Homage to Malthus, Ricardo, and Boserup: Toward a General Theory of Population, Economic Growth. Environmental Deterioration, Wealth, and Poverty

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Abstract

The debates over the future of human population and the earth's environment, and similar large issues, usually take place without reference to explicit models. Debate would be clarified if such models were employed. We propose that the logistic equation and its extensions like the Lotka-Volterra equations, so familiar to ecologists, can easily be modified to model the important "macro" questions that motivated the three thinkers of our title. The long term rate of population growth must normally be controlled by the rate of improvement in K, the carrying capacity of the earth. K will in turn be controlled by the rate of technological progress. The present situation, in which technological improvement (but also, perhaps, environmental deterioration) are increasing at rates above r, the Malthusian intrinsic rate of natural increase, is probably unique in human history. Can present levels of human prosperity and population growth be sustained? What processes are most likely to determine the answer to this and similar questions? We here sketch a model that endogenizes technological progress and environmental deterioration in the logistic framework. We discuss extensions of the logistic approach to multiple populations, such as other species, and sub-populations, such as human social classes, using the Lotka-Volterra equations.

The General Idea

The relationship between economic growth and environmental deterioration is a complex and controversial topic. So are other issues like the relationship between social-structural variables and economic growth and environmental deterioration. To clarify the issues at stake and facilitate discussion, it would be helpful to have models that incorporate these things in a common framework so that many variables can be readily endogenized. Ideally, we would like to have simple models that incorporate everything so that an analysis of what is at stake in different arguments is transparent. Of course, human life and the environment that we live in are far too complex to expect miracles from models. Nevertheless, physical scientists, economists, ecologists, and evolutionary biologists have found the construction of simple heuristic models one of the most important tools for studying complex phenomena. Even if it is too hard to deal with everything at once, it is often possible to use relatively innocent simplifications to reduce the biggest problems to manageable proportions. Even when simple models are not enough to settle the issue, they are always the best place to start. Malthus, Ricardo, and Boserup are among the pioneers of human ecology who preached the doctrine of simple models. Malthus' discussion of the power of exponential growth, Ricardo's analysis of the link between economic, social and demographic variables, and Boserup's proposed link between demography and cultural evolution are excellent examples of the use of simple models. The IPAT analysis of human impacts on environment as a function of population, affluence, and technology is a contemporary example (Dietz and Rosa 1994). We suggest here that a family of generalized Malthusian models used very frequently by biological ecologists—the logistic equation and its derivatives, the Lotka-Volterra equations—can be readily modified for the human case. What follows is a programmatic sketch for how we might proceed.

Economic Growth and Environmental Deterioration

Let us start with the vexing problem of the relationship between economic growth and environmental deterioration. Models of economic growth and environmental deterioration can be linked if we consider that economic growth is a form of cultural evolution. Suppose that we define economic growth as all the good things that happen to human populations and environmental deterioration as all the bad things. Most long run changes in the efficiency of economic production are due to technological or institutional improvements—new, better ideas—most growth economists and economic historians agree. In an evolutionary ecologist's terms, economic growth is adaptive change. In the logistic model of population regulation, economic growth increases the human carrying capacity $(K(T))$, where T indicates that carrying capacity is a function of prevailing technology, including social "technology" (North et al. 1983). Thus, the familiar logistic equation with technological evolution added becomes

