Population and Environment

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Abstract

The interactions between human population dynamics and the environment have often been viewed mechanistically. This review elucidates the complexities and contextual specificities of population-environment relationships in a number of domains. It explores the ways in which demographers and other social scientists have sought to understand the relationships among a full range of population dynamics (e.g., population size, growth, density, age and sex composition, migration, urbanization, vital rates) and environmental changes. The chapter briefly reviews a number of the theories for understanding population and the environment and then proceeds to provide a state-of-the-art review of studies that have examined population dynamics and their relationship to five environmental issue areas. The review concludes by relating population-environment research to emerging work on human-environment systems.

Contents

INTRODUCTION

Humans have sought to understand the relationship between population dynamics and the environment since the earliest times (1, 2), but it was Thomas Malthus' *Essay on the Principle of Population* (3) in 1798 that is credited with launching the study of population and resources as a scientific topic of inquiry. Malthus' famous hypothesis was that population numbers tend to grow exponentially while food production grows linearly, never quite keeping pace with population and thus resulting in natural "checks" (such as famine) to further growth. Although the subject was periodically taken up again in the ensuring decades, with for example George Perkins Marsh's classic *Man and Nature* (1864) (4) and concern over human-induced soil depletion in colonial Africa (5, 6), it was not until the 1960s that significant research interest was rekindled. In 1963, the U.S. National Academy of Sciences published *The Growth of World Population* (7), a report that reflected scientific concern about the consequences of global population growth, which was then reaching its peak annual rate of two percent. In 1968, Paul Ehrlich published *The Population Bomb* (8), which focused public attention on the issue of population growth, food production, and the environment. By 1972, the Club of Rome had released its World Model (9), which represented the first computer-based population-environment modeling effort, predicting an "overshoot" of global carrying capacity within 100 years.

Carrying capacity: the animal population that can be supported given the quantity of food, habitat, and water present in a given area

Clearly, efforts to understand the relationship between demographic and environmental change are part of a venerable tradition. Yet, by the same token, it is a tradition that has often sought to reduce environmental change to a mere function of population size or growth. Indeed, an overlay of graphs depicting global trends in population, energy consumption, carbon dioxide (CO_2) emissions, nitrogen deposition, or land area deforested has often been used to demonstrate the impact that population has on the environment. Although we start from the premise that population dynamics do indeed have an impact on the environment, we also believe that monocausal explanations of environmental change that give a preeminent place to population size and growth suffer from three major deficiencies: They oversimplify a complex reality, they often raise more questions than they answer, and they may in some instances even provide the wrong answers.

As the field of population-environment studies has matured, researchers increasingly have wanted to understand the nuances of the relationship. In the past two decades demographers, geographers, anthropologists, economists, and environmental scientists have sought to answer a more complex set of questions, which include among others: How do specific population changes (in density, composition, or numbers) relate to specific changes in the environment (such as deforestation, climate change, or ambient concentrations of air and water pollutants)? How do environmental conditions and changes, in turn, affect population dynamics? How do intervening variables, such as institutions or markets, mediate the relationship? And how do these relationships vary in time and space? They have sought to answer these questions armed with a host of new tools (geographic information systems, remote sensing, computer-based models, and statistical packages) and with evolving theories on human-environment interactions.

This review explores the ways in which demographers and other social scientists have sought to understand the relationships among a full range of population dynamics (e.g., population size, growth, density, age and sex composition, migration, urbanization, vital rates) and environmental changes. With the exception of the energy subsection, the focus is largely on micro- and mesoscale studies in the developing world. This is not because these dynamics are unimportant in the developed world—on the contrary, per capita environmental impacts are far greater in this region (see the text below on global population and consumption trends)—but rather because this is where much of the research has focused (10). We have surveyed a wide array of literature with an emphasis on peer-reviewed articles from the past decade, but given the veritable explosion in population-environment research, we hasten to add that this review merely provides a sampling of the most salient findings. The chapter begins with a short review of the theories for understanding population and the environment. It then proceeds to provide a state-of-the-art review of studies that have examined population dynamics and their relationship to the following environmental issue areas: land-cover change and deforestation; agricultural land degradation and improvement; abstraction and pollution of water resources; coastal and marine environments; and energy, air pollution, and climate change. In the concluding section, we relate population-environment research to the emerging understanding of complex human-environment systems.

Global Trends in Population and Consumption

At the global level, research has found that the two major drivers of humanity's ecological footprint are population and consumption (11), so we provide a brief introduction to the status and trends in these two indicators.

The future size of world population is projected on the basis of assumed trends in fertility and mortality. Current world population stands at 6.7 billion people (12). The 2006 revision of the United Nations *World Population Prospects* presents a medium variant projection by 2050 of 9.2 billion people and still growing, although at a significantly reduced rate. All of the projected growth is expected to occur in the developing world (increasing from 5.4 to 7.9 billion), whereas the developed world is expected to remain unchanged at 1.2 billion. Africa, which has the fastest growing population of the continents, is projected to more than double the number of its inhabitants in the next 43 years—from 965 million to approximately 2 billion. Globally, fertility is assumed to decline to 2.02 births per woman (below replacement) by 2050; it is population momentum arising from a young age structure that will cause global population to continue to grow beyond 2050 (the 2006 revision does not make prognoses about ultimate stabilization). The medium variant is bracketed by a low-variant projection of 7.8 billion (and declining) and a high variant of 10.8 billion (and growing rapidly) by 2050. Fertility in the former is assumed to be half a child lower than the medium variant, and in the latter, it is assumed to be half a child higher.[1] As Cohen (2) points out, minor variations in

Land degradation: any human induced or natural process that negatively affects soil structure, nutrients, organic matter, moisture-holding capacity, acidity and salinity

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[1] Fertility in most of the developed world is at or below replacement levels (2.1 births per woman). Fertility has declined significantly since the middle of the twentieth century in many developing countries owing to many factors, such as urbanization, the improved status of women through education and job opportunities, and increasing access to contraception. The different projections make different assumptions concerning future progress in reducing fertility.

IPAT: This identity holds that environmental impacts (I) are the product of population size (P), affluence or consumption (A), and technology (T).

above- or below-replacement fertility can have dramatic long-term consequences for the ultimate global population size; hence, projections are highly conditional, and their sensitivity to the underlying assumptions needs to be properly understood. Finally, the impact of the HIV/AIDS epidemic on future mortality is assumed to attenuate somewhat on the basis of recent declines in prevalence in some countries, increasing antiretroviral drug therapy, and government commitments made under the Millennium Declaration (13).

Consumption trends are somewhat more difficult to predict because they depend more heavily than population projections on global economic conditions, efforts to pursue sustainable development, and potential feedbacks from the environmental systems upon which the global economy depends for resources and sinks. Nevertheless, several indicators of consumption have grown at rates well above population growth in the past century: Global GDP is 20 times higher than it was in 1900, having grown at a rate of 2.7% per annum (14); CO_2 emissions have grown at an annual rate of 3.5% since 1900, reaching an all-time high of 100 million metric tons of carbon in 2001 (15); and the ecological footprint, a composite measure of consumption measured in hectares of biologically productive land, grew from 4.5 to 14.1 billion hectares between 1961 and 2003, and it is now 25% more than Earth's "biocapacity" according to Hails (16). In the case of CO_2 emissions and footprints, the per capita impacts of high-income countries are currently 6 to 10 times higher than those in low-income countries. As far as the future is concerned, barring major policy changes or economic downturns, there is no reason to suspect that consumption trends will change significantly in the near term. Long-term projections suggest that economic growth rates will decline past 2050 owing to declining population growth, saturation of consumption, and slower technological change (14).

POPULATION-ENVIRONMENT THEORIES

As in any contested field—and population-environment studies certainly fit this description—a wide array of theories have emerged to describe the relationship among the variables of interest, and each of these theories leads to starkly different conclusions and policy recommendations. Here we review the most prominent theories in the field of population and environment.

The introduction briefly touched on the work of Malthus, whose theory still generates strong reactions 200 years after it was first published. Adherents of Malthus have generally been termed neo-Malthusians. In its simplest form, neo-Malthusianism holds that human populations, because of their tendency to increase exponentially if fertility is unchecked, will ultimately outstrip Earth's resources, leading to ecological catastrophe. This has been one of the dominant paradigms in the field of population and the environment, but it is one which many social scientists have rejected because of its underlying biological/ecological underpinnings, treating humans in an undifferentiated way from other species that grow beyond the local "carrying capacity." Neo-Malthusianism has been criticized for overlooking cultural adaptation, technological developments, trade, and institutional arrangements that have allowed human populations to grow beyond their local subsistence base.

Neo-Malthusianism underpins the Club of Rome World Model (mentioned above) (9) and implicitly or explicitly underlies many studies and frameworks. The widely cited IPAT formulation—in which environmental impacts (I) are the product of population (P), affluence (A), and technology (T)—is implicitly framed in neo-Malthusian terms (17), although not all research using the identity is Malthusian in approach (18). IPAT itself has been criticized because it does not account for interactions among the terms (e.g., increasing affluence can lead to more efficient technologies); it omits explicit reference to important variables such as culture and institutions (e.g., social organization); impact is not linearly related to the right side variables (there can be important thresholds); and it can simply lead to wrong conclusions (19).[2]

The so-called Boserupian hypothesis, named after agricultural economist Esther Boserup, holds that agricultural production increases with population growth owing to the intensification of production (greater labor and capital inputs). Although often depicted as being in opposition to Malthusianism, Malthus himself acknowledged that agricultural output increases with increasing population density (just not fast enough), and Boserup acknowledged that there are situations under which intensification might not take place (20). As Turner & Ali (21) point out, the main difference between the theories of Malthus and Boserup is that Malthus saw technology as being exogenous to the population-resource condition and Boserup sees it as endogenous. Cornucopian theories espoused by some neoclassical economists stand in sharper contrast to neo-Malthunisianism because they posit that human ingenuity (through the increased the supply of more creative people) and market substitution (as certain resources become scarce) will avert future resource crises (22). In this line of thinking, market failures and inappropriate technologies are more responsible for environmental degradation than population size or growth, and natural resources can be substituted by man-made ones.

Political ecology also frequently informs the population-environment literature (23). Many political ecologists see population and environment as linked only insofar as they have a common root cause, e.g., poverty, and that poverty itself stems from economic imbalances between the developed and developing world and within developing countries themselves (e.g., 24). In this view, migrants to deforestation hot spots in frontier areas may be victims of historical inequalities in land access in their country's core agricultural areas, or they may be responding to global inequalities in which industrialized countries depend on resource extraction from tropical countries to maintain their high standards of living, or both. Whatever the impact of the migrant on the rainforest, it is merely a symptom of more deeply rooted imbalances. Similarly, political ecologists see land degradation as stemming from poor farmer's lack of access to credit, technology, and land rather than population growth per se.

A number of theories—often subscribed to by demographers—state that population is one of a number of variables that affect the environment and that rapid population growth simply exacerbates other conditions such as bad governance, civil conflict, wars, polluting technologies, or distortionary policies. These include the intermediate (or mediating) variable theory (23) or the holistic approach (25) in which population's impact on the environment is mediated by social organization, technology, culture, consumption, and values (26, 27). Some also group IPAT in this category because population is only one of the three variables contributing to environmental impacts.

Many theories in the field of population and environment are built on theoretical contributions from a number of fields. A case in point is the vicious circle model (VCM), which attempts to explain sustained high fertility in the face of declining environmental resources (28, 29). In this model, it is hypothesized that there are a number of positive feedback loops that contribute to a downward spiral of population growth, resource depletion, and rising poverty (see the land

Thresholds: a point in a system's condition in which abrupt change is observed and beyond which recovery of earlier conditions is difficult

Intensification: increasing crop output per unit of land and/or per unit of labor

VCM: vicious circle model

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[2] For example, Myers (156), finding that the CO_2 emissions grew annually by 3.1% from 1950–1980 and that population grew by 1.9% annually during the same time period, concluded that population growth contributed nearly two thirds of emissions. Yet Preston (157) shows that the logical fallacy behind this by pointing out that most of the growth in fossil fuel use during this period was in developed countries with limited population growth and that population grew much faster in countries with the lowest per capita emissions.

degradation section). At the simplest level, the model is neo-Malthusian, but it also owes a debt to a number of other theories. First, it builds on the intergenerational wealth flows theory from demography, which holds that high fertility in traditional societies is beneficial to older generations owing to the net flow of wealth from children to parents over the course of their lifetimes (30). It also borrows from a demographic theory that describes fertility as an adjustment to risk, which argues that in situations where financial and insurance markets and government safety nets are poorly developed, children serve as old-age security (31). Finally, it is partially derived from the ecologist Garrett Hardin's famous (32) "tragedy of the commons," which holds that as long as incentives exist for each household to privatize open access resources, then there will be a tendency at the societal level to overexploit available resources to the detriment of all users.

It is important to note that population-environment theories may simultaneously operate at different scales, and thus could all conceivably be correct. At the global level, we cannot fully predict what the aggregate impacts of population, affluence, and technology under prevailing social organization will be on the global environment when the world's population reaches 9 or 10 billion people (3). But many scientists—neo-Malthusian or not—are justifiably concerned with the impact that even the current 6.7 billion people are having on the planet given consumption patterns in the global North and the booming economies of China and India. Meanwhile, at the national level the cornucopian theory may be correct, say, for a country like Denmark, whereas neo-Malthusianism, political ecology, and intermediate variable theories may each illuminate different facets of Haiti's environmental crisis. Finally, Boserup's theory of intensification has been found to hold true in the historical experience of many developed countries and in many localized case studies spanning the developing world (33).

Although theory may seem dry and academic, theoretical frameworks can be important guides to action. A good theory helps to develop well-targeted policies. However, bad theory can become the "orthodoxies" that are very difficult to overcome and that underlie government and development agency policies and programs (34, 35). Each of the above theories identifies one or more ultimate causes for environmental degradation, which if remedied would "solve" the problem. In the case of neo-Malthusianism, population growth is the primary problem, and the solution is population programs. In the case of cornucopianism, market failures are the primary problem, and the solution is to fix them. For political ecologists, inequalities at different scales are the main problem, and policies should address those inequalities. Multivariable theories offer few magic bullets but do underscore the need for action on multiple fronts to bring about sustainability. Unfortunately, many theories in the realm of population and the environment have not been subjected to the level of rigorous empirical testing that would allow them to be categorized as robust. This is partly because the linkages are complex and difficult to disentangle. Fortunately for the field as a whole, the picture is beginning to change, and a number of studies at the microlevel have used robust statistical methods and multilevel modeling in order to test theories such as the VCM (36).

We now turn to a review of the five issue areas.

REVIEW BY ENVIRONMENTAL ISSUE AREA

In this section, we review the literature on population-environment interactions in each of five issue areas: land-cover change, agricultural land degradation, water resource management, coastal management, and energy and climate change. We focus largely on peer-reviewed articles published in the past decade with an occasional reference to important earlier work.

Land-Cover Change and Deforestation

The conversion of natural lands to croplands, pastures, urban areas, reservoirs, and other anthropogenic landscapes represents the most visible and pervasive form of human impact on the environment (37). Today, roughly 40% of Earth's land surface is under agriculture, and 85% has some level of anthropogenic influence (38). Although the world's population is now 50% urban, urban areas occupy less than three percent of Earth's surface (39). We can conclude from this that large-scale land-cover change is largely a rural phenomenon, but many of its drivers can be traced to the consumption demands of the swelling urban middle classes (40).

As with the demographic and development transitions, the world remains divided in various stages of the land-use transition (41) (**Figure 1**). Although the developed nations have achieved replacement (2.1 births per woman) or below replacement-level fertility, have urbanized, and have economies dominated by service and technology industries, developing nations continue to experience rapid population growth, remain largely rural, and have labor forces concentrated in the primary sector (agriculture and extractive industries).

In part because most developed countries largely deforested their lands in past centuries, today most land conversion from natural states to human uses is occurring in the developing world, particularly in the tropics through forest conversion to agriculture. (One exception is the Russian Far East, which is one of the few developed world regions with high rates of primary forest conversion—mostly for logging and not for agricultural lands.) Given the scale of these transformations and their intimate but complex linkages with population dynamics, research on land-use/-cover change (LUCC) and particularly deforestation constitutes a large portion of the population-environment literature. Demographic variables are linked at different scales to this phenomenon (42). But there is disagreement on the impact of population versus other factors, with some studies suggesting that demographic dynamics contribute more than any other process to deforestation (43) and others suggesting the superiority of economic factors (44). Geist & Lambin's meta-analysis of 152 case studies of tropical deforestation suggests that, although most cases of

Land-use and land-cover change (LUCC): changes in human use of land (e.g. from agricultural to residential) or natural land cover types

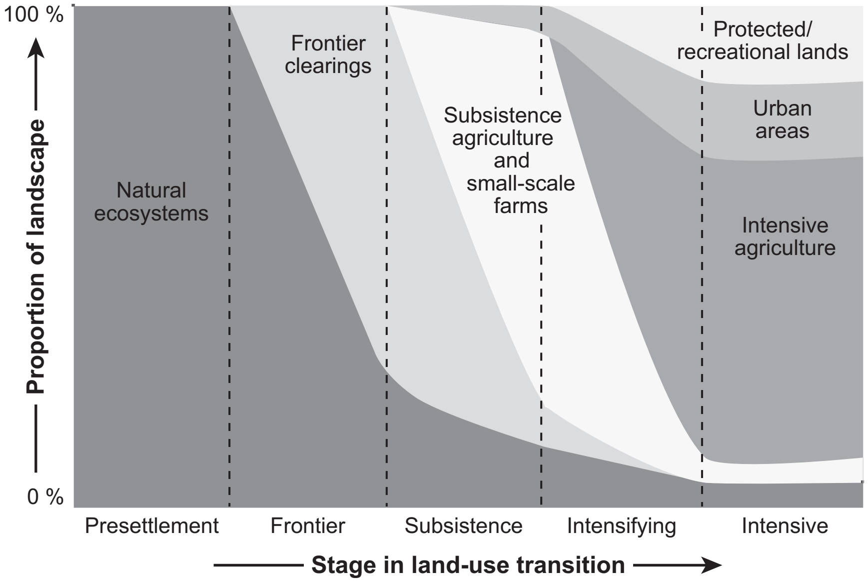

Figure 1

Land-use transitions. Reprinted from Reference 163 with the permission of *Science*.

deforestation are driven at least partially by population growth, population factors almost always operate in concert with political, economic, and ecological processes, and the relative impact of each factor varies depending on the scale of analysis. In this section, we briefly outline how population dynamics affect LUCC through changes in fertility, population structure, and migration as well as how these interactions are largely mediated by scale. We also reference case studies illustrating the sometimes counter-intuitive relationship between population variables and LUCC.

In much of the developing world fertility rates are plummeting, and nowhere have they declined so rapidly as in urban areas, where (apart from sub-Saharan Africa) fertility is at or below the replacement level. Conversely, in most developing countries, the regions of highest fertility also coincide with the most remotely settled lands where the agricultural frontier continues to advance; areas that are both biodiverse and ecologically fragile. This high fertility and associated rapid population growth directly contributes to land conversion in these forest frontier areas. Fertility in remote areas of the tropics is buoyed by a combination of low demand for and supply of contraception (45). In such regions, children constitute an asset to farm families that are often short on labor (30). Furthermore, poor health care access contributes to high rates of child mortality—promoting so-called "insurance births" that guarantee a family a certain number of surviving children (31). Children compensate for land insecurity through income security to parents in their old age (46), and a dearth of education and work opportunities for women also maintains high fertility (47). Positive correlations between fertility and deforestation have been found in studies in Central (48, 49) and South America (50, 51).

Household age and sex composition and life cycle stages are also important factors in frontier LUCC. Although young children divert household labor resources from agriculture, older children contribute labor to the farm or capture public access resources such as firewood, game, and water. The settlement life cycle of farm homesteads also helps to explain when and where forest clearing will occur (52, 53). Immediately following settlement, deforestation is high as land is cleared for subsistence crops (51, 54). A later deforestation pulse may occur as farms move from subsistence to market-oriented crops or expand into livestock. These processes are enabled by children growing old enough to provide labor or capital investments (through, for example, remittances) to the farm household (53).

Despite the high fertility of remote rural populations, migration remains the primary source of population growth in forest frontiers (44). Indeed, at a key point along the forest transitions causal chain, in-migration is a necessary precedent to frontier deforestation. Migration will remain a major driver of frontier forest conversion, often in a leap-frog manner, as more established farm households send younger family members as migrants to the new frontier (55).

Although population dynamics are central to LUCC, in all cases population exerts its influence synergistically with other factors. Demand for agricultural land among small holders directly impacts forest conversion, whereas, owing to market forces, urban and international demand for forest and agricultural products further contribute to LUCC through logging and large-scale agriculture. Political and institutional factors also play an important role in shaping LUCC. For example, government investments in roads, subsidies to the agricultural sector, or land tenure policy can directly influence deforestation rates. Such effects are well researched in the Brazilian Amazon (56–58). Cultural preferences can also affect LUCC, such as the desire for cattle as a status symbol among Central American frontier farmers (59). Thus, intervening variables help explain inconsistencies in population-LUCC dynamics (60).

Changing the scale of analysis reveals examples in which population growth declined yet deforestation accelerated, population growth was accompanied by reforestation, or population growth attended a number of different human-environment responses (60). Examples of this are evident in the literature for Latin America where many nations have experienced declining rural populations but continued deforestation (48). A dramatic example is Ecuador whose Amazon region's forest canopy is facing rapid attrition owing to growing settlements of frontier farmers, although overall rural population is declining because of falling fertility and rapid urbanization (61). This apparent anomaly is explained by the small populations, which account for a minority of a nation's rural population, that move to forest frontiers and contribute a disproportionate amount to the nation's total deforestation. In parts of the Brazilian Amazon, forest conversion has been driven increasingly by exogenous factors, such as the global demand for soybeans, and owing to increasingly mechanized farming, the region has also experienced rural population decline (62). Interestingly, the same association—rural depopulation and continued deforestation in Ecuador and Brazil—results from a completely different causal mechanism in the two cases, highlighting the importance both of scale and place-based effects. Similar scale-dependent phenomena emerge in Asian forest frontiers. Research in Thailand's northeast suggests, for example, the importance of population factors at finer scales and of biophysical factors at coarser scales for explaining variation in plant biomass levels (63).

Land-cover dynamics are the most evident mark of human occupation of Earth. Links to population are both obvious (without human population presence there is no human impact on forests apart from acid rain) and exceedingly complex, e.g., at what spatial and temporal scales does population interact with political, economic, and social processes to produce LUCC? A challenge for future research is to disentangle the contributions of population and other dynamics across spatial and temporal scales. For example, more research is needed at the mesoscale (subnational) and to build causal chains across spatial scales. A diversity of research methods needs to be combined to improve our understanding of these space-dependent links, including remote sensing, geographic information systems, ecosystem process and multilevel modeling, surveys and interviews, participant observation, and stakeholder analyses.

Agricultural Land Degradation or Improvement

Land-cover change research also considers changes in the quality of land resources as a result of human uses, which is the focus of this section. Perhaps the most contentious debate in the population-environment literature concerns the relationship between increasing population density in subsistence agricultural areas and land degradation or improvement. This is, in part, the result of widely differing estimates regarding the extent of land degradation, with global estimates ranging from 20 to 51 million km^2 (64). This section considers arguments and evidence marshaled by two major schools of thought: the vicious circle proponents who believe that increasing population density in the context of high poverty almost inevitably leads to land degradation and the Boserupians who suggest that increasing density leads to intensification of agricultural systems such that yields per unit area (and per capita) are increased (see the theory section, above).

In the VCM, it is hypothesized that there are a number of positive feedback loops that contribute to a downward spiral of resource depletion, growing poverty, and population growth. An elaboration of these linkages can be found elsewhere (29, 65), but in its simplest form, the model describes the following causal connections: poverty leads to high fertility through mechanisms such as a demand for farm labor, insurance births owing to high infant mortality, and women's low status. High fertility contributes to population growth, which further increases demands for food and resources from an essentially static resource base; the declining per capita resource base reinforces poverty through soil fertility loss, declining yields, and poor environmental sanitation; and poverty, in turn, contributes to land degradation by increasing incentives for short-term exploitation (versus long-term stewardship) and because poor farmers lack access to costly fertilizers and other technologies. The implication of these reinforcing linkages is that, absent intervention, the circle will continue and soil fertility will decline until the land is no longer suitable for crops or pasture.

Economists have been among the major proponents of the VCM. For example, Panayotou (66) and Dasgupta (28, 67) have suggested that children are valued by rural households, in part, because they transform open access resources (forests, fisheries, and rangeland) into household wealth, resulting in the "externalization" of the costs of high fertility. One manifestation is the process of "extensification," whereby farm households in frontier areas use additional labor to open up new lands for cultivation (68). Thus, household-level responses to resource scarcity can lead to problems at the societal level as each household copes with increased risk and uncertainty by maximizing its number of surviving children.

A number of modeling efforts, such as the Population-Environment-Development-Agriculture model (69) and work by Pascual & Barbier (70) borrow concepts from the VCM hypothesis. Testing of the VCM is difficult, however, because one is searching for a relatively small "resources effect" on fertility when there are at least a score of potentially confounding variables, and testing the direction of causality requires time series data on social and environmental variables, which is quite rare. Economists Filmer & Pritchett (71) found qualified support for the vicious circle hypothesis using detailed data from Pakistan on children's time use, firewood collection activities, and recent fertility. They find that collection activities do absorb a substantial part of household resources and that children's tasks are often devoted to collection activities. However, they could not establish a "fertility effect" on resource or land degradation. A longitudinal study in the western Chitwan Valley of Nepal (72) found that three measures of local resource depletion—the time to collect fodder, the increase in time required to collect fodder in the prior three years, and household's dependence on public lands for fodder—were significantly and positively correlated with desired family size, even when controlling for household wealth and numerous other factors found to influence desired fertility. Yet, several other indicators of environmental decline had no significant relationship to either desired fertility or pregnancy outcomes, and the actual relationship to desired fertility depended in part on whether the respondents were men or women. Pascual & Barbier's (70) modeling of shifting cultivation in the Yucatan found that among poor households, as population density increased, the response was extensification or a reduction in fallow periods, whereas among better-off households, labor was shifted to off-farm employment. Thus, although anecdotal evidence is abundant and development policymaking has been heavily influenced by VCM assumptions, there is only qualified support for the hypothesis in the few existing quantitative studies.

The Boserupian or intensification hypothesis has been tested in a number of studies spanning Africa, Asia, and Latin America. A frequently cited study by Tiffen et al. (6) examined changes in population density and agricultural productivity in Machakos District, Kenya. From 1930 to 1990, the population of Machakos District grew sixfold, from 240,000 to 1.4 million people, with a 1990 population density of 654/km^2. The region is mountainous and semiarid ($<$500 mm rainfall a year), and in the 1930s, it was suffering already from soil erosion (mass wasting and gullies). The region was also isolated from national markets, and there were colonial restrictions on access to certain lands and crops. In the 1950s and 1960s, a new form of terracing was propagated by local work groups, agricultural systems shifted from livestock to intensive farming with emphasis on higher-value crops, feeder roads were built to market towns, and market towns developed with agricultural processing facilities and other small industries. By 1990, the value of agricultural production had doubled on a per capita basis. Many factors led to a positive outcome for this region, including infrastructure development, market growth, private investment, increasing management capacity and skills, self-help groups, food relief during drought, and secure land tenure. This study confirms the basic Boserupian hypothesis: increased food demand, a denser network of social and market interactions, labor-intensive agriculture and economies of scale helped to avert a Malthusian crisis. Yet even in this textbook study, other researchers working in the district found important social differentiation in livelihood improvements, land alienation, and government-imposed limitations on mobility—elements that tend to mar an otherwise rosy picture (73).

Mortimore (74) found similar "success stories" in three dryland areas of West Africa: Kano State in northern Nigeria, the Diourbel Region of Senegal, and the Maradi Department, Niger. Outcomes were assessed in four domains: improved ecosystem management, land investments, productivity, and personal incomes. Taking pains to point out that in none of these regions were indicators under all four domains positive, the author nevertheless found some common ingredients that resulted in improved or stable soil fertility and yields despite rapid population growth and high densities. These ingredients include markets for agricultural produce, physical infrastructure, producer associations, knowledge management, and incentives for investment and income diversification. He concludes that productivity enhancements respond to economic incentives and that the capacity of resource-poor farmers to invest in on-farm improvements should not be underestimated.

In Asia, there have also been successes, thanks largely to success of the "green revolution," a package of improved seeds and agricultural inputs that resulted in higher yields (75). Turner & Shajaat Ali (21) studied time series data (1950–1986) for 265 households in six villages in Bangladesh. They found support for the induced intensification hypothesis, with yields largely keeping pace with or exceeding population growth despite high population densities (783 persons per km^2). Soil conditions in Bangladesh are, on average, much better than in dryland Africa owing to deposits of alluvium during monsoon season flooding and therefore can support far higher densities. They posit that, as smallholders come in contact with the market economy, their redundant production is reduced, and their aspirations increase. Although cropping intensities on average increased significantly (in one village almost tripling), they also found increasing production disparities, with large land holders accounting for most of the surplus production, whereas the growing number of landless suffered shortfalls and malnutrition. They conclude that Bangladesh passed several threshold steps at points along its path towards intensification in which Malthusian outcomes of involution and stagnation might have occurred but were fortunately averted.

As these case studies make clear, population is but one among many factors that influence degradation or intensification. Other variables that are of crucial significance include institutional factors (land tenure regimes, local governance, resource access), market linkages (road networks, crop prices), social conditions (education, inequality of landholdings), and the biophysical environment itself (original soil quality, slopes, climatic conditions). Thus, it would appear that population growth is neither a necessary nor sufficient condition for either declines or improvements in agricultural productivity to occur. Population growth can either operate as a negative factor, increasing pressure on limited arable land, or a positive factor, helping to induce intensification through adoption of improved technologies and higher labor inputs. Where it does which depends on factors in the economic and institutional realms. This conclusion is supported by two ambitious meta-analyses of studies that looked at dryland degradation (or desertification) and agricultural intensification (76, 77). The authors reject both single-factor causation and irreducible complexity but propose instead that a limited number of underlying driving forces, including population, and proximate causes are at work to produce either degradation or intensification.

Although population can perhaps be discounted as the only relevant variable, there is little doubt that rapid population growth in poor rural areas with fragile environments can be a complicating factor in the pursuit of sustainable land use, especially because policies and markets are rarely aligned in such a way as to produce the most favorable results. Furthermore, trends on the basis of past precedents can only be extrapolated with caution, because the exact locations of thresholds in any given system are still largely unknown (21). One important advance for studies in this area will be the development of better maps of soil quality and land degradation with the aid of remote sensing and local soil samples, as at least part of the debate over population's impact can be explained by differing interpretations of what constitutes degradation and by a paucity of empirical evidence for the relationship.

Abstraction and Pollution of Water Resources

The water cycle ties together life processes. It is fundamental to the biochemistry of living organisms; ecosystems are linked and maintained by water; it drives plant growth; it is habitat to aquatic species; and it is a major pathway of sediment, nutrient, and pollutant transportation in global biogeochemical cycles (78). Population-environment researchers have not dedicated the same level of attention to population dynamics and water resources as they have to research on land-cover change, agricultural systems, or climate change. Yet there are clear relationships between population dynamics and freshwater abstraction for agricultural, domestic, and industrial uses, as well as emission of pollutants into water bodies.

Human settlement is heavily predicated upon the availability of water. A map of global population distributions closely tracks annual rainwater runoff, with lower densities in the most arid regions and as well as the most water abundant, such as the Amazon and Congo Basins. Whereas the former areas are water constrained for agriculture, in the latter areas, year-round rainfall in excess of 2000 mm has rendered these environments less favorable for agriculture (owing to soil leaching and oxidation) and more favorable for human and livestock diseases.

At the global level, irrigation water for agriculture is the biggest single user (about 70% of water use), followed by industry (23%) and domestic uses (8%) (79). If "green water" is added to the mix (water that feeds rainfed crops), then crop production far and away outstrips other water uses. As demand for food increases with growing populations and changing tastes (including growing demand for animal versus vegetable protein with its far greater demands for water), it is expected that water diversions for agriculture will only increase. Today, humanity is estimated to use 26% of terrestrial evapotranspiration and 54% of accessible runoff (80). Falkenmark & Widstrand (81) established benchmarks for water stress of between 1000 and 1700 m^3 per person, water scarcity of between 500 and 1000 m^3 per person, and absolute scarcity of less than 500 m^3 per person. Northern and southern Africa and the Middle East already suffer absolute scarcity. As population grows and water resources remain more or less constant, many countries in the rest of Africa are projected to fall below 1000 m^3 per person (82).

Perhaps because such water resources are hidden underground, groundwater resource depletion could potentially remove some agricultural areas from the map. Although it is well known that some Arab countries rely on fossil water for wheat production, less recognized is that 70% of Chinese and 45% of U.S. irrigation is based on nonrenewable water resources (C. Vorosmarty, EM Douglas, personal communication). Groundwater levels in India have been dropping for more than a decade owing to the unregulated tapping of aquifers (83), rendering some semiarid regions vulnerable to shortages. A study in Karnataka State, India, identified a major shift from surface to groundwater use in the past decades and found that groundwater use is highly inequitable; large farmers possessing 12–16 ha of land make up only 8% of all farmers but consume 90% of groundwater (84). In the lower delta of the Ganges-Brahmaputra Basin, upstream diversions at the Farakka Barrage, rather than local demands for irrigation water, appear to be causing dry season groundwater deficits and intrusion of the saline front, illustrating how complex basin-wide hydrological connections complicate the attribution of population impacts (85).

Other studies at the local level reveal a similarly complicated picture. Research in the Mwanza region of western Tanzania finds that accessible runoff varies significantly across a relatively small area and that population density closely tracks available water (86). Migrants to towns were generally less likely to have access to water from standpipes and more likely to rely on unimproved wells. Rural-urban migration is not correlated to relative water scarcity in places of origin but rather to proximity to roads and to towns. The researchers conclude that high fertility—a traditional adaptation to peak labor demands during the short cropping season—increases the problems of water access and supply maintenance in agricultural and domestic spheres. But they also note that gloomy prognoses about future water shortages often fail to acknowledge that large portions of developing country populations never have had the kind of access to water, or levels of consumption, deemed necessary by international bodies.

In the Pangani Basin of northeastern Tanzania, a complex set of factors is leading to water conflicts (87). Population is one factor: Owing to high fertility and migration, rural population is doubling every 20 years, and the population of towns is doubling every 10 years. But other factors include water extraction and land alienation for export flower production and protected areas, growth and mobility of livestock herds, declining summer runoff from glaciers on Mount Kilimanjaro owing to global warming, and hydroelectricity generation. The greatest conflict is between farmers and pastoralists, as farmers progressively moved into areas previously considered too marginal for agriculture and pastoralists were squeezed by restrictions on grazing areas owing to newly established protected areas. In recent years, the pressure on land has led to stresses on water and other resources, leading to heavy out-migration from the basin.

Researchers in the densely populated Sao Paulo State in Brazil examined water resources in the Piracicaba and Capivari River Basins within the Campinas Administrative Region (AR) (88). Campinas is Brazil's fourteenth largest city, as well as its third largest industrial center, and an important agricultural region as well. The Metropolitan Region of Campinas (the 19 core municipalities of the AR) saw high, though declining, average annual population growth rates during the 1970–2000 period: 6.5% (1970–1980), 3.5% (1980–1991); and 2.5% (1991–2000). The authors find that problems in the form of urban growth and the patterns of population distribution during these three decades have accentuated water quality problems because the rapidity and low density of growth meant that water supply and sanitation infrastructure could not keep up. By mid-1995 only 5% of waste was treated before reentering streams, and large reaches of the Piracicaba and Capivari River Basin tributaries were deemed of poor quality. Water supply

Natural increase: endogenous growth (local births minus deaths), excluding migration

infrastructure (mostly surface reservoirs as groundwater is scarce) did not kept pace with population growth, and the situation was reported as critical as of the mid-1990s. In response, state water basin agencies are applying some institutional solutions such as fees for water withdrawals and restrictions on residential development, as well as some technical ones, particularly the treatment of waste waters.

In summary, as in other areas, the relationship between population dynamics and water resources is complex. At the aggregate level, other things being equal, population growth most assuredly does reduce per capita water availability. It is in this light that the Global International Waters Assessment listed population growth first in a series of root causes of the "global water crisis" (89). Yet there is more to population change than growth alone, and rarely are other factors equal, so the specific impacts of population dynamics on water often come down to a complex array of place-specific factors that relate to economic and climatic changes, agricultural and industrial technologies, sewage treatment, and institutional mechanisms, to name but a few. One of the challenges to research in this area is the common property nature of water resources, and another challenge is caused by rapid regulatory changes as water resources become scarcer, which alters the institutional context. The field could use more basin or watershed studies to understand how variables such as population and climate change may affect future water availability and required institutional responses (90). Basin-level population-development-environment modeling would also help understand and resolve competition between urban and rural water uses as the world becomes more urbanized (91).

Coastal and Marine Environments

From the earliest times, the preponderance of global economic activity has been concentrated in the coastal zone (92), with settlements often growing on the continental margins to take advantage of overseas trade and easy access to the resources of the rural hinterlands. As a result, the coastal zone has attracted large and growing populations, with much of their growth attributable to migration rather than natural increase (93). Today, 10% of the world's population lives at less than 10 m above sea level (even though this area only accounts for 2.2% of the world's land area), and coastal zones have higher population densities than any other ecologically defined zone in the world (39, 94). Coastal and marine environments are very important for human health and well-being, and they are also quite vulnerable to anthropogenic impacts. Yet, until recently most population-environment research has focused on terrestrial ecosystems, possibly because the human "footprint" on coastal and marine ecosystems is harder to discern.

Not surprisingly, over half of the world's coastlines are at significant risk from development-related activities (95), and the potential (and realized) environmental damage is substantial. Population growth is often named as the driver of coastal and marine environmental problems, whereas proximate causes can be traced to specific practices (96). A recent study highlights how the Kuna population (an indigenous population in Caribbean Panama) has practiced coral mining and landfilling for decades in response to population growth (97). Since 1970, live coral cover declined 79%, and at the same time, the Kuna population increased by 62%. The Kuna gradually enlarged their island landmass to adjust for their growing population by building coral walls out into the water and then filling in the enclosed areas with corals, seagrass, and sand. In addition to direct loss of coral reef, consequences include coastal erosion and a local increase in sea level. This example provides a clear and direct link between population growth and coastal degradation.

Population growth can lead to many other coastal and marine environmental disturbances. For instance, tropical mangroves are being converted to fish and shrimp aquaculture farms, which undermines coastal protection and decreases natural habitat that many fish species use for reproduction. Expanding coastal cities undermine natural protection from storms and hurricanes as well as increase pollution and runoff. Additionally, untreated sewage and agricultural runoff continue to be a worldwide problem. Although listed as a driver, like other issues, the impact of population size and growth depends on many other factors such as the sensitivity of coastal systems to stress, local institutions, and global markets. For example, demand for shrimp is the ultimate driver of mangrove loss, and sewage treatment systems and no-till agriculture could significantly reduce nutrient loading in coastal areas.

The relationship between human activities and environmental impacts are hard to assess and regulate in coastal and marine environments because the environmental resources are almost always governed by common property resource (CPR) management systems, whereas terrestrial environments are generally managed by the government or private sector. CPR management systems may be especially vulnerable to disruption caused by in-migration or urbanization. However, the social and economic context largely determine whether in-migration and population pressure disrupt the CPR system and thus cause environmental degradation (98–100). Thus, a significant recurring theme in this research is that the social and economic context in which the population is changing as well as when, how, and with whom people interact is more important in determining the impact on the environment than simply demographic change (101, 102).

Studies in developing countries on migration and the marine environment have focused on a mediating variables approach, such as how technology, local knowledge, social institutions of kinship or marriage, and markets mediate the role of population in resource extraction and consequent environmental degradation or enhancement. For example, some work has hypothesized that migrants misuse resource extraction technologies, which leads to environmental degradation (103). In a coastal Brazilian population, technological change imposed by outsiders who lacked knowledge of the ecological and social context of the community contributed to decreased ecological resilience (104), and rapid in-migration and technological changes in sea cucumber fishing techniques in the Galapagos led to a collapse in the sea cucumber industry (105). In both cases, the results seem to be a function of the migrants' limited local knowledge as well as expansionist attitudes and short-term time horizons for profiting from the extraction of coastal and marine resources.

Thus, population-environment researchers have begun to incorporate other social theories such as social capital and migrant incorporation to understand when population pressures do not necessarily degrade the environment (106). Most studies have found that, in systems with strong land tenure or social capital, migrants do not disrupt the environment and are able to develop local knowledge that mitigates environmental impacts (107–109). A case study in the Solomon Islands contests the notion that sea tenure regimes are weakened by in-migration and population growth. Rather, potentially negative impacts of population pressure on the environment are diminished significantly with greater reciprocal ties among close kin or neighbors (110, 111). Similarly, intermarriage between a migrant and a nonmigrant in Sulawesi, Indonesia, has been shown to mitigate the otherwise negative association between migrant households and coral reef degradation (106).

Migration has been the most studied component of population dynamics in coastal and marine environments. Yet, urbanization and tourism are other primary human drivers affecting coastal ecosystem quality (112, 113). Fourteen of the worlds largest 17 cities are located along a coast; this affects freshwater flows to coastal estuaries, sewage emissions, and ecological processes at the land-sea interface (114). Also, without careful planning in

Common property resource (CPR): a resource that is so large or widespread that it is difficult to exclude people from using it

Social capital: the resources (networks, relationships of trust, access to wider institutions of society) upon which a household or individual may draw anticipation of a growing tourist market, cultural and ecological resources may be overexploited, resulting in unsustainable development, as is the case in Turkey (115).

Human impacts on coastal and marine environments are not a simple function of population size or density. As the aforementioned studies suggest, technology, knowledge systems, social cohesion, common property systems, migrant incorporation, and the economic and ecological context in which these interactions take place all play an important role in population and environment research, especially in developing countries. Nonetheless, coastal and marine environments continue to be among the most threatened ecosystems in the world, owing in part to the sheer scale of detrimental human activities associated with urbanization along the coasts, continued population growth, and a growing number of tourists in search of coastal amenities.

An unresolved issue in this area of research—as in the case of LUCC research—is how to spatially and temporally link populations and human activity to a specific environmental outcome. This is especially difficult in marine and coastal ecosystems because environmental boundaries are fluid. Also important is the impact of local and global consumption on marine and coastal environments. For instance, per capita consumption of seafood is high in many traditionally seafaring countries even though population sizes are low (116), and specialized tastes for rare species can have dramatic impacts on fish stocks (117). Further research is needed to assess how population-environment linkages in marine and coastal areas are influenced by the global food trade connecting consumers and producers from opposite sides of the world.

Energy, Air Pollution, and Climate Change

Even when they are connected to the electric grid, some two billion poor people in the developing world still largely rely on biomass to meet their energy needs. That leaves approximately 4.7 billion people with more energy-intensive lifestyles who consume, with little help from the world's poorest, the energy equivalent of 77 trillion barrels of oil a year (118).[3] More than 80% of global energy consumption is derived from fossil fuels (119), and it is this dependence on fossil energy that is responsible for the release of the greenhouse gases and airborne pollutants that are altering atmospheric composition and processes on a global scale. As concern mounts over the health impacts of urban air quality (particularly in developing countries) and the potential adverse effects of climate change across multiple systems and sectors, population-environment researchers have paid particular attention to understanding the demographic drivers of energy consumption. Although it is clear that there are vast differences in consumption levels (per capita energy consumption in the United States is 48 times what it is in Bangladesh and 4.7 times the world average), it would be wrong to suggest that population variables are irrelevant. Hence, we review a number of empirical studies that examine population-energy linkages in a systematic and quantitative manner.[4]

In studies of energy consumption researchers have found that it is more appropriate to use the household rather than individuals as the unit of analysis because a large portion of energy consumption related to space conditioning (heating and air conditioning), transportation, and appliance use is shared by household members. This sharing results in significant economies of scale, with large households generally showing lower per capita energy use than small ones

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[3] Of this total, the equivalent of 66 trillion barrels is actually from fossil fuels (petroleum, natural gas, and coal). The remaining energy supply (13.7% of the world total) comes from renewable sources and nuclear energy.

[4] Although there is extensive research on the reciprocal impact of air pollution and projected climate change on demographic variables such as morbidity, mortality, and migration (158, 159), this is beyond the scope of this review.

(29, 120). Energy studies have identified a range of household characteristics as key determinants of travel patterns (121–123) and of other types of residential energy demand, such as for heating, cooking, and operating domestic appliances (124–127). In a pioneering study, MacKellar et al. (128) used the IPAT identity to decompose the annual increase in energy consumption of the more developed regions during the period 1970–1990. They found that, because growth in the number of households outpaces population growth owing to trends in fertility, divorce, and ageing, growth in household numbers accounted for 41% of the total increase in energy consumption, whereas population growth accounted for only 18%. However, this study did not take into account the lower energy requirements of smaller households, so it likely exaggerated the contribution of the growth in household numbers to energy use.

O'Neill & Chen (129) drew on household survey data to quantify the influence of household size, age, and composition on residential and transportation energy use in the United States and found that changes in household size have caused 14% of the increase in per capita energy use over the past several decades. Lenzen et al. (130) assessed the importance of various demographic characteristics on household energy demand in Australia, Brazil, Demark, India, and Japan, and they found similar patterns across countries: The average age of residents is positively associated with per capita energy consumption, whereas household size and urban location are negatively associated. To explore the importance of adopting adequate demographic variables in understanding transport-related energy consumption, Prskawetz et al. (131) combined a cross-sectional analysis of car use in Austria with detailed population/household projections and tested the sensitivity of projections of future car use across a wide range of households by size, age, and sex of householder and the number of adults and children. They found that car use will likely increase by 20% in the period 1996–2046 if the number of households is the unit of analysis. However, it will only increase by 3% if one applies a composition that differentiates households by size, age, and sex of the householders. Therefore, household characteristics can impact aggregate demand for car use via differences in demand across households as well as likely changes in household composition.

Energy intensity: the amount of energy required to produce one unit of output; more efficient use of energy results in lower intensities

In studying demographic impacts (via energy consumption) on air pollution, scