CONTEMPORARY ISSUES

Rethinking the Environmental Impacts of Population, Affluence and Technology[1]

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How might we better understand the linkages between population, resources and environmental impacts? How might we proceed to develop organized research programs to examine these linkages? How might we discipline our conceptual models with empirical tests? In this paper, we address these three questions, focusing on anthropogenic environmental change. We suggest that an adaptation of the widely known **IPAT** model (Commoner 1972, 1992; Ehrlich and Ehrlich 1990; Ehrlich and Holdren 1971, 1972; Holdren and Ehrlich 1974) modified to meet statistical testing requirements, is one strategy for addressing these questions. We provide a brief historical account of scholarly discourse bearing on the questions posed above. We note that the social sciences, on the one hand, and the biological and environmental sciences, on the other hand, have addressed them in parallel, but generally separately--and often antagonistically. Then, we describe the original **IPAT** model and our proposed modifications, evaluating the respective strengths and weaknesses of both. We map out guidelines for further modification, elaboration and testing of the model. Finally, we sketch some suggestions for superseding the **IPAT** model.

History of an Idea. The idea that population growth affects environmental resources and human welfare is as old as civilization, perhaps as old as written history itself.[2] Heroditus, writing in the 5th century before Christ, noted how the population of the Lydians had outpaced production leading to a prolonged famine that lasted eighteen years (The History, Book I:22-23).[3] And Seneca the Younger writing in the first decades of the Christian era (Naturales Quaestiones) noted a connection between population and pollution in Rome.[4] He traced pollution to the growth of household cooking fires and the increased traffic on the dusty streets of the city, and also to the burning of dead bodies just outside the city limits. Despite this early recognition, connections between population and environment were anecdotal and inchoate in classical writings.

The idea of a causal link between population and resources developed into a more concrete form in the eleventh century. In 1086, William the Conqueror commissioned an enumeration of the population and its landed wealth, recording the results in the Domesday Book (the word "domesday" being a corruption of the word doomsday, the final day of judgment (Weeks 1986)). This accounting was instrumental in carrying forward the idea that there was a link between population and resources. But it wasn't until the eighteenth century, with the writing of the classical economists, particularly, Thomas Robert Malthus, that the population-resource link received systematic attention. Malthus posed a pivotal questions in his first essay that gave structure to an inchoate idea: What effect does population growth have on the availability of resources needed for human welfare? (1960[1798]). His answer, known by nearly every educated person for the past two centuries, was that "geometric" growth (exponential growth in modern parlance) in population would eventually outstrip the "arithmetic" growth (or linear growth) in the means of subsistence. In other words, unless population was held in check, the inevitable outcome would be perpetual misery and poverty.

Malthus is considered a classical economist because his writings appeared during the period (the late 18th and early 19th century) when the practice of economics was crystallizing into a recognizable social science discipline.[5] While the foundation he laid was social scientific in origin, its more general applicability to the problem of species-to-environments interactions and species dependency on finite resources was soon recognized. Charles Darwin experienced an intellectual "a ha" upon reading Malthus. He developed his theory of evolution in The Origin of Species (1958[1859]) around the same basic idea: species have the tendency to overproduce, with the result that only those most "fit" to their environmental circumstances survive and reproduce.[6] Thus population pressure on critical environmental resources drives evolutionary change.

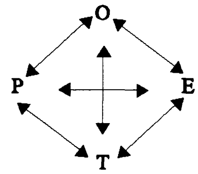
The important point to note here is the convergence of the social and biological sciences to a common problem, but with each side looking through the same eyes with a different disciplinary lens. Even in Malthus' time, disciplinary specialization that separated the social from the biological sciences was evident. By the late 19th century, sharp boundaries were drawn between the social sciences and the biological sciences, and even between disciplines within the social sciences. One consequence of specialization was a prolonged debate about population and human welfare that lasted over 200 years, though its intensity waxed and waned. Not much has really changed since. In the nineteenth and especially the twentieth century, the discipline of ecology would take the pattern of relations between organisms and environments as the focus of its investigations. Even so, it did not systematically bring the social and biological sciences into a common focus, a human ecology, but instead added a third lens to the common perspective. Systematic investigation of human-environment interrelations usually was ignored. This intellectual history set the stage for the current state of affairs: the investigation of a common problem along parallel, but separate tracks and with specialized foci. It also set the stage for the rekindling of the two-centuries old debate. This has been very visible in the dispute between Paul Ehrlich (1981, 1982) and Julian Simon (1981b, 1982), which is summarized in Dunlap (1993). In the last two decades, the upturn in the intensity of the debate is due to an increased concern with anthropogenic changes in the physical and biological environment.

Revisiting IPAT. We view anthropogenic global change as a real and challenging problem, in need of systematic investigation. The **IPAT** model, first proposed two decades ago, represented the efforts of population biologists, ecologists and environmental scientists to formalize the relationship between population, human welfare and environmental impacts. Here we revisit the **IPAT** model that postulates that environmental impact (**I**) is the product of population (**P**), per capita affluence (**A**) and technology (**T**). Why revisit the model in the context of global environmental change? First, because it has been adopted as the orienting perspective for much of the discussion about the principal factors, called "driving forces," of global environmental change. Population is theorized to be a key driving force, along with economic activity, technology, political and economic institutions, and attitudes and beliefs (Stern et al. 1992). Second, a number of treatments of population (e.g. Green 1992), including the award winning work of Paul Harrison (1992-1993, 1994) have likewise used it as an orienting perspective. But, third, there has been little effort to discipline the model with empirical tests since its inception two decades ago. In particular, social scientists have generally ignored the model, while biological, ecological and other physical and environmental scientists, by generally assuming the model to be true, have not been motivated to test it rigorously.[7] We propose the adoption of the **IPAT** model as one, but by no means the only, procedure for addressing global change problems systematically. We also argue that the **IPAT** model may be an effective device for operationally bridging the differing perspectives--social sciences and biological sciences--on these contemporary environmental problems. That is, the **IPAT** model may be a way to examine the problem from an human ecological point of view. Thus our ultimate goal is to generate more disciplined research and less debate that is not grounded in empirical research.

The **IPAT** model has appealing features. It has structured much of the debate about the effects of population, affluence and technology on the environment, and has been a widely adopted perspective in ecology. But, the model also has serious limitations. Key among these is that in its current form it does not provide an adequate framework for disentangling the various driving forces of anthropogenic environmental change. As a consequence, the **IPAT** model stifles efforts toward cumulative theory and empirical findings. We propose a stochastic reformulation of the model that renders it amenable to empirical "disentangling." Once we describe the theoretical and empirical advantages of our reformulation, we go on to sketch alternative ways of conceptualizing the driving forces of anthropogenic change.

