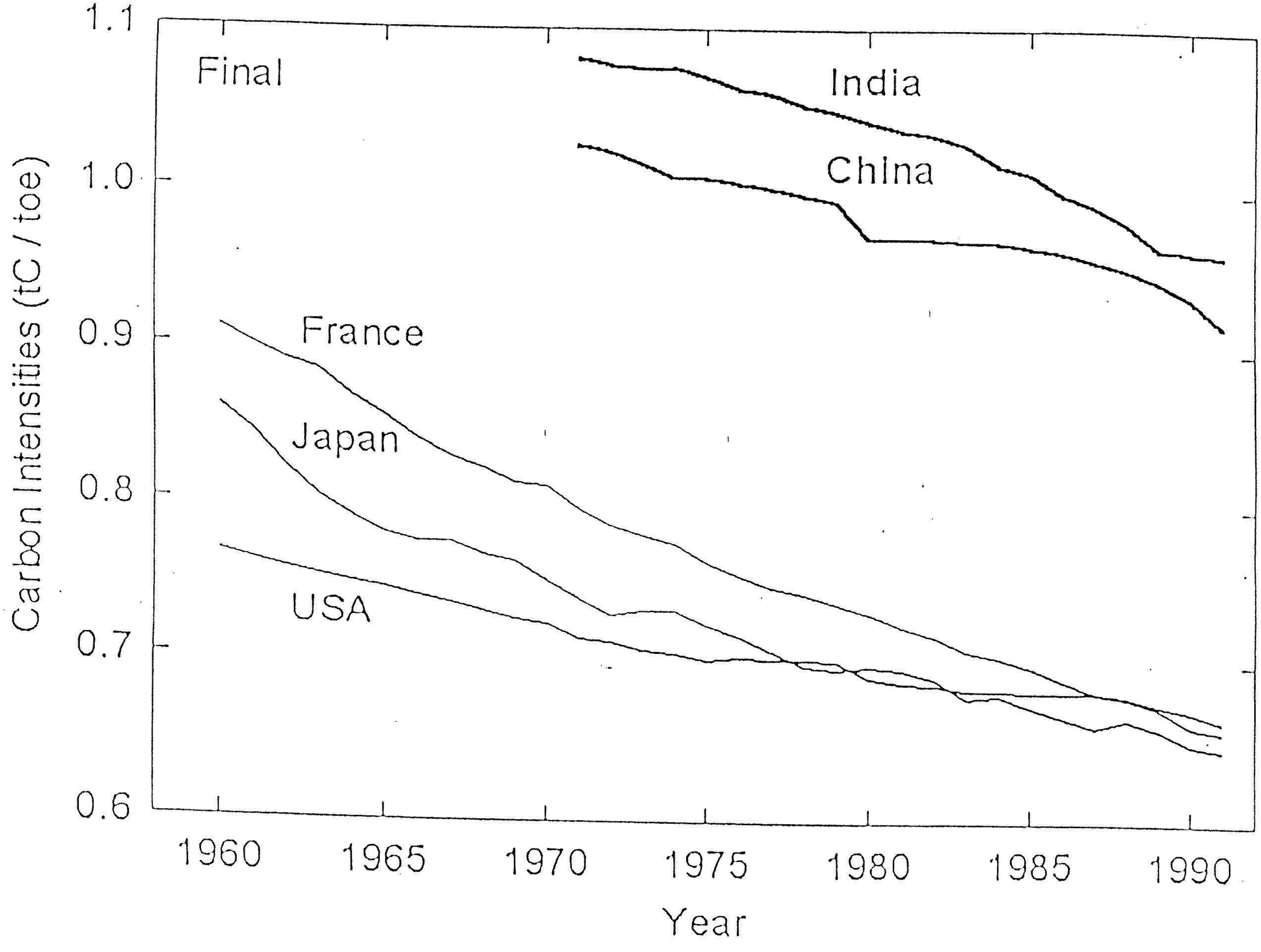

Fig. 7. Reproduced from (Nakicenovic, 1996).