$$\frac{dN}{dt} = rN\left(\frac{K(T)-N}{K(T)}\right) \tag{1}$$

In a simple model, we might neglect the effect of physical and human capital on $K(T)$, assuming that the current capital stock lags behind current knowledge base only slightly. Alternatively, we could define T in the simplest case as that technology that the population in the aggregate knows rather than technology in the abstract, so that T also includes social capital. (This is a common trick in the use of simple models; they are so general that the same variable can mean somewhat different things in different arguments. This is a useful feature, but also a pitfall if the level of abstraction obscures the issue at stake.) If technological improvement is rapid enough compared to population increase, N will lag K, and human populations will grow prosperous on the gap between resources and carrying capacity at current technology. Call this **surplus** capacity "prosperity," where per capita prosperity (P) will be some function of surplus capacity, say $(K(T) - N)/N$. Viewed this way prosperity is a unitless standard, potential persons per person. Monetary or other measures would require a conversion coefficient, say a to convert the measure to monetary units, thus expressing surplus population capacity as money wealth. Other measures of prosperity might be number of leisure hours, quality of diet, amount of desirable material possessions, the opportunity to experience natural beauty, etc. More realistically, measures of prosperity will be more complex functions of N & $K(T)$. It requires technology to convert P into things people can actually enjoy, population density can affect some pleasures negatively (wilderness experiences) and others positively (quality of restaurants), etc. Such realism is easily added, but at great cost to the ease of analysis of the model. The simple model strategy is to accept considerable penalties on account of unrealism to preserve ease and hence transparency of the analysis, grudgingly adding realism when it is clear that the simpler approach has been milked *dry* without definitive results.

Taking advantage of the flexibility of such very general models, we could imagine the whole formalism here in monetary units if desired. For example, N could be measured in terms of the wealth needed to support an average person. The total production of the economy would be measured in terms of the income flows from the various categories of wealth. That is, in some sense $K(T)$ represents the total wealth, at least potential wealth, of the economy, and the income streams from this wealth are what sustain the human population, its prosperity, and its ability to increase N and P. It seems useful to an ecologist interested in relatively long time scale processes to maintain the Malthusian/Ricardian structure of the model as fundamentally people based and let the monetized version be a transformation of the demographic model. Economists interested in the shorter-term dynamics of market economies naturally choose a rather different set of simplifying assumptions.

Environmental deterioration decreases $K(T)$ as a function of N, P, and T. We can divide the effects of these variables into those that are effectively permanent (depletion of non-renewable resources, extinctions of species) and thus cumulative, and those that affect renewable resources and hence are dependent, as a first approximation, only on current N, P, and T (depletions of populations that may regrow, most forms of air and water pollution). In a more realistic model, there would have to be a spectrum of resource renewal rates to capture interesting cases like CO_2 whose dynamics has a time scale in the atmosphere of centuries. Let the current stock of slowly renewable resources be D. We can capture the effects of capital investment by imagining that there is a spectrum of long-lived helpful environmental "negative deteriorations" (agricultural terraces, roadbeds, durable buildings) that tend to make the D term grow instead of shrink. Finally, the natural environment (E) will be in some state or another independent of human activity. The state of E may be better or worse for the human population. The last glacial event of the Pleistocene before 10,000 years ago was colder, drier and more variable than the present climate and was probably intrinsically capable of supporting fewer people at any level of technology than current environments. Thus the functional form for K might look something like

$$K(T,D,E,N,P) = E + bT - cN - dNP + eD \qquad (2)$$

where the constants (more generally functions) convert the natural units of the variables to population units. The terms $-cN$ $-dNP$ measure the deteriorating impact of the current economy on the environment, incorporating the idea that subsistence (bread) and luxury (caviar) goods production may have different impacts. D will be a function of the initial endowment of non-renewables, D,, and a history of depletion, substitution, and long-term improvements. The instantaneous change of D would look something like

$$\frac{dD}{dt} - \; fN - gNP + hT \qquad (3)$$

We might consider the terms $-fN$ and $-gNP$ net of the constructive and consumptive-destructive acts of people, so that in principle the signs can be positive. hT measures the tendency of technology to add to the stock of usable non-renewables by discovering techniques to use leaner ores, recycle waste, and invent substitutes.

Technology can be taken as a given, but it would be nice to think of it as endogenous to the system. According to various hypotheses, the rate of technical innovation is a function of existing technical sophistication (T, Romer 1994), prosperity (P, Lee 1986; Boserup 1981) or population size (N, Simon 1981; Diamond 1997). There is also some cost to maintaining a given level of technology. Under some historic circumstances, like. the European Dark Ages, the local stock of useful knowledge declined as literacy rates fell, libraries were burned, and religious fundamentalism caused neglect of secular knowledge. If we assume that technology is cumulative, we can build a variety of evolutionary models of technological growth, for example

$$\frac{dT}{dt} = iT + jN + kNP - lT \qquad (4)$$

Once again, these simple relationships can again be made different or more complex if desired. For example, to capture Boserup's hypothesis, innovation should rise as prosperity declines, perhaps still rising even if population forges past $K(T)$ and starts to decline (implying that P can take on negative values to measure unsustainably desperate poverty). In this case the prosperity term would have to have a form like $(P_0 - kP)N$. When kP is above P_0, people will feel so rich they will begin to neglectfully forget technology they already know. As kP begins to decline past P_0, individuals become ever more driven by necessity to innovate.

In principle, we now have a coupled system of equations describing the human economy that can be expressed in population or monetary units. Everything is endogenous except the aspects of the environment not under human control. Depending on the functional form and values of constants we think reasonable for equations 2-4, the economy might have a variety of trajectories. Conjecturing, if i, j, and k are positive constants or stable or increasing positive functions, the economy could have an exponential (or even super-exponential) growth path forever. On the other hand, if D_0 is very large and the hT and bT terms cannot exceed the terms deteriorating D, then the economy will eventually have to contract due to environmental deterioration. Long term deterioration will also occur if the $-cN - dNP$ terms are large relative to bT, as in the classic neo-Malthusian models. If the $- fN - gNP$ terms are large the economy will tend to oscillate. Sustainable growth could be defined as growth paths that result in continued growth of population and/or prosperity in the face of environmental deterioration. If non-renewables are at issue, as Pezzey (1992) discusses eloquently, sustainability implies technological progress. In a purely renewable world simple overexploitation is the problem. If we want to maintain or increase prosperity, social institutions must exist to prevent the Malthusian tendency of reproduction to convert P to N. Within the context of a relatively simple model system, every position in the debates over environmental deterioration, economic growth and limits to growth is allocated a term or terms in the system that can potentially dominate the behavior of the economy. The models themselves are not biased in favor of any particular hypothesis about the future. Debates between neo-Malthusians and technological optimists, we advocate, should debate the forms these terms should take and values of variables and parameters. It is unproductive sophistry to chuck from the full model those terms that might be hostile to one's hypothesis, and then argue that the result proves one's case.

The model thus highlights the fact that controversial opinions about the long run behavior of the economy overtly or tacitly assert that some of the terms in the above equations are large relative to others. For example, the famous *World Dynamics* model did not include the possibility of technological progress. As Boyd (1972) showed, adding that possibility can completely transform its results. Most modern economists assume that technological progress can forever stay ahead of the depletion of D_0, though only a few like Simon suppose that it can stay ahead of both depletion of D_0 and rapid population growth. Environmentalists often assume that slowing or ending population growth *and* reducing all the deteriorating coefficients c, d, f, and g will be necessary to do the trick. Environmentalist reformers imagine manipulating the economy so that N is kept low because people demand high P, but that the gap between N and K is enjoyed in a manner that keeps d and g small. Environmentalists would like us to use P to purchase labor-intensive but not natural-resourceintensive goods—organic produce, paintings and fine wine perhaps, but not powerful cars and airliner vacations. Neo-liberal economists doubt that any of this is necessary. To keep P increasing it is merely necessary to allow the natural action of market forces, plus a measure of public investment in basic research, to keep h, i, j, and k at high levels, and in public education to keep l low.

Embedding the Human Economy in Natural Communities

The basic picture of the human economy is thus complete within its very simple limits. From an ecologist's or environmentalist's point of view, the model so far is extremely anthropocentric; the quality of the environment is measured strictly with reference to supporting human populations and their prosperity. This is easy to fix. There is a similar economy for every species, and, if the species interact, the numbers of competing, predating, disease causing, and symbiotic species are arguments in the expressions for each others' carrying capacities. Ecologists have long studied models of such a system, the Lotka-Volterra equations. The increase in numbers of humans in California has utterly ruined the environment for grizzly bears and a few other species, and damaged it for many more. The evolution of new disease adaptations has deteriorated the environment for humans in recent years. The Lotka-Volterra equations have the form

$$\frac{dN_1}{dt} = r_1 N_1 \left(\frac{K_1 - N_1 - \alpha_{12} N_2}{K_1} \right) \qquad (5a)$$

$$\frac{dN_2}{dt} = r_2 N_2 \left(\frac{K_2 - N_2 - \alpha_{21} N_1}{K_2} \right) \qquad (5b)$$

If humans are the first population and grizzlies the second, it is likely that, after Europeans came to dominate the human population of California, K_1 was large relative to K_2 and α_{12} rather smaller than α_{21}. Human populations built up rapidly in the nineteenth century, and, with firearms, encounters between humans and bears became much more dangerous for the latter. Industrial human populations outcompete or out predate bears. Model communities with arbitrarily large numbers of species can be created, but, of course, analytical complexity goes up accordingly. Many other extensions are interesting. For example, the α's and K's of these equations are characters that are subject to evolution by natural selection, as we see in the case of the evolution of new strains of pathogens. Other organisms undergo adaptive improvements, much as human societies adapt by developing new technology. The species in such a community influence each other's evolution; evolutionary biologists say they *coevolve.* As human populations have become denser, fundamentally due to the evolution of technology, they have become an increasingly inviting resource for virulent microbes. Only a steady improvement in public health technology fends off catastrophic epidemics.

The Analysis of Social Structure

Another important class of extensions is to disaggregate the human population. Classic demography is concerned with many aspects of this sort of extension, for example age structure, that we pass over. More interesting in an evolutionary context, human subgroups behave partly as if they are different, coevolving, species. Our partners in the division of labor are like symbionts. Criminals are like predators. Upward mobility between two classes would also be analogous to predation, one class growing at the expense of another. Other nations or firms are like competitors. Thus, human society can be disaggregated to any level desired. Consider an extension to class. The wealthier classes in modern economies have high reserve wages, essentially allowing their prosperity to affect their reproduction by inducing the use of preventative checks

$$\frac{dN_1}{dt} = r_1 N_1 \left(\frac{K_1(T) - (N_1P_1 + N_1) - \alpha_{12}(N_2P_2 + N_2) + \beta_{12}N_2}{K_1(T)} \right) \quad (6a)$$

whereas a subordinate class may have different values of the same parameters

$$\frac{dN_2}{dt} = r_2 N_2 \left(\frac{K_2(T) - (N_2P_2 + N_2) - \alpha_{21}(N_1P_1 + N_1) + \beta_{21}N_1}{K_2(T)} \right) \quad (6b)$$

where P_1 is now the amount of prosperity people in class 1 demand in order to reproduce at replacement, the α_{12} terms are the effect on the economy of the competitive effects of a second class, and the $\beta_{12}N_2$ term represents the value class 1 obtains from the work of class 2. The equation for the second class is symmetrical. In a Marxist model of class exploitation, the $\beta_{12}N_2$ term would dominate the first equation and the $\alpha_{21}(N_1 + N_1P_1)$ the second. Marx would also wish us to make the α's and β's functions of T to capture the idea that changes in technology tend to upset the class structure, changing the relative advantage of classes and expanding the K's of some relative others. Industrial technology expanded the industrial working class and privileged the capitalist class in the struggle over the fruits of industrial production. Conservative defenders of an inegalitarian class system will highlight the term $\beta_{21}N_1$— whatever services the elite provide to the masses, such as the provision of government welfare and police services. If the situation is one of two economically equal and socially similar groups joined in a division of labor, $\alpha_{12} = \alpha_{21} = 1$ and $P_1 = P_2$. If we assume that the economies of the two classes are somewhat different (urban versus rural), each class will have a different carrying capacity, assuming that the two classes deploy different technologies. Conjecturing, if class 1 is a secular middle class with a high P_1 and class 2 is a fundamentalist middle class with a lower P_2 and if a,, is large relative to α_{21} class 2 will drive class 1 to extinction. (In the linear case, proving these conjectures is a straightforward extension of analyzing the analogous classical biological cases.) Under other conditions, the two classes can coexist. Once again, in principle there is no limit to how complex a society we could create in this way. It would be interesting to investigate the impact of social change on environmental problems and vice versa. For example, technical innovations may come disproportionately from the secular class, and their flow might slow as fundamentalism increases, leading ultimately to a slowing in the rate of growth of $K(T)$. Or, in a quasi-Marxist manner, a fall in $K(T)$, by reducing prosperity below P_1, might cause the contraction of the innovating secular modernist class (or their investment in technological improvement), accelerating a fall in $K(T)$. In applications to global environmental deterioration questions, it might be useful to study highly aggregated social models, representing all the rich countries as one population and all the poor ones as another.

Modeling human ecological problems in the Logistic/Lotka Volterra framework hews closely to the thinking of the founding fathers and mothers of human ecology but this is not its primary virtue. The flexibility of the approach recommends it. It is easy to add terms to capture important arguments in a unitary framework. The analysis of simple versions of the models is easy, and, for more complex cases, population biologists have broken many paths.

Getting Some Numbers to Work With

The theoretical analysis of the system of equations tell us something about the logic of problems, but things get seriously interesting only if we can put numbers to the terms in the equations. Are the models any help for this much more difficult task? Will not the problem have to be addressed through a plethora of "middle range" theories and empirical studies? We believe that the models tell us what the empirical task is. Unless we can aggregate the data to the level indicated by the models, we can never have a transparent empirical analysis of these important problems at the necessarily global scale. A myriad of disconnected middle range analyses, no matter how well verified, don't really tell us what we need to know. In theory we can link the middle range analyses into giant input-output analyses, but such are very hard to understand and are often do not produce very good forecasts. It is better to have robust general analyses that we can understand. Also, it is not clear that it is easy to make better than crude guestimates about the values of variables and parameters. Solow's (1988) and followers' classic investigations of technological progress depended upon using highly aggregated statistics about the impact of capital investment on growth and estimating technological progress as a residual. The state of the art is better advanced today, but technological progress is still disaggregated into only a few categories.

Malthus' intellectual biographer William Petersen (1979) credits him with being a canny empiricist who tracked down the best available information, used his mathematical arguments to make sense of it, and gave rather sensible policy advice based on the combination. We face the same problem. We can make sense of the problem of environmental deterioration only if we can somehow estimate things like the original size of D_0, the rate that deterioration is whittling away at nature's original endowment of non-renewable resources, and the rate that technology is finding work-arounds to that deterioration. Unlike in Malthus' and Ricardo's day, there is plenty of data out there; we just have to find clever ways to make the most of it. It is awful to contemplate that the planet may have offered **us** the opportunity to grow up huge populations on the basis of a large D_0 that no amount of cleverness can avoid depleting in the long run. Are we creating a huge population overhang that one day must come crashing down? ***Or*** are we scaring ourselves with Malthusian bogeymen? Joel Cohen's (1995) recent book on the earth's carrying capacity shows that we are not close to an answer to these questions. The next step should be to think hard about how to estimate the terms in models of the complexity described here. With a little luck, we should be able to close the gap quite a bit.

An Analysis Based on the "Limiting Nutrient"

One possibility for applying the model empirically is to pick a particular key element of the human ecological niche and use it as a surrogate for the whole of our adaptation. Nitrogen recommends itself in this regard. Nitrogen is an essential element. From this point of view every organism, including every human, is just so much nitrogen. Nitrogen is the limiting element in many ecological communities, including agricultural ecosystems. Thinking in terms of Liebig's law of the minimum, if we were to pick a single element that most closely represents the total carrying capacity of the earth, for life as a whole and for humans in particular, it would be nitrogen. Of course, in particular locations, many other elements limit production.

We might suppose that an analysis based on nitrogen is likely to be a close enough surrogate for other nutrients/pollutants to get answers well within the limits of any uncertainties in the existing data and guesses about the future. The ubiquitous importance of nitrogen makes it a handy, if quite rough, way to represent variables that are in principle much more complex. For example, prosperity is reflected in consumption of meat and so the luxury Consumption of nitrogen rich protein. The minimum necessary protein in the diet defines the subsistence minimum. Nitrogen is not a non-renewable resource exactly, but the present world nitrogen budget is heavily subsidized by industrially fixed N. Vitousek, et al. (1997) estimate that natural terrestrial N fixation runs around 90-140 Tg yr-1. Industrial fixation is about 80 Tg yr-1 and, together with the planting of leguminous crops, fixation due to combustion, and so forth, the total anthropogenic increase in the terrestrial N budget is approximately equal to natural production. This massive increase in the global N budget depends substantially on depleting D_0 resources, especially fossil fuels. Indeed, one can see here the *potential* for generating an ultra-Malthusian "overhang" of population built up by an unsustainable bulge in $K(T)$ due to the use of fossil fuels and other industrial resources to fix nitrogen. On the other hand, the N in the atmosphere represents an effectively undepletable source, so innovations in technology have the *potential* to keep $K(T)$ high or even growing indefinitely so far as the availability of N is concerned. N is also an ordinary pollutant. The massive increase in the N budget has many short term environmental impacts on a local scale (lake and forest eutrophication). NO is an important greenhouse gas and a stratospheric ozone depleter. Photochemical smog, with its hazards to human health, is intimately related to the generation of NO, by combustion. NO, contributes to acid rain. NO, is a serious contaminant of ground water. Deposition of NH_3 and NO, is fertilizing natural ecosystems and will disrupt competitive relations between species, favoring weedy species at the expense of climax species with thrifty N demands. Thus, anthropogenic N will have a negative effect on biodiversity and perhaps on ecosystem services.

It is clear what a path of sustainable development means in terms of the N cycle. Technical innovations, say more efficient nitrogen-fixing plant varieties, must replace fossil fuels as the main source of agricultural nitrogen. The leakage of anthropogenic nitrogen out to natural ecosystems, ground water, and the atmosphere must be reduced. Luxury consumption of N may need to be curtailed. Thus, even if we neglect everything else in the interests of getting a first cut empirical analysis of the human ecological situation, the nitrogen budget covers all the basic questions.

In fact, from a neo-Malthusian point of view, and virtually all human ecologists are neo-Malthusians, a focus on nitrogen is usefully conservative. We know that there are other greenhouse gasses, other threats to biodiversity, other essentials that depend upon the exploitation of non-renewables. Neo-Malthusians have an oft-deserved reputation for being woolly-minded alarmists who trade in worst-case scenarios and seldom deal seriously with numbers. Working out the implications of the nitrogen cycle in the framework of the logistic/Lotka-Volterra equations is a species of intellectual earnest money. It is a useful exercise to take a certain burden of proof upon oneself and see what a best guess from the results of a conservatively simplified analysis looks like. The capacity to run up $K(T)$ to unsupportable levels via industrial N fixation and the other nasty features of the anthropogenically augmented N budget has the capacity to generate grim future scenarios. There is a hard nitrogen constraint on the size of the human population. If population growth is sufficiently subsidized by unsustainable industrial N fixation, there might be a hard landing on the way to the sustainable population path, an overshoot and crash. On the other hand, a rapid rate of technical innovation in N budget management might permit a soft transition to a sustainable economic growth path.

Suppose we develop future scenarios based on the best available data by fitting our model of $K(T)$ to the past and then begin forecasting, all assuming that N is the master limiting nutrient/pollutant. Any scenario of population growth, changes in prosperity, depletion of fossil fuels, tolerable short-term insults to the environment, long-term impacts on biodiversity and so forth will generate a certain need for innovation to manage the N budget. We know something about the economics of innovation in the R&D sectors related to the nitrogen budget. Does your favorite growth path generate needs for technical innovation that seem too large to be supportable? That is, at some point in the future might managing the N budget start to generate R&D expenditures that are a significant multiple of current expenditures? Any future ballooning of projected R&D expenditures in this one sector would be a serious warning signal. For example, modest increases in fossil fuel prices in the mid twenty-first century (to cover reductions in CO, load to the atmosphere or to cover the cost of synfuel production from tar sands, oil shales, and coal) might seem to require the efficiency of industrial N fixation to approximate thermodynamic limits. Large R&D expenses would likely be required to achieve very high efficiencies. Worse yet, we might convince ourselves that in addition large increases in the efficiency of symbiotic fixation would likely be required, and that the need to reduce the load of N waste products to the environment is likely to become acute.

Our own intuition is that such an exercise will suggest that N limitation in one form or another is likely to put a limit on human population and prosperity that no plausible amount of R&D will overcome. On pessimistic days, we even suspect that the industrial N fixation supported population and prosperity of today have generated a grossly unsustainable population/prosperity overhang. Intuitions are notoriously unreliable (ours are anyway), and the task at hand is to milk the available data for the best guess we can make. If the argument here is correct, this exercise will move the debate forward. We might show fairly convincingly, with a conservative analysis, that the medium term future management of the N budget of the earth either is well within the kinds of rates of improvement in production and pollution control that are routine with current R&D, or that they are not. The objective should be to construct an analysis sound enough to shake reasonable skeptics on either side of the debate.

In the spirit of Liebig's Law, there are many factors that might control the growth (decline) of $K(T)$ more tightly than N. Ultimately it will be useful to repeat the analysis with other essentials, fresh water, agricultural land area, energy, and so forth. Can we smoke out the most stringent limiting factor? There is no reason why social factors might not prove more important than natural resources. For example, North-South conflicts might well stymie efforts to manage the N cycle even if in-principle solutions exist.

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References

Boserup. E. 1981. ***Population and Technological Change: A Study of Long-term Trends.*** Chicago: University of Chicago **Press.**

Boyd, R. 1972. World dynamics: anote. ***Science*** 177:516-519.

Diamond, J. 1997. ***Guns, Germs, and Steel: The Fates of Human Societies.*** New York: Norton: Jonathan Cape/Random House.

Cohen, J.E. 1995. ***How Many People Can the Earth Support?*** New York Norton.

Dietz, T., and E.A. Rosa. 1994. Rethinking the impacts of population, affluence, and technology. ***Human Ecology Review*** 1:277-300.

Lee, R.D. 1986. Malthus and Boserup: a dynamic synthesis. In ***The Stare of Population Theory: Forward From Malthus.*** eds. D. Coleman and R. Schofield, 96-130. London: Basil Blackwell.

North, **D.C.,** T.L. Anderson, and P.J. Hill. 1983. ***Growth and Welfare in the American Part, 3rd Edition.*** Englewood Cliffs, NJ: Prentice Hall.

Petersen, W. 1979. ***Malthus.*** Cambridge: Harvard University Press.

Pezzey, J. 1992. ***Sustainable Development Concepts: An Economic Analysis. World Bank Environment Paper 2.*** Washington: The World Bank.

Romer, P.M. 1994. The origins of endogenous growth. ***J. Economic Perspectives*** 8:3-22.

Simon, H.A. 1981. 1990. Amechanism for social selection and successful altruism. ***Science*** 250: 1665-1668.

Solow, R.M. 1988. Growth Theory and After. The Radcliffe **Lectures** University of Warwick 1969. In. ***Growth Theory: An Exposition.*** R.M. Solow. New York Oxford University Press.

Vitonsek, P.M., J. Aber, R.W. Howarth, G.E. Likens, P.A. Matson, D.W. Schindler, W.H. Schlesinger, and G.D. Tilman. 1997. ***Human Alterations of the Global Nitrogen Cycle: Causes and Consequences. Issues in Ecology Number 1.*** Washington: Ecological Society of America.