Population and Economic and Social Change. The causes of population and economic change have been addressed in a literature too vast to cite, let alone review. Indeed, the causes of population and economic change are central topics of demography and economics. There is also a substantial literature on the social consequences of population and economic change.[8] For example, one of the founders of sociology, Emile Durkheim (1964[1893]) argued that leaps in population growth lead to an increased competition for environmental resources which, in turn, leads to the division of labor in society. An early, effort to organize these various factors into a coherent conceptualization was the POET model, displayed in Figure 1, proposed by sociologist Otis Dudley Duncan (1964). Duncan sought to alert social scientists to the importance of ecology, arguing that an ecological framework could enrich the theoretical understanding of societies. In particular, because the four components--population, technology, social organization and physical environment--are constituent to the operation of literally all societies, an examination of their interactions could be the foundation of cumulative social theory. While useful for pointing a social scientific lens toward the environment, and while influential as a foundation for theory, the model has generated very little empirical research. The principal reason is not hard to discern: it is very difficult to map the framework into operational procedures. According to POET, everything is connected to everything else, with the consequence that the framework--in the language of statistical modeling--is badly underidentified.[9]

Figure 1. The POET Model of the Human Ecological Complex



P = (Human) Population
O = (Social) Organization
E = Environment
T = Technology

Recently there has been a focus on the impacts of population growth on resource availability and environmental impacts. The overwhelming majority of this work has examined problems of resource (especially food) shortages and human welfare. While optimists and pessimists persist, a consensus view today probably is close to that offered by Coale and Hoover (1958) in their pioneering study of India.[10] Production increases driven by price increases can keep rough pace with population growth and thus prevent the misery envisioned by Malthus. But rapid population growth retards capital accumulation and improvements in standard of living.

An even more optimistic tradition is usually traced to Boserup (1965, 1980) and holds that population growth and concentration lead to economic growth, not, as Malthus would have it, the other way around. Simon (1981a) is the advocate of the view that population most committed growth leads to enhanced welfare.[11] He argues that potential shortages of any key resource or necessity of life generate creative responses that increase productivity and the efficiency of resource use. Thus population growth produces innovation that ultimately enhances welfare. This body of work has focused on agriculture, food production, employment and per capita income.

Another tradition examines the effects of growth on the supply of renewable resources such as forests and fisheries and non-renewable resources, such as minerals and energy.[12] It comes to roughly the same conclusion as the literature following Coale and Hoover on growth and welfare: while population growth generates some problems, price mechanisms and human ingenuity provide the solutions to those problems. Slower population growth might improve the efficiency of resource use. But the worst fears of Malthus have not been realized, and factors other than population growth, particularly institutional arrangements, are more important than population size in determining the adequacy of resource supplies.

Of course, scholars in the field remain cautious about the empirical evidence supporting these conclusions. For example, the editors of a recent U.S. National Research Council study (Johnson and Lee 1987: xi) note: "drawing firm conclusions about the overall impact of slower population growth is difficult because the research base is inadequate. Studies completed to date are often on limited samples and data of poor quality, as well as on only partial and occasionally inappropriate conceptual models and statistical techniques." But whatever the concerns about the quality of evidence, and whatever the remaining disputes and dissension, the relationship between population and human welfare has been far more carefully studied than the effects of population growth on the biophysical environment.

The Character of Environmental Degradation

Our understanding of the role of population in anthropogenic change is far from complete. Nevertheless, some impacts are better known than others and it will be useful to distinguish the kinds of impacts that have been relatively well researched from those that have not. Malthus' First Essay was concerned with the ability of agricultural productivity to keep pace with population growth. As classical economics developed, factors of production were clarified, and thus population became one element in studies of growth. This literature viewed land and raw materials (the classical concepts closest to current notions of environment) simply as other factors of production. To a substantial degree, the question of population impacts posed by Malthus is a question of whether or not growth in output and productivity can keep pace with population growth (cf. Ricardo 1891[1817]).

Starting in the 1960s, increased concern with environmental problems made scholars aware of the broad character of human interactions with the physical and biological environment. In particular, concerns were raised about environmental "services" that were collective goods not given a market value, and about the "externalities" of production processes that may have adverse effects on the environment and thus on the ability of ecosystems to provide critical services. For simplicity, we will refer to these effects as environmental impacts.[13] Here we will focus on the global environmental change complex: greenhouse climate change, ozone depletion, acid precipitation, species loss and the broad dispersion of toxics. But, ceteris paribus, the argument applies equally well to less global problems such as local air and water pollution.

Environmental impacts of these sorts are different in two ways from the problem of resource shortages and production shortfalls that have been analyzed in the literature cited above. First, these problems involve the environment as a collective good. And unlike some common property resources that have been well studied, such as fisheries, no market value is assigned to the environmental benefits that are threatened by negative environmental impacts. Climate is a factor of production, but unlike land, minerals, fish catch or other renewable and non-renewable resources, it is not subject to the pricing mechanisms that underlie the logic of previous research on population, welfare and resources. In effect, climate is treated as a free good.

Of course, the goods and services provided by the environment do have real value whether or not prices are assigned to them. For example, Pimentel (1992; Pimentel and Hall 1989) has argued for the critical importance of "ecosystem services" to even the most highly managed agricultural systems. But because they are non-market collective goods, that value is not reflected in price mechanisms. It may be possible to find institutional arrangements that will allow prices to be assigned to ecosystem services. This could be accomplished through either a market for the relevant goods and services, as in the air basin experiments currently being conducted in the U.S., or a Pigouvian tax on the activities that generate environmental degradation.[14] But the point for the present discussion is that conclusions about the effects of population growth on human welfare have assumed that welfare and its determinants have prices. Those conclusions do not necessarily apply to unpriced goods and services. Or to put it differently, whatever the policy mechanisms used to address current environmental impacts, cumulative impacts have evolved under conditions in which no economic value is assigned to ecosystem services. Thus, while existing work on population growth and welfare is tantalizingly suggestive, we have a far from perfect understanding of the driving forces of global environmental change.

Second, the fact that population growth may not retard economic growth is little comfort to those concerned about anthropogenic environmental change. It has been argued, that economic growth is not tightly coupled to human welfare (e.g. Nussbaum and Sen 1993; Scotvsky 1976; Sen 1993; Rosa et al. 1980). Yet even without advancing welfare, increased per capita consumption and the attendant generation of residuals is a cause of environmental impacts. Thus concern with the biophysical environment leads to questions about the impacts of economic growth as well as of population growth. Indeed, much of the debate of the last twenty years centers around the relative importance of economic growth and population growth in generating environmental impacts.

