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The effect of population growth on environmental quality

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Abstract. This paper summarizes research on the effect of population growth on environmental quality. Land transformations induced by the spatial expansion of agriculture are probably the major route by which population growth has affected features of the natural environment. These transformations are not automatic and their extent is influenced by social institutions. Intensification of agricultural land use is an alternative response with its own set of environmental implications. These are especially salient in the case of expanded irrigation. In contrast to relations in the agricultural sector, a new version of the conventional I = PAT equation is introduced to suggest that population growth is a minor influence on the extent of industrial pollution. Nevertheless, population policy may play a useful role in strategies to reduce industrial pollution.

Key words: Agriculture, Environment, Pollution, Population

The hazard to human well-being posed by population growth has conventionally been framed in terms of the ratio of population or labour supply to other factors of production. For Malthus, the salient ratio involved land resources. In the 1940s, concern shifted to exhaustible resources, to minerals and especially energy supplies. In the 1950s, Coale & Hoover (1958) reframed the debate in terms of physical capital. By the 1980s, the primary concern had shifted to human capital (World Bank 1984).

In the 1990s, much of the anxiety about population growth has returned to its Malthusian origins. Land scarcity and degradation of soils in developing regions is seen by many as a major constraint to agricultural development. Since most of the world's poor are located in rural regions of developing countries and are primarily dependent on agriculture for their livelihood, a special focus on poverty has redirected attention to the agricultural sector. Certain agricultural economists have become more pessimistic about prospects for productivity advances that outpace population growth. And the example of Africa, where food production has lagged behind population growth for two decades, has added empirical content to what might otherwise seem vague apprehensions.

These genuine concerns have been reinforced by the growth of popular attention to environmental issues in western countries. George Gallup is quoted as saying that commitment to the environment is the most deeply and widely held value among Americans that his research had ever uncovered (Thompson 1985). Much of the growth in attention to enviromental issues in the West is undoubtedly a result of increased affluence: ordinary people have come to expect standards of cleanliness and safety in their surroundings that were previously the exclusive province of the rich or well-born (Kneese 1988). Since the markets that helped to produce affluence did little to protect citizens from industrial waste products, a catch-up phase of government activism was initiated. In addition, ethical systems have been changing in ways that place higher value on the maintenance of a natural order, including the survival of other species. Mathews (1991) traces the rapid emergence of the environment into the realm of high politics during the 1980s, when western politicians were racing to keep up with their greener and greener constituencies.

Whatever its origins, the growing concern with environmental issues means that the relationship between population growth and environmental quality is increasingly salient in international discussions of population policy. This paper provides a brief review of what is known about the effect of population growth on environmental quality in various settings, and concludes with some comments about population policy.

1. Land transformations and food production

As a simple collection of mass, the human population has no environmental implications. If they stood together, today's 5.6 billion humans would occupy a circle with a radius of less than 8 miles that extended an infinitesimal distance into the atmosphere. It is human activity that has changed the face of the globe, and the relation between human activity and human numbers is not always straightforward. The most direct connection involves a basic biological requirement: human beings must consume an average of 1700 calories per day to meet minimal metabolic demands. The basic reason why human beings do not stand together but have dispersed across the earth's surface is that the nutrients to sustain plant growth, and the solar energy required for photosynthesis, are themselves widely dispersed. When labor requirements in food production are relaxed, people congregate to a far greater extent than when agriculture is the dominant activity.

Farming is by far the most important human activity that has transformed the land, and continues to be the principal route by which humans affect the environment. Eleven percent of the earth's land surface is now cultivated, although less than one percent is in permanent crop (Waggoner 1994). Another 26 percent is pasture, and 31 percent is forest. The amount of land that could, under certain circumstances, be used to grow crops is roughly three times the amount that is currently used for this purpose (Bongaarts 1993).

1.1 *Deforestation*

The food needs of a growing population can be met either through intensification of production on land that is already cultivated or through expansion of cultivation into new territories (extensification). Both processes have ecological consequences that vary from setting to setting. Until the early part of the 20th century, the principal means of expanding production was the cultivation of new lands, typically after the destruction of forest cover. Forests that covered nearly all of Europe in 900 AD had virtually disappeared by 1900. They were converted primarily into agricultural fields and pastures to feed Europe's growing population (Wolman 1993). A similar process is occurring on a much-compressed time scale in most developing countries today.

In view of the amount of attention that has been directed to deforestation, it may be surprising to learn that the world's forested area has declined by only 20% since the dawn of agriculture 10,000 years ago (Miller et al. 1991). Just how rapidly the remaining forests are disappearing is a matter of some dispute. Recent reports using high-resolution satellite photography suggest that previous estimates of deforestation in the Amazon were approximately 50 percent too high. About 6 percent of the 4.1 million square kilometers of Amazon closed canopy forest had been deforested by 1988, compared to only 2 percent in 1978. Another 15 percent in 1988 had been affected to the point of threatening biological diversity in the habitat (Skole & Tucker 1993). According to data on forest cover in 99 countries assembled by the World Bank (1992: Table A6), 58 countries had less forest cover in 1989 than in 1965. The more densely settled parts of the globe, in general, have less forest cover. In Asia, Cruz (1994) estimates that 82 percent of the land that could be used to grow crops is already cultivated.

The destruction of forests has several adverse consequences that vary in intensity from place to place. When forests are destroyed on hillsides, rates of soil erosion typically increase, sometimes dramatically. Fuelwood from forests supplies much of household energy needs in poorer parts of the world, especially in Africa. Faster rates of evaporation in deforested areas can lead to dessication of soils and potential climatic change. Forests, especially tropical forests, are the home to millions of species whose disappearance depletes the genetic stock available to humans and raises profound ethical concerns. And esthetically, forests are often more appealing than what replaces them.

There is no doubt that population growth has played and is playing a major role in the destruction of forests. But like any other process subject to purposive human action, the process of deforestation is influenced by a wide range of factors that modify, mute, or accentuate the direct influence of population growth. Among the most important of these factors are social institutions that are capable of controlling access to forest resources. Their role is highlighted by a comparison of forest resources in China and Japan (Mather 1986). In China, the pressure of population on land resources, combined with weak administrative structures, led peasants to pursue short-term strategies of forest clearance. By the 19th century, the country had been almost entirely denuded of its forest cover. In Japan, on the other hand, the increasing demand for timber beginning in the 17th century was accompanied by an awareness of the adverse effects of deforestation. First the lords and later the imperial government prevented extensive depletion of forest cover. Since 1900, two-thirds of the forests have been in the hands of public institutions where they have been effectively preserved.

It is an open question whether most governments in developing countries are powerful enough to control access to land resources. The most important issue relates to lands that are in a sense common property resources. It is widely recognized that common property, open access resources are depleted too rapidly because those who exploit them have little or no incentive to preserve them for future use. But such exploitation often occurs in frontier areas of developing countries where administrative structures are weakest and least likely, at least in the short term, to 'internalize the externalities' arising from land misuse. Squatting and land-grabbing are the predominant means of gaining access to land in the Amazon, with little government control of the process (Cunha & Sawyer 1991). Even the most advanced industrial democracies have had difficulty establishing rules for access to fish stocks in international waters. As a result, the majority of fish stocks in Europe are classified as 'overutilized', fished beyond the point where natural increase can sustain the yield (Rosenberg et al. 1993).

The three major processes responsible for deforestation are, in order of their quantitative importance, the clearing of land for agricultural purposes, the harvesting of fuelwood for energy, and commercial logging. The last of these processes has the weakest link to population growth, since it is primarily responsive to supply and demand conditions on an international market. The clearing of forests for cultivation of crops accounts for a majority of recent deforestation. Population growth will stimulate forest clearance for agriculture when it raises the demand for food, which it almost inevitably will, and/or reduces the wages for unskilled labor. This latter response is also likely but far less certain (National Research Council 1986). Both of these responses have the effect of increasing the profitability of agriculture. However, forest clearance will occur only if new lands are accessible and if extensification is competitive with intensification as an economic strategy for producing more food.

Because the connection between population growth and deforestation is subject to many contingencies, one should not expect close statistical relationships between the two. However, if population growth is playing an important role in the process, there should nevertheless be a positive statistical relationship between them. A number of studies have used cross-national data to investigate the statistical relationship between the rate of population growth and the rate of deforestation These studies have recently been reviewed by Bilsborrow (1994), Birdsall (1994), and Palloni (1992). Palloni's review is most thorough. Although he issues many qualifications and notes that deforestation can occur under conditions of rising population pressure, declining pressure, or no pressure, he finds that in the four most satisfactory studies, the relation between rates of deforestation and population growth is invariably positive. In three cases, the relation is statistically significant. Without any attempt to specify a more precise model, I simply note that, for the 99 countries for whom the World Bank (1992) has assembled data on rates of population growth and deforestation (expressed over a denominator of the amount of preexisting forest cover), the simple correlation between the two rates is +0.32.

These results are consistent with the common-sense notions that (1) population growth increases the incentives to produce more food; (2) that in some places extensification of production is an economically efficient means of doing so; and that (3) in some of these latter places, new land resources are accessible to potential cultivators. In other words, they give little reason to doubt that, when averaged across the many ecological and institutional settings that humans inhabit, faster rates of population growth will produce faster rates of deforestation.

1.2 *Intensification of production*

Alternative responses to an increased demand for food involve increasing production on lands already cultivated. The most important ways of doing so are the introduction of new crop varieties, increased frequency of cropping, application of additional fertilizers, expansion of irrigation, and better control of pests. In addition, improvements in transportation, storage, and marketing can result in a higher proportion of product reaching consumers.

In certain settings, the economic attractiveness of intensifying production dominates that of extensification. For example, total food production has increased in Europe between 1966 and 1983 while cropland fell by a quarter and the total forested area grew by 30 percent. The US Department of Agriculture projects a 30 percent shrinkage of cropland in the USA between 1982 and 2020 (Waggoner 1994). Waggoner (1994) describes feasible strategies by which the projected 10 billion people in the middle of the 21st century can be fed while total cropland is reduced. He notes that the world's farmers are already producing enough calories and protein to sustain 10 billion people on a vegetarian diet. However, it seems unlikely that those who can afford to eat meat will forgo the opportunity to do so; instead, they will likely be joined by hundreds of millions more who will be able to act on a preference for meat in their diets. The additional food needs of a much larger human population are certain to be met primarily by increased production rather than by redistribution among food types.

Perhaps the most ecologically-damaging component of intensified production is associated with the expansion of irrigation. Already, 70 percent of the freshwater used by humans is used for irrigation, which waters one-sixth of the world's arable lands (MacKellar & Horlacher 1994). The best possibilities for irrigation, where streams carry water from snow-clad mountains, are already heavily exploited. Fields already irrigated are being abandoned as levels in wells sink, soils become salty, and competition for water sharpens. Of the 235 million hectares under irrigation, some 20 to 30 million are affected by salinity and another 25 percent are threatened. The UN Food and Agriculture Organization estimates that 1 to 1.5 million hectares of irrigated land are abandoned annually, mainly due to salt damage (de Haen 1991). Irrigation is not, of course, a singular process and there are many ways of improving irrigation systems that both save water and save soil (Waggoner 1994). Most of these involve increased energy expenditures.

Soils are being degraded by many other processes as well. A recent UN Environment Program assessment concludes that, of the 4700 million hectares of agricultural land, some 19 per cent are moderately, and 6 percent are severely, degraded. In the latter case, the biotic functions are destroyed and the productive potential is not reclaimable, or reclaimable only at a very high cost (de Haen 1991). The risk is especially great in tropical Africa, where the fragile and inherently infertile soils must support the most rapid rate of population growth of any region. The removal of ground cover is leading to widespread compacting, crusting, and erosion of the soil while shorter fallow periods are reducing the restorative potential of traditional bush-fallow systems under shifting cultivation (Spencer & Polson 1991). Because of soil conditions, fertilizer is less successful in enhancing soil fertility in tropical Africa and often produces acidity, compaction, and erosion.

Population growth is not the only factor affecting the rate of resource degradation, and in many contexts it is undoubtedly not the most important factor. The World Bank's (1992) review of population/environment/agriculture linkages in sub-Saharan Africa lists a huge array of obstacles to expanded food production and better resource management. These include weak land tenure systems, inadequate credit availability, biased agricultural prices and exchange rates, adverse tax policies, weak agricultural extension services, excessive government control, and civil wars. But few if any of these problems will be resolved through rapid population growth. They are the context on which this growth will he imposed. According to the Bank, they have the effect of compelling growing populations to exploit ever more extensively the resources available.

Diminishing returns to irrigation and fertilizer use, combined with evidence of extensive soil depletion, have made some of the most sober agricultural economists pessimistic about the prospects that food supplies will outpace population growth in developing countries. According to the dean of agricultural economists, Vernon Ruttan,

> It is apparent that the gains in agricultural production required over the next quarter century will be achieved with much greater difficulty than in the immediate past. The incremental responses to the increases in fertilizer use have declined. Expansion of irrigated areas has become more costly. Maintenance research, the research required to prevent yields from declining, is rising as a share of research effort. (Ruttan 1991)

There is no question that population growth is one of the principal factors that is putting pressure on agricultural systems in developing countries and on the environmental base that supports them. Certainly the capacity exists to feed a much larger population. But there are few parts of the developing world where prospects for the food/population balance would not be more favorable if the population were growing more slowly.

2. Industrial pollution

The principal environmental threat in most developed countries, and in several developing countries as well, is the pollution of air and water supplies by the production or consumption of industrial products. Air and water supplies have historically functioned as common property resources that serve as a repository or sink for the byproducts of industry. Like other common property resources, they have been too heavily exploited because users have inadequate incentives to maintain their quality. Perhaps the form of 'pollution' that is currently eliciting the most alarm is carbon dioxide, whose rapid rate of increase in the atmosphere has raised the threat of global warming.

The role of population growth in producing industrial pollution is less obvious than in the case of agrarian transformations. The reason is that people require a certain amount of food to stay alive. If the population is to grow, resources must be reshuffled to ensure that their needs are met. No such compelling logic comes into play in the case of, say, automobile emissions or chlorfluorocarbons. These are the product of industrial processes that vary dramatically in intensity and nature from place to place, with little if any direct link to human biological requirements.

In order to gain some sense of the contribution of population growth to various forms of pollution, analysts have frequently resorted to an identity developed by Paul Ehrlich:

$I =$ PAT, where
$I =$ environmental impact, i.e. the numerical value of some pollutant
$P =$ population size
$A =$ affluence, usually measured as GNP per capita
$T =$ technology, usually measured as the amount of pollution per unit of GNP

The components of this identity are arbitrary; It could have been expressed in terms of pianos instead of population, since whatever appears on the right-hand side in a numerator also appears in a denominator. But Ehrlich's formulation has face validity. Since people's activities are the principal source of pollution, it is reasonable to suppose that more people will produce more pollution. Most pollution is a product of industrial production, the per capita volume of which is captured in the A term; and production can occur with different technologies, the pollution content of which is effectively captured by T.

For present purposes, we will assume that the $I = \text{PAT}$ equation is a properly-specified causal model of the sources of pollution at a country or regional level. When a process is studied through time, it is customary to take natural logs of both sides of the equation, divide by the length of time over which it is studied, and thus express the equation in terms of the growth rate of each element:

$$r_I = r_P + r_A + r_T$$

A conventional application of the equation is presented by Norman Myers (1994). He notes that carbon dioxide emissions in the world grew by an estimated 3.1 percent between 1950 and 1985, during which period world population grew by 1.9 percent. Therefore, he concludes, population growth was responsible for about two-thirds of the rise in carbon dioxide emissions.

There are several reasons to be skeptical about this form of calculation. For one thing, it is obvious that carhon dioxide emissions, most of which are produced by the burning of fossil fuels, are heavily concentrated in developed countries where rates of population growth have been well below 1.9 percent per year. Put another way, the rapid population growth in developing regions should have a much lower pollution 'multiplier' than whatever growth occurred in developed regions. Such interactions between population growth and the other elements of the formula are obviously not represented therein. Wolfgang Lutz (1992) shows that the resulting error is very serious. Using the United Nations' medium population projections by major region and keeping constant the level of per capita carbon dioxide emissions in each region, he shows that population growth alone would increase levels of emission by 20 percent in 10 years. However, if he ignores regional differences and simply does a projection for the world as a whole, population growth appears to produce an 86 percent increase in levels of emission. Failure to recognize the regional pattern of emmissions leads to an overestimate of the role of population growth by a factor of four!

A second important interaction that is not reflected in the equation is the connection between population growth and levels of per capita GNP. And the third interaction, that between per capita GNP and level of technology, may be the most important of all in some applications. The World Bank's World Development Report for 1992, which focused on the environment, concluded that higher levels of affluence were generally associated with lower levels of pollution because less polluting 'techniques' (which include the industrial composition of output) were used in richer countries.

One way of incorporating these interactions into the analysis is to express the formula not in terms of means but in terms of variances. This change also moves the assessment in the direction of a causal analysis, which is principally directed towards understanding the sources of variation in out-comes. Our reformulation of Ehrlich's question asks how the different factors combine to account for international variation in rates of change of pollution. Using the formula for the variance of a sum (in this case, the sum of three growth rates) we have

$$\sigma_I^2 = \sigma_P^2 + \sigma_A^2 + \sigma_T^2 + 2 \cdot COV_{PA} + 2 \cdot COV_{PT} + 2 \cdot COV_{AT},$$

Each term in this equation refers to the variance in the rate of growth of a particular element or to the covariance between two rates of growth. The subscripts refer to each of the elements in the additive growth rate equation and COV_j refers to the covariance of elements i and j. These are the terms that capture the interactions among the different elements that were noted above. If the interactions are not substantively important, the value of the interaction terms will be close to zero.

Our first application of this expanded formula will be to carbon dioxide emissions over the period 1980–1990. We use data on the growth rate of each element assembled by the World Bank (1992). The data refer to nine regional groupings that together constitute the world's population. Results are shown in Table 1. The left-hand side, the variance in growth rates of carbon dioxide emissions among the nine regions over the period 1980–1990, has a value of 5.200 when expressed in percentage growth rate terms. The variance in the rate of population growth is only 0.620, some 12 percent of the variance in carbon dioxide. In this additive framework, population growth can account for little of the interregional variance in carbon dioxide emissions observed over this period. The covariance between growth rates of population and of affluence is negative – regions with faster growing populations had slower growth rates of GNP per capita – and that between population growth and the technology term is positive. Even assigning all of these terms to the population component, population growth can account for only 25 percent of the variance in growth rates of carbon dioxide emissions.

The remaining 75 percent must be attributed to the affluence and technology terms. By itself, the variance in growth rate of per capita GNP is larger than the variance in carbon dioxide growth rates, so that the former is fully capable of accounting for the latter. However, the covariance between affluence and technology is huge and negative: countries with faster rates of economic growth had slower (often negative) growth rates of emissions per unit of GNP.

Table 1 also presents the components of this equation for four other environmental hazards: emission of carbon monoxide and nitrogen oxide and agricultural uses of pesticides and nitrogen fertilizer. The data were assembled by Commoner (1994) from OECD sources and refer only to OECD countries. It is obvious that population growth is playing a small role in accounting for variance in the rate of growth of these hazards among OECD countries; in all cases, the variance in the growth rate of the hazard exceeds that of population growth by a factor of at least 30. The covariances involving population growth are very small and usually negative; they do not elevate

Table 1. Analysis of the international or interregional variance in growth rates of different forms of environmental hazards

				Population (P)		Affluence (A)		Technology (T)		2 · Covariances				
Hazard (I)	Units	σ_I^2	=	σ_P^2	+	σ_A^2	+	σ_T^2	+	PA	+	PT	+	AT
Carbon dioxide emissions (1)	9 regions, 1980–1990	5.20	=	0.62		5.56[a]		3.71		−1.91		2.62		−5.40
Carbon monoxide emissions (2)	15 OECD countries, 1970–1987	8.83	=	0.13		1.04[b]		11.70		−0.04		−0.52		−3.48
Nitrogen oxide emissions (2)	16 OECD countries, 1970–1987	4.89	=	0.11		1.60[b]		7.65		0.06		−0.12		−4.40
Pesticide use in agriculture (2)	10 OECD countries, 1975–1986	10.98	=	0.07		1.13[c]		8.96		−0.28		−0.60		1.72
Nitrogen fertilizer usage in agriculture (2)	18 OECD countries, 1975–1986	4.26	=	0.13		0.92[c]		3.91		−0.40		0.50		−0.80

Sources: (1) World Bank (1992), and (2) Commoner (1994).
[a]Indicator: GNP per capita.
[b]Indicator: vehicle kilometers per capita.
[c]Indicator: agricultural production per capita.

the role of population growth in these processes to substantive significance. Instead, the technology term is the dominant factor in accounting for international variation in rates of growth of these environmental hazards, as Commoner himself concluded from a more informal appraisal.

The role of increased affluence in Table 1 is worthy of comment. While variation in rates of change of affluence indicators is greater than that of population growth, in four out of five processes depicted in the Table (all except pesticide use), its direct contribution is almost entirely offset by the negative covariance between affluence and technology. As the World Bank suggested, more affluent countries generally choose techniques that are less polluting.

The role of population growth in the production of hazards from industrial pollution will vary from hazard to hazard, place to place, and time to time. There is no presumption that the estimates in Table 1 would be similar when applied to other contexts. For example, among very poor countries, increased affluence may be accompanied by increasingly polluting technologies, at least until some threshold level of per capita income is achieved (World Bank 1992: 11). With respect to the population term itself, the variance in population growth rates among OECD countries is much less than what would be observed if a broader range of countries were included. For example, the variance in population growth rates among 99 large countries (during 1980–90 is 1.2. But this figure is still much smaller than the variance in enviromental hazards shown in Table 1, even if attention is confined to OECD countries. It seems likely that, in accounting for variation in changing levels of environmental hazards produced by industrial processes, population growth is destined to play a minor role.

3. Population policy

In a very important sense the question asked in the preceding section is poorly specified for policy purposes. The question attempts to quantify the role of population growth in producing a variety of environmental hazards. One problem is that no conceivable population policy can eliminate population growth altogether; it is the incremental rate of population growth, the part that can be affected by legitimate and feasible social policies, that should be the object of scrutiny. The more important problem is that the calculations take no account of the costs of implementing various policies. Even if population growth were playing a minor role in producing a particular problem, population policy may provide one of the most cost-effective ways of addressing it.

This distinction is illustrated effectively by Nancy Birdsall (1994) with respect to carbon dioxide emissions. She assumes independence between population growth and the other elements of the I = PAT equation and uses World Bank population projections to distinguish between the baseline scenario and a scenario of more rapid fertility decline. By 2050, carbon dioxide emissions are approximately 10 percent lower when fertility declines more rapidly. This figure is low because of the momentum of population growth and because the regions where the speed of projected fertility declines is most variable, e.g., Africa, are those where per capita emissions are relatively low. The fact that carbon dioxide build-up is a cumulative process makes the total volume of atmospheric carbon dioxide in 2050 even less sensitive to alternative population futures.

Nevertheless, she estimates that population policy is more cost-effective than a direct tax on carbon dioxide emissions. She estimates that a tax of $20 per ton is required to reduce emissions by 10 percent, and that it costs $220 to avert a birth through family planning programs. Combined with estimates of lifetime carbon dioxide emissions the cost of reducing emissions through family planning programs is about $4 per ton, less than half of the tax that would be required. Her estimate of the cost of reducing emissions through advances in female schooling and their indirect effect on fertility is comparable to that achieved through family planning programs. Even though reducing population growth rates would contribute only a modest amount to reducing greenhouse gas emissions, it represents a cost-effective component of a global strategy.

Two elements of this exercise deserve elaboration. First, the benefits of the family planning program presumably extend to many other domains than carbon dioxide emission, even though it is only in the latter where benefits are being counted. The tendency among scientists and policy makers to divide the world into many highly discrete problem areas can lead to serious biases against initiatives, such as family planning programs, whose benefits may extend across many sectors. Second, the widely recognized momentum of population growth cuts both ways. While it reduces the apparent advantages of lower fertility in the short run, it may increase them in the long run. The fact that population growth is a ponderous process means that whatever happens today has multiplier effects in each successive generation. In a very real sense, today's births are tomorrow's momentum. The more concerned we are with long-range futures, the more important are population policies in the array of strategies for enhancing the human condition.

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References

Bilsborrow, R. E. (1994). Population, development, and deforestation, in *Population, Environment, and Development*. Proceedings of the United Nations Expert Group Meeting on Population, Environment, and Development, January 1992. United Nations, New York, pp. 117–134.

Birdsall, N. (1994). Another look at population and global warming, in *Population, Environment, and Development*. Proceedings of the United Nations Expert Group Meeting on Population, Environment, and Development, January 1992. United Nations, New York, pp. 39–54.

Bongaarts, J. (1993). Population growth and the food supply: Conflicting perspectives, Population Council Working Paper No. 53. The Population Council, New York.

Coale, A. J. & Hoover, E. (1958) *Population Growth and Economic Development in Low Income Countries*. Princeton University Press, Princeton, N.J.

Commoner, B. (1994). Population, development, and the environment: Trends and key issues in the developed countries, in *Population, Environment, and Development*. Proceedings of the United Nations Expert Group Meeting on Population, Environment, and Development. January 1992. United Nations, New York, pp. 64–80.

Cunha, A. & Sawyer, D. (1991). Agricultural growth and sustainability: Conditions for their compatibility in the humid and sub-humid tropics of South America, in S. Vosti, T. Reardon, & W. von Urff (eds.), *Agricultural Sustainability, Growth, and Poverty Alleviation: Issues and Policies*. International Food Policy Research Institute, Washington, D.C., pp. 311–324.

de Haen, H. (1991). Environmental consequences of agricultural growth, in S. Vosti, T. Reardon & W. von Urff (eds.), *Agricultural Sustainability, Growth, and Poverty Alleviation: Issues and Policies*. International Food Policy Research Institute, Washington, D.C., pp. 31–48.

Kneese, A. V. (1988). The economics of natural resources, in M. S. Teitlehaum & J. M. Winter (eds.), *Population and Resources in Western Intellectual Traditions*. Supplement to Volume 14 of *Population and Development Review*. The Population Council, New York, pp. 281–309.

Lutz, W. (1992). Population and environment: What do we need more urgently, better data, better models, or better questions? Forthcoming in John Clarke & Basia Zaba (eds.), *Environment and Change*. Ordina Editions, Liege, Belgium.

Mather, A. S. (1986). Global trends in forest resources, in *Population and Resources in a Changing World*. pp. 289–304.

Mathews, J. T. (1991). Introduction and overview, in J. T. Mathews (ed.), *Preserving the Global Environment*. W. W. Norton and Company, New York, pp. 15–38.

Miller, K. R., Reid, W. V. & Barber, C. V. (1991). Deforestation and species loss: Responding to the crisis, in J. Mathews (ed.), *Preserving the Global Environment*. W. W. Norton and Company, New York, pp. 78–111.

Myers, N. (1994). Population and the environment: The vital linkages, in *Population, Environment, and Development*. Proceedings of the United Nations Expert Group Meeting on Population, Environment, and Development, January 1992. United Nations, New York, pp. 55–63.

National Research Council (1986). *Population Growth and Economic Development: Policy Options*. National Academy Press, Washington, D.C.

Palloni, A. (1992). The relation between population and deforestation: Methods for Drawing causal inferences from macro and micro studies, Working Paper 92-14 of the Center for Demography and Ecology, University of Wisconsin, Madison, Wisc.

Rosenberg, A. A., Fogarty, M. J., Sissenwine, M. P., Beddington, J. R. & Shepard, J. G. (1993). Achieving sustainable use of renewable resources, *Science* 262: 828–29.

Ruttan, V. (1991). Sustainable growth in agricultural production: Poetry, policy and science, in S.Vosti, T. Reardon & W. von Urff (eds.), *Agricultural Sustainability, Growth, and Poverty Alleviation: Issues and Policies*. International Food Policy Research Institute, Washington D.C., pp. 13–28.

Skole, D. & Tucker, C. (1993). Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 to 1988, *Science* 260: 1905–1910.

Spencer, D. & Polson, R.A. (1991). Agricultural growth and sustainability: Conditions for their compatability in the humid and sub-humid tropics of Africa, in S. Vosti, T. Reardon & W. von Urff (eds.), *Agricultural Sustainability, Growth, and Poverty Alleviation: Issues and Policies*. International Food Policy Research Institute, Washington, D.C., pp. 273–94.

Thompson, G.P. (1985). The environmental movement goes to business school, *Environment* 27: 7–11.

Waggoner, P.E. (1994). How much land can ten billion people spare for nature? Task Force Report No. 121, Council for Agricultural Science and Technology, Ames, Iowa.

Wolman, G. (1993). Population, land use, and environment: A long history, in C. Jolly & B. B. Torrey (eds.), *Population Growth and Land Use Change in Developing Countries: Report of a Workshop*. National Academy Press. Washington, D.C.

World Bank (1984). *World Development Report* 1984. Oxford University Press, New York.

World Bank (1992). *World Development Report* 1992: Development and the Environment. Oxford University Press, New York.

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