Population, Affluence and the Environment

In the late 1960s and early 1970s the argument that population growth would have a strong adverse effect on human welfare was revisited (e.g. Ehrlich 1968; Meadows et al. 1972). The reaction to these analyses was forceful, stimulating a debate that continues today (Luten 1980). While population growth seems not to have had the catastrophic effects on human welfare suggested by Malthus, the effects of population and economic growth on environmental degradation have not been extensively researched.[15] Indeed, only a handful of papers offer empirical or conceptual analyses of the human driving forces of environmental change. The U.S. National Research Council (1986), in a report that generally rejects the Malthusian thesis noted above, also states that there is "no evidence" about the effects of population growth on the environment. In a later report, the National Research Council concluded that research on the driving forces of global environmental change should be one of the highest priorities in "human dimensions" research efforts (Stern et al. 1992:238-241). The approach proposed here is intended as an initial step towards building a better understanding of the effects of population growth on the environment relative to the other driving forces. Of course, to understand the effects of population growth, it is necessary to consider the direct and indirect effects of population on the environment and on other driving forces. It is also necessary to understand how these impacts vary across temporal, spatial, socio-cultural and technological contexts.

There are at least four distinct positions regarding the effects of population and economic growth on the environment. They parallel the positions held on population growth and welfare. One view, held most notably by Ehrlich and his collaborators, suggests anticipated population growth will have very severe, even catastrophic, impacts on the natural environment and human welfare (Daily and Ehrlich 1992; Ehrlich 1968; Ehrlich and Ehrlich 1990; Ehrlich and Holdren 1971, 1972; Holdren and Ehrlich 1974; Holdren 1991. See also Catton, 1982; Green, 1992). A second position, derived in part from the work of Boserup (1965, 1980), acknowledges that population growth and economic growth create increased demand for resources. But the resulting perceived or anticipated scarcity is presumed to drive technological progress and with it the search for substitutes and increased efficiency. Thus, the net effect of population and economic growth on resource scarcity, human welfare and the state of the environment is neutral or even positive. According to Simon (1981), the most forceful advocate of this position, the effect of growth is invariably positive. A third position suggests that technologies used to stimulate growth are often selected without regard to their environmental impact (Barkin 1991; Commoner 1992; O'Connor 1988, 1989; Schnaiberg 1980; Schnaiberg and Gould 1994). Thus adverse environmental impacts are more a function of the political economy of technological choice than of population or economic growth *per se*. To the extent population has an effect on environment, it is an indirect effect that could be mollified by institutional or technological change. The fourth position, rather like the consensus on the relationship between economic welfare and population, is a middle ground. Population is seen not as the dominant driving force, but as a contributor to environmental impact acting in consort with affluence, technological choice, institutional arrangements and other factors (Keyfitz 1991a, 1991b, 1993; Ridker 1972, 1979, 1992; Ridker and Cecelski 1979).

How are these four positions sustained? As noted above, there has been little empirical work on the impacts of population on the environment. The most extensive literature is found in a series of papers prepared for the U.S. Commission on Population Growth and the American Future (U.S. Commission on Population Growth and the American Future, 1972; Ridker, 1972). The general conclusion of the editor of those papers and of the Commission itself is that population growth contributes to environmental degradation, but that the impact of population is generally less than the impact of economic growth (Ridker, 1972:19). Ridker also notes that the effects of both kinds of growth can be mitigated by the appropriate choice of policies, technologies and institutions. Thus the conclusion is generally consistent with the line of work following from Coale and Hoover's study.

Methodologies. Three methodologies were employed in the Population Commission report and subsequent studies of population, affluence and the environment. The most common is a simulation/ projection (S/P) approach. Resource demand or pollution generation is estimated as a function of per capita income. Projections of population and income are then used to estimate future resource demand or pollution. In the more sophisticated models, such as those used for the Population Commission studies, input-output analysis is used to account for intersectoral demand for goods and services (Herzog and Ridker 1972). These demands are also translated into impacts on resources and pollution generation. Typically, the final estimated outputs from each sector of the economy are multiplied by coefficients representing the impact per unit output at the most recent point in time for which data are available. In some models, these coefficients can be adjusted to take account of environmental policies or increased efficiency resulting from technological improvement. The S/P model is used to project environmental impacts under various scenarios of population and economic growth. These projections then provide the basis for determining the effects of population and economic growth.

The basic logic of the S/P model is to first establish a linkage between total economic activity (per capita activity multiplied by population) and environmental impact. Then alternative scenarios of population and economic growth are projected to assess environmental impacts. In some models, like the Limits to Growth study (Meadows et al. 1972), the structure is very simple--a set of linked differential equations and multipliers. In others, such as the models used for the Population Commission, and some successor studies to Limits to Growth (Barney 1980; Mesarovic and Pestel 1974), the linkages become much more complex. Also, they disaggregate economic activity in terms of sector by sector output.[16] But all S/P models make assumptions about environmental impacts per unit output and then extrapolate into the future under different scenarios of growth. Thus they do not provide an historical or comparative assessment of the contribution of various driving forces but rather a projection of what may happen, given the assumptions of the model. In other words, S/P models are used to ask "What if?"

The conclusions drawn vary across the several S/P models. The Population Commission results suggest only moderate impact of population growth on the environment. The "Limits to Growth" models and their successors see far greater population impact. Bongaarts (1992) partitions CO_2 emissions into components for population, affluence, energy intensity due to affluence and the carbon intensity of energy. He finds that in the less developed nations, affluence changes will dominate the growth in emissions, with population growth the second most important factor. In the more developed countries, growing affluence also drives emissions but changes in energy intensity are more important than changes in population. Kolsrud and Torrey (1991) reach similar conclusions regarding population when they examine scenarios for future commercial energy consumption.

The second common approach is an accounting analysis (A/A). The most commonly used form is the **IPAT** model (Commoner 1972; Ehrlich and Holdren 1971, 1972; Holdren and Ehrlich 1974). This model postulates that:

$$\mathbf{I=P*A*T}$$

where **I** is environmental impact, **P** is population, **A** is per capita economic activity (referred to as affluence) and **T** is the impact per unit economic activity (referred to as technology).

In typical applications, data are obtained on impact, population and affluence and the equation is solved for **T**

$$\mathbf{T=I/(P*A).}$$

This approach has also been applied to the CO_2 efficiency and energy efficiency of economies (Stern et al. 1992:60-67).[17] Recently, Mazur (1994) has used a similar approach--though not **IPAT** itself--in assessing the relative contribution of population and all other factors in the growth of energy consumption in the U.S.[18]

When the model is used to assess the relative impact of population and affluence as driving forces, data for two points in time are usually translated into percentage increases for each term in the model. Change in **I** is then allocated to percentage changes in **P**, **A** and **T**. For example, Commoner (1992: 155) calculates that the use of synthetic organic pesticides in the U.S. increased by 266% from 1950 to 1967 (a 1967 to 1950 ratio of 3.66).[19] During that same period, population grew 30% (a ratio of 1.30), crop production per capita by 5% (a ratio of 1.05) and pesticide consumption per unit crop production--the technology factor for Commoner-- by 168% (a ratio of 2.68). That is

$$3.66=(1.30)*(1.05)*(2.68).$$

Commoner attributes most increase in the use of synthetic pesticides to technological change, with increased consumption per capita and increased population each responsible for a smaller share in the increased value of **I**--here the use of synthetic pesticides.

The key problem with this approach is that the relationship is definitional. Once three of the variables are fixed, the fourth is also fixed. Thus Ehrlich and Holdren (1972:369-371) suggest that Commoner's calculations underestimate the effect of population on the environment by attributing to the **T** term changes that could more properly be allocated to **P** or **A**. The accounting model is useful for developing efficiency or intensity measures but does not provide an adequate basis for testing hypotheses about the human driving forces of environmental change.

The third approach uses historical or cross-sectional data on **I**, **P**, **A** and **T** to assess impacts. In its simplest application, this approach uses simple graphs of bivariate relationships between **I** and driving forces or of historical trends in **I** and driving forces. (Bilsborrow 1992; Bilsborrow and Geores 1991; Peierls et al. 1991; Simon 1981). More sophisticated formulate stochastic models of impact as a function of independent variables. Stochastic models have substantial advantages, as we will note below. But they have seen little use to date. For example, in Ridker (1972), only one paper uses this approach. Hoch's analysis (1972) uses regression models to estimate the effects of the population size and density of U.S. urban areas on air pollution levels, wages and crime rates. His analysis fits into a small tradition that attempts to determine urban size effects in sociology, geography and economics (Applebaum 1978; Appelbaum et al. 1976; Duncan 1951; Singer 1972). He finds that both population size and density have adverse effects on his dependent variables.

The stochastic modeling (S/M) approach has been used most often in studies of deforestation (Allen and Barnes 1985; Dietz et al. 1991; Rudel 1989). Despite using slightly different specifications and data sets, all three of these studies find that population size, growth rate or density has a stronger effect on deforestation than does economic activity. Rudel (1989) also finds population growth to have a stronger effect than a common measure of trade dependency. These preliminary applications and their findings suggest that the stochastic approach to the assessing the impacts of population, affluence, technology and other factors on the environment is a useful way to ground the debate about driving forces in stronger theory and empirical evidence.

A Reformulation of the IPAT Model

Despite the paucity of strong evidence regarding the effects of population and economic growth on the environment, strong conclusions about the relative importance of the driving forces still appear. For example, a recent, unprecedented joint statement by the Royal Society of London and the U.S. National Academy of Sciences (1992) asserts that population growth is a major threat to human well-being, but there is little empirical evidence to support their claim (Stern 1993). In order to move the debate to more solid ground, it will be necessary to reformulate the **IPAT** model in six ways.[20] First it must be considered a stochastic model rather than an accounting scheme so that it can be used to test hypotheses. Second, it would be helpful to employ a variety of indicators of environmental impact and consider the possibility of creating general indices from individual indicators. Third, modeling should incorporate effects of the rate or pace of growth, of population distribution and of the composition of the population in addition to the effects of population size. Rate or pace of growth, distribution and composition may have greater environmental impacts than size per se. Fourth, alternatives to gross national and gross domestic product including distributional measures should be considered as measures of affluence. Fifth, technology needs to be assessed directly, rather than as the residual of the accounting format. One approach should incorporate operational measures of technology, such as the efficiency of energy conversion. Another should reconceptualize technology to include a variety of candidate driving factors that influence how human activity effects the environment, including culture, social structure and institutional arrangements. Sixth, because the various driving forces interact in complex ways, it ultimately will be necessary to move from a single equation model--one that estimates only direct effects net of other variables in the model-- to a systems model that estimates both direct and indirect effects of driving forces. That is, the model must acknowledge that the driving forces influence each other, as illustrated in the **POET** model. While some of the earliest formulations of the **IPAT** model acknowledge this (e.g. Ehrlich and Holdren 1971, 1972; Holdren and Ehrlich 1974), there has been no elaboration of how these interactions may work.

With all these modifications, it may seem that the **IPAT** model is being abandoned altogether. Eventually, the elaboration of theory about the forces driving anthropogenic environmental change may lead to models that have little relationship to **IPAT**. But **IPAT** is a useful starting point for theory building and testing for three reasons. First, any viable theory of anthropogenic environmental change must consider population, affluence and technology as determinants of environmental change. There are other potentially important driving forces and that may have strong direct or indirect effects (Stern et al. 1992). But **P**, **A** and **T**, almost everyone would agree, must be part of any serious effort to understand human impacts on the environment. Second, the **IPAT** model is at the heart of debates regarding the driving forces. Research that elaborates on it is more likely to influence those debates than research that rejects it. Third, the **IPAT** model forms a general framework that can structure both research and discussion, thus providing a means for integrating disparate literatures.

A Stochastic Reformulation

The **IPAT** model can easily be reformulated in stochastic form:

$$\mathbf{I = Ap^bA^cT^de}$$

where **I**, **P**, **A** and **T** remain environmental impact, population size, per capita economic activity and impact per unit economic activity. Now **a**, **b**, **c**, and **d** are parameters and **e** a residual term. Data on **I**, **P**, **A** and **T** can be used to estimate **a**, **b**, **c**, **d** and **e** using standard statistical methods such as regression analysis and its kin. This reformulation of the model requires multiple observations (over units, over time or both) on **I**, **P**, **A** and **T**. This is an important distinction from the accounting model where one term is derived from the values of the other three. The accounting model only requires data on any three of the four variables for one or a few observational units. But the advantage of this stochastic reformulation is that it converts the **IPAT** accounting model into what is certainly the most standard formulation for quantitative social research--the general linear model. As a result, the substantial array of statistical tools used in quantitative social research can be applied to the problem of assessing the importance of each of the driving forces. Assertions about the driving forces can be converted into hypotheses that are specific to the impact (e.g. CO_2 loads) and the spatial (e.g. nation states) and temporal (e.g. a decade) context under study. The stochastic version preserves the original model because the accounting model is nothing more than a special case in which $\mathbf{a}=\mathbf{b}=\mathbf{c}=\mathbf{d}=\mathbf{e}=1$.[21] Early tests of the reformulated stochastic version of **IPAT** can be undertaken by operationalizing the components with readily available indicators for well-defined social units, such as the nation state. For example, first approximations of the relative effects on a given impact (**I**), such as yearly CO_2 loads, could be assessed by plugging total population (**P**), gross national product per capita (**A**), and energy efficiency (**T**) into the model. Or the model could be estimated with the exact same operational indicators, except for technology (**T**), which can be treated as a residual term. Indeed, work in progress takes these various approaches (Dietz and Rosa 1994).

A key consideration in the application of the reformulated **IPAT** is the proper units of analysis. Previous applications of the **IPAT** model have used data for a single country at two or three points in time. Simulation/ projection models have been applied more widely: to single countries, to the world as an aggregate, and to world regions. The stochastic reformulation we suggest allows even broader scope for units of analysis. The world as a whole should be considered at least for exploratory efforts.[22] But because of the limited data available, and the marginal quality of some of what is available, most analyses must rely either on the nation-states or on subnational units such as states, provinces or counties, as a unit of analysis. Broad cross-sectional analyses have long been used for comparative analysis in economics, political science and sociology (e.g. Bollen et al. 1993; Jackman 1985; Mazur and Rosa 1974). These can be supplemented by individual country time series analyses where data are available, and by pooled cross-section time series analysis when short time series are available for a moderate number of cross-sectional units. The cross-national and pooled approaches offer the critically important advantage of contextualizing the **IPAT** model--that is, of acknowledging that the effects of driving forces may vary over time and across nations or regions. Time series, cross-sectional and pooled data sets allow the estimation of models in which the coefficients of a model change over time, across cross-sectional units or both (Judge et al 1980). This permits analyses that are sensitive to the effects of socio-economic structure and social, economic and technological change on the relationship between driving forces and environmental change. Indeed, we believe a major advantage of the stochastic model is that it places work on driving forces squarely in the methodological tradition of quantitative social science, and invites the application of a powerful repertoire of well-developed tools.

Reformulating I

Examining impacts rather than human activity. Most research on human driving forces has taken measures of human inputs into the natural environment as the impact measure rather than examining the resultant environmental change. Thus in the example noted above, Commoner (1992) examines the use or production of inorganic nitrogen fertilizer, synthetic organic pesticides, synthetic fibers and phosphorous based detergents rather than the effects of these compounds on human health or on ecosystem structure and function. Ehrlich and Holdren (1971, 1972; Holdren and Ehrlich 1974; Holdren 1991) have examined energy consumption rather than environmental effects of energy use. Similarly most work on greenhouse climate change uses CO_2 emissions rather than the change in atmospheric concentration of CO_2 (Dietz and Rosa 1994). The use of human action as an impact measure is a reasonable first approximation, and to some extent dictated by the availability of data on human activities and paucity of data on actual environmental change. But it does have the disadvantage of ignoring the capacity of natural systems to absorb impacts, and the (probably non-linear) limits of those abilities. Over the last decade, there has been a sharp increase in the availability of data on the natural environment. While some of this data are of only poor to moderate quality (for example data on deforestation rates are notoriously unreliable, and data for extinction rates are even more flawed), other measurements such as atmospheric gas concentrations are very reliable. Work on the **IPAT** model should eventually move toward the use of variables that describe the physical and biological systems of concern, not just the human inputs to those systems. Only by studying the links can we expect to monitor and understand the non-linear responses that are so troubling.

Creating an impact indicator. Most studies to date have examined only one or a few impacts. When comparisons are made using a single indicator, results may be misleading due to the "Netherlands" effect (Ehrlich and Holdren 1971, 1972).[23] Much of the environmental impact of a nation state may be displaced across its borders due to the mix of imports and exports and to the international division of labor. This can be compensated for in part by taking account of imports and exports of high environmental consequence.

The single indicator approach also is flawed because it ignores substitutions within a social system. For example, a nation might have relatively low CO_2 emissions per unit affluence because it makes extensive use of nuclear and/or hydroelectric power rather than fossil fuels. But the disposal of nuclear waste and the disruption of riparian ecosystems are also environmental problems. Therefore an adequate environmental indicator should take account of such trade-off effects as well as the possibility of displacing impacts.

In the social sciences it is commonplace to have problems of measurement where no single indicator is adequate to capture a concept, where each indicator is subject to measurement error and where there is no obvious a priori method for assigning weights to indicators. Standard measurement theory can be used to develop multi-dimensional models of environmental impact. Also, environmental impacts can be treated as latent variables, while specific indicators such as CO_2 emissions, tropical wood imports or species endangerment serve as observed indicators or proxies linked to the latent variables. Standard structural equation modeling methods allow tests of hypotheses about the links between latent variables and manifest indices and the construction of indicators that pool individual measures (Bollen 1989). Analyses of this type will aid in the detection of tradeoffs among types of impact and can assess the role of impact displacements in a nation's overall effect on the global environment.

Reformulating P

Most examinations of population impacts use population size as the indicator of that driving force. This oversimplifies population impacts in a number of important ways. First, the distribution of population may be as important or even more important than size and needs to be considered (see, for example, Day and Day 1973). A few studies of deforestation have examined the impact of rural population growth, population density and intra-national migration (Allen and Barnes 1985; Dietz et al. 1991; Rudel 1991). Hoch's (1972) work considers urban density. But more sustained work on impacts due to the spatial distribution of population deserves a high priority in **IPAT** analyses.

Second, because children may produce substantially less impact than adults, age structure of the population should also be considered in assessing population impacts. As the populations of the low fertility nations of the world (the most affluent nations, the newly industrializing nations and some exceptional non-industrial nations) grow older, resource consumption patterns may shift radically. We know, for example, that age/cohort is one of the best predictors of environmental concern in the U.S. (Jones and Dunlap 1992) In the high fertility nations, the next few decades will see very sharp increases in the number of people in dependent age groups and even sharper increases in the size of the population forming families and seeking work.

Third, and perhaps most important, the pace of population growth influences a nation's ability to develop innovations and institutions. The research on population and human welfare reviewed above suggests that population growth is only a moderate detriment to human welfare and resource adequacy. This research also notes that the more rapid the growth, the more likely the effects are to be detrimental and that very rapid growth can be very detrimental (see especially U.S. National Academy of Sciences 1971). Very rapid growth exacerbates the kind of socio-economic disarticulation proposed by Amin (1974, 1976, 1977; Stokes and Anderson 1990). Thus it is plausible to hypothesize that the pace of population growth will in itself contribute to environmental impact over and above any effects of population size.[24]

Reformulating A.

National income figures, especially gross national product per capita or gross domestic product per capita, are the usual measures of economic activity in **IPAT** models, although some simulations use output disaggregated by sector of the economy.[25] For assessing the effects of economic growth on the environment, these very standard and relatively well measured variables are appropriate. But the last few decades have also seen criticisms of these indicators as measures of human welfare. Other indicators of welfare, such as health, don't always correlate highly with economic measures (Mazur and Rosa 1974; Sen 1993). A number of alternatives have been proposed, such as the "physical quality of life index" (PQLI) that combines infant mortality, literacy and life expectancy (Morris 1979; London and Williams 1988). An important line of sociological research has shown that welfare is no longer tightly coupled to energy consumption (Mazur and Rosa 1974; Rosa, Keating and Staples 1980; Olsen 1992). Preliminary work suggests that for a number of nations CO_2 emissions have also decoupled from welfare, while the correlation persists in other industrial nations (Rosa and Krebill-Prather 1993). Work has also begun to develop alternative measures of economic activity that correct gross production for consumption of non-renewable resources, military spending and other activities perceived as neither renewable or productive.[26] All this work, critical of standard national economic accounts as indicators of human welfare, suggests that alternatives to gross domestic or national product should be explored as measures of affluence.

The disadvantage of the PQLI and similar measures is that their units are quite arbitrary (Sen 1993). A better alternative to measuring affluence lies in life expectancy at birth. Life expectancy at birth is a function of the age specific mortality rates occurring in a population, and thus can reasonably be interpreted as a key quality of life indicator.[27] Life expectancy has the additional advantage that, when multiplied by population, the product represents the number of years of life that can be expected for members of a nation under their current living conditions. Thus it holds a strong parallel to the multiplication in the **IPAT** model of population by economic activity per capita to produce total economic activity.

Reformulating T.

Most students of environmental issues would acknowledge that it is reasonable to examine the role of population and affluence in generating environmental impact, whatever may be the relative importance of these two factors. But most social scientists are frustrated by the truncated vision of the rest of the world offered by the **T** in the **IPAT** model. As noted above, if **IPAT** is treated as an accounting model, then the normal practice is to solve for **T**. In that sense **T** captures not just technology in the narrow sense, but everything else not included in the model: attitudes, values, institutional arrangements etc. of the population. All of these must be considered as driving forces.[28]

The stochastic model estimates the effect of **T** independent of **I**, **P** and **A**. Generating these estimates first requires an operational definition of **T**. Once accomplished, researchers can offer specific hypotheses about **T** and test those hypotheses with the operational indicators. For example, the common hypothesis that values are key determinant of environmental impact can be tested using cross national or time series data on indicators of values, such as environmental attitudes. Arguments that a shift to a service economy will reduce environmental impacts can be tested using data on the distribution of labor or gross product across economic sectors. Ultimately, it is possible to substitute a vector of cultural, political and social structural variables for **T** and examine the net effect of each on **I**. To do so, we must develop a human ecological model of environmental impact.

A Human Ecological Model of Environmental Impact

We have argued that the **IPAT** model is a useful framework for directing the investigation of anthropogenic environmental impacts. Such investigations are likely to shed light on an issue that more often attracts heat. Yet, it is also useful to think beyond **IPAT**. We are so far from a fully articulated model of environmental impact that many may despair and retreat to the relatively robust initial formulation of **IPAT**. But population and affluence effects cannot be properly estimated if they are included in a model that is badly mis-specified. Thus it is useful to propose some first steps towards a social model of environmental impact. There are a number of variables that can be reasonably hypothesized to influence anthropogenic environmental change, and a number of ways to operationalize each. Parsimony suggests a sharp delimitation and therefore we propose the following concepts and operationalizations.

Culture. Culture has been posited as a driving force of environmental change at least since White's (1967) essay. While the argument for cultural forces is plausible, existing evidence is equivocal (Tuan 1968). We suggest three operationalizations. First, <u>public opinion</u> data measuring environmental values and attitudes for a number of nations (circa 1991) are available from the recent Gallup "Health of the Planet Survey" (Dunlap et al. 1993). These can be used to develop a crude indicator of public environmental concern. Such concern may influence technological choice.

Second, <u>social movements</u> are a principal mechanisms by which public concern is translated into policy, and thus one of the means by which the environmental impacts of nations and regions are transformed (Brulle 1993). Dietz and Kalof (1992) have developed a measure of environmentalism for nation states and find it related to some measures of state action on the environment. But there are few empirical comparisons of the environmental movement across a diversity of nations. We would expect that a strong environmental movement would, <u>ceteris paribus</u>, lead to polices that reduce the environmental impact of consumption and population.

Third, the <u>cultural history</u> of a nation may shape current actions toward the environment. Since White (1967) posited religion as a critical determinant of environmental impact, religious heritage of a nation is a candidate indicator. The recent work by Lenski and Nolan (Lenski and Nolan 1984; Lenski 1986; Nolan and Lenski 1985) on the technological/ecological heritage of a nation suggests that pre-colonial mode of agriculture may continue to have important ramifications for social and economic organization.

Political Economy. Many scholars have suggested that political economy is a key determinant of environmental impact. The problem is finding a conceptualization of political economy that is sufficiently parsimonious that it can be operationalized. We suggest three dimensions: <u>position in the global economy</u>, <u>democracy</u> and <u>government involvement in the economy</u>.

The two most commonly used concepts of position in the global economy are investment dependence and position in the world system. A small literature has examined the impacts of dependency and world system position on the environment (WP and Frey 1990; Bunker 1984, 1985; Evans 1979; Hecht 1985; Rudel 1989). It suggests that adverse environmental impacts will be greatest in nations that are dependent and in the periphery of the world economy. Other arguments suggest that institutional arrangements may have an important influence on environmental quality. Congleton (1990) reviews these arguments, and suggest that democratic governments may be more concerned with environmental quality than authoritarian governments. There may also be a relationship between government involvement in the economy and environmental degradation, but the direction of the effect is difficult to predict.

Social Structure. The social structure of a nation may also have an influence on environmental impact. For example, the likely mechanism is that poverty and inequality reduce concern with environmental quality (Inglehart 1990). Recent analyses by Dunlap et al. (1993) do not support the presumed relationship between a nation's economic prosperity adn environmental concerns, but further analysis is needed. Poverty is to some extent captured by national product per capita. But distribution of income and land may be more important that aggregate income. Amin's (1974, 1976, 1977; Stokes and Anderson 1990) concept of disarticulation is closely related to inequality (it is usually conceptualized as sectoral inequality) and is likely to have a strong link to environmental impact. Finally, there is substantial evidence for gender differences in environmental concern at the individual level (Stern et al. 1993), and this may translate into a link between gender stratification and the environmental policy of nation-states.

Model Structure. Of course, there is no reason to limit analysis to a single equation that estimates only net effects. The stochastic approach allows estimates of the effects of driving forces on each other and thus can take account of direct effects (e.g. the effects of affluence on CO_2 emissions directly via consumption of fossil fuels in transportation) and indirect effects (e.g. the effect of affluence on CO_2 emissions indirectly by lowering fertility and thus reducing long term population size). Such simultaneous equation models underpin the analysis of the link between population growth and human welfare. In these models growth generates scarcity, which in turn generates a price signal that fosters efficiency, substitution and innovation. To account for such simultaneity, it may be useful to imbed the stochastic version of **IPAT** in a larger structural model that allows all elements of the expanded **IPAT** model to effect each other over time.

As noted above, the effects of independent variables on environmental impacts may vary across contexts. A series of methods allow for increasingly complex models of this variation. The time series and pooled methods noted above, as well as generalized least squares applied to correct for heteroscedasticity in cross-sectional models capture variation over time and across units in disturbance terms. Dummy variables (multipliers in the multiplicative form) allow for shift effects across units. Interaction models allow parameters to vary across units. Time-varying coefficient models can be applied with long time series to estimate secular trends in the effects of the independent variables, though we anticipate that the time series available for these analyses are not sufficiently long to allow the use of this method. Our general point is that a stochastic version of the **IPAT** model allows the application of a rich array of conceptual and statistical tools.

Conclusions

We wish to emphasize that standard social science research methods can take us a long way towards better understanding of the human driving forces of environmental change. What we lack are theoretical frameworks that adequately conceptualize human-environment interactions. We believe the **IPAT** model, despite its limitations, provides a useful starting point for developing a better framework and for structuring empirical tests of competing arguments.

The recognition that humans are having untoward impacts on the bio-physical environment, a perception once confined to the industrial nations, has now reached virtually the entire globe (Dunlap et al. 1993). No one would deny the importance of deepening our understanding of the anthropogenic linkages and causes of environmental impacts. But while there is a singular vision of a common destination, there continues to be considerable debate about the best route to get there. Part of the debate stems from the "trained incapacity" of scholars working within a discipline to recognize affinities in other disciplines, and part stems from the fact that a defining feature of different disciplines is a difference in metatheoretical assumptions. Such tacitly accepted presuppositions about the proper approach to comprehending a problem allow knowledge to advance within a domain of inquiry, but block attempts to integrate and to learn at the interface between disciplines. Split-level dialogues between the social and biological sciences on the topic of population growth have been taking place for over a century. This is precisely why an integrative, human ecological approach is needed.

In this paper we have suggested that the **IPAT** model provides a useful, if fallible compass for setting us on our journey toward a deeper understanding of anthropogenic environmental change than we possess at present. The model is simple, systematic and robust: simple because it incorporates key anthropogenic driving forces with parsimony; systematic because it specifies the mathematical relationship between the driving forces and their impacts; and robust because it is applicable to a wide variety of environmental impacts. We have suggested a reformulation of the model to stochastic form, so that it can be tested readily with conventional statistical procedures. First approximations for some impacts, such as CO_2 emissions and deforestation, can be obtained immediately with the application of these statistical procedures to available data. We also recognize that key challenges for the model remain, such as the choice of the most appropriate indicators for the model's primary variables and limitations on the availability of relevant data as well as quality problems on existing data. We adumbrate some strategies for meeting these challenges. Our keen intent in this effort has been to prod us on the journey toward a deeper understanding of one of the most challenging intellectual problems of our age: anthropogenic environmental change.

NOTES

1. This work was supported in part by U.S. National Science Foundation grants SES-9109928 and SES-9311593, by the Northern Virginia Survey Research Laboratory of George Mason University and by the Dean of the College of Liberal Arts at Washington State University. We thank William Catton, Don Clark, Riley Dunlap and Linda Kalof for their very helpful comments on an earlier draft.

2. The history of research on the link between population and human welfare recently has been given thoughtful review by Keyfitz (1991a,b, 1993). See also Overbeek (1977) and Teitelbaum and Winter (1989).

3. Heroditus further writes that during this period the method of adjustment of the Lydians was to invent a number of games, including dice, and "to engage in games one day entirely so as not to feel any craving for food, and the next day to eat and abstain from games" (The History, Book I:22) Eventually, because scarcities continued and conditions worsened, the King decreed that half the population should emigrate to Smyrna, the choice of movers and stayers determined by lot. Thus Heroditus tells us something about not only population and resources, but also about the role of risk and uncertainty in human affairs.

4. Lucius Annaeus Seneca, c. 4 B.C.-65 A.D., the second son of the Roman educator and author, Seneca the Elder, is considered the most brilliant thinker and writer of his time, the age of Nero.

5. The contributions of Malthus, while usually acknowledged, have been overshadowed by Adam Smith, David Ricardo, John Stuart Mill and others. John Maynard Keynes, an ardent admirer of Malthus, sought to correct this historical neglect. Calling him "the first of the Cambridge economists" (1933:144), Keynes was unabashed in his praise for Malthus: "If only Malthus, instead of Ricardo, had been the parent stem from which nineteenth-century economics proceeded, what a much wiser and richer place the world would be today" (1933:120).

6. Wallace's independent discovery of evolution through natural selection was also inspired by a reading of Malthus. Note that the phrase "survival of the fittest" was developed by the sociologist Herbert Spencer, rather than by Darwin. In some sense, Spencer was one of the last scholars who had major influence within a discipline who could also be considered interdisciplinary or transdisciplinary. Unfortunately, one of his legacies is "Social Darwinism," recently revisited as a "vulgar sociobiology." This crude caricature of Darwin's thought has given a bad name to the evolutionary thinking that is essential to form adequate links between the social and biological sciences (Burns and Dietz 1992; Dietz et al. 1990; Rosa 1979)

7. As we will see later in the discussion, the lack of motivation may stem from the typical use of the model as an accounting equation, which is true by definition, thereby making statistical testing unnecessary.

8. See, for example King (1987), U.S. National Research Council (1986), Schultz (1987), United Nations (1973), World Bank (1984).

9. For modifications and elaborations of the POET framework, see Dunlap et al. (1994).

10. More recent studies that reach the same general conclusion include Ahlburg (1987), Binswanger and Pingali (1985), Hayami and Ruttan (1987a, b), Kelley (1988), King (1987), Mason (1987), McNicoll (1984), Pingali and Binswanger (1987), Ridker (1979) and Srinivasan (1987, 1988). While these studies differ in the sectors of the economy modelled, the nations or regions considered and the methods employed, the findings are remarkably robust and remain roughly consistent with the general findings of Coale and Hoover (1958).

11. Closely related to this argument is the early work of Geertz (1963) on "agricultural involution" and the "induced innovation" analysis of Ruttan and his collaborators (Binswanger and Ruttan 1978; Hayami and Ruttan 1987a, b; see also the classic treatment by Hicks (1932) and its revival by Fellner (1961) and Kennedy (1964)). It is interesting to note the Simon (1981) seems unaware of Geertz's detailed analysis of agricultural development in Java and the problems associated with it. He also does not cite any of the key work on induced innovation even though that work provides a rigorous model for some of the effects he posits.

12. Again, this literature is vast, incorporating much of resource economics and of research on common property resources. The classic reference on resource economics is Barnett and Morse (1963). More recent reviews include Dasgupta and Heal (1979), MacKellar and Vining (1987), Repetto (1986), Ridker (1979) and Slade (1987). Common property issues are reviewed in Ostrom (1990).

13. Normative issues enter into discussions of the environment in subtle ways. The term degradation implies a change from a more desirable to a less desirable state. In economic analysis, the desirability of a state of the environment must be considered in terms of the ability of that state to produce utility through its use in production processes, its existence value, or some other function related to human welfare. The environmental changes of current political concern, such as climate change, ozone depletion, loss of biodiversity, accumulation of toxics, etc. are usually discussed in terms of their adverse effects on human welfare. But there is a philosophical position that argues some states of the environment have intrinsic worth independent of humans (e.g. Devall and Sessions 1985; see also Stern et al 1993; Dietz 1992). The issue is further complicated by differences in preferences. For example, some may consider an undisturbed wilderness the ideal recreational site, others may prefer walkways or roads to make access more convenient.

In this discussion we will avoid these thorny issues by focusing on environmental changes that are part of the global environmental change complex: greenhouse climate change, ozone depletion, species loss, dispersal of toxics. It may be that the actual effects on human welfare of some of these changes are minimal (e.g. Nordhaus, 1992) but all are considered at least potential threats to both the "state of nature" and human welfare.

14. The literature on "optimal pollution" follows this logic. The classic works that underpin this approach are Pigou (1920) and Coase (1960). See Baumol (1988) or Randall (1987) for a more recent discussion. Note that although Coase provides an argument about how efficient levels of externalities like pollution <u>might</u> be achieved, he offers no proof that these mechanisms actually operate.

15. Of course, those who argue that rapid population growth is very harmful emphasize the problem of tipping points and non-linearities. Current data and models may be derived from experience with a linear part of a relationship that is actually non-linear. If the biosphere or specific ecosystems are approaching asymptotes or discontinuities, key relationships embedded in existing models will change abruptly. Under such conditions existing models may not be an adequate guide to the future.

16. For a recent review of such models, see Toth, Hizsnyik and Clark (1989).

17. The forumla is directly related to the energy efficiency of a nation. Energy efficiency is **(P*A)/T** or 1/**I**.

18. In particular, Mazur differentiates the following identity:

$$De = edP + Pde,$$

where E equals total energy consumption, e is per capita energy consumption and P equals total population.

19. Between 1950 and 1987 the percent increase is 484% (Commoner 1992:85-86).

20. Doubtless that some scholars will be chary to the use of such a simplified model to capture the myriad factors--with complex linkages and feedbacks--underlying anthropogenic environmental change. On the one hand, we are sympathetic to and share that caution. On the other hand, we note that many scientific endeavors begin with first approximations based upon crude heuristics and, further, that many scientists accept Ockam's razor as a useful convention for proceeding with their work.

Models are, after all, crude approximations to reality. They are abstractions of the real world that are stated in sufficient detail to be realistic but have omitted the inessential detail that would complicate them needlessly and stiffle generalization. They are neither categorically correct nor incorrect, but serve as vehicles for focusing our attention in a disciplined way. Stated in analytic form, such as mathematics, they permit a systematic examination of the relationships postulated by the model.

Expectations about models conjure the time-worn image of the blind scholars feeling around an elephant. The ideal model would simultaneously maximize generality, realism and precision. Unfortunately, it is literally impossible for a model to simultaneously maximize all three at once. This unavoidable fact prompted Levins (1966) to suggest the following set of compromises: (1) sacrifice generality to realism and precision; (2) sacrifice realism to generality and precision; or (3) sacrifice precision to realism and generality. Our argument for the utility of the **IPAT** model in understanding anthropogenic environmental change is one that begins with Levin's compromise (2), then hopes to elaborate our understanding by modifying the model to accommodate compromises (1) and (3).

21. If **T** is derived as **I/PA** as in the accounting model and entered into the regression, the estimated values for **a**, **b**, **c**, **d**, and **e** will equal 1 and the R^2 value will also equal 1. This indicates the limit of the accounting model. It assumes each driving force has equal impact in the sense that the elasticity (the percentage change in **I** accompanying a percentage change in **P**, **A**, or **T**) of the driving forces are assumed equal. For example, a 1% change in population is assumed to produce a 1% change in impact.

22. While global level time series analyses may seem the ideal method, the data quality and methodological problems are formidable. Data are limited, most of the interesting time series data are highly collinear, and for some variables (for example, energy intensity of the world economy) year to year fluctuations are more likely a result of measurement error than real structural change. In addition, lack of attention to problems of functional form and cointegration can lead to spurious inferences (Engle and Granger 1991). Global analysis aggregates across contexts and thus may miss important influences of institutions, culture and the political economy that are context specific. While the stochastic model does not make these problems disappear, its engagement with an existing methodological literature makes us aware of pitfalls that might otherwise trap unwary researchers.

23. The term "Netherlands effect" derives from the fact that the environmental impacts for nations such as Holland appear to be low for their level of population and affluence. This is because international trade places the impacts of some Dutch consumption elsewhere (e.g. deforestation to produce wood does not take place within Dutch borders; pesticide use on food crops takes place in food exporting nations rather than in Holland, etc.).

24. It appears that in the 21st century migration will continue to be a very important determinant of population change. Migration can lead to very rapid transformations of population size, distributions and structure. Thus migrations streams may have a critical effects on the environment. And in turn, some migration is certainly driven by environmental conditions--migration may be the most common human response to adverse environmental change.

25. The original logic of the **IPAT** model uses the term "affluence" as a convenient abbreviation for consumption patterns and some measure of national income as the indicator of affluence. It is clearly consumption patterns and the associated forms of production that drive environmental impact. Here we are suggesting two ways of reconceptualizing **A**. One is to dissaggregate the "affluence/ consumption" variable in ways that reflect actual consumption and production practices. Another is to consider the link between environmental impact and quality of life.

26. This literature has its origins in Nordhaus and Tobin (1973), Nordhaus (1977) and Zolotas (1981). Recent efforts include Daly and Cobb (1990: 401-455) and Repetto et al. (1989).

27. It has sometimes been suggested that life expectancy is an inappropriate quality of life measure because it incorporates the later years of life. Current life extension technologies, while adding years do not always add quality to human existence. While this argument is well founded with regard to medical ethics, the marginal additions to life span afforded by heroic technologies have almost no effect on either cross-section or time series comparisons of life expectancy. Indeed, since infant mortality is a component of life expectancy at birth, two of the three variables that compose the widely used PQLI measure are in fact components of life expectancy.

28. Ehrlich and Holdren (1972, 1972; Holdren and Ehrlich 1974) are aware of the complexity of **T**, but little has been done to elucidate the complexity of this part of the model. We have little social theory to suggest how to specify and measure **T**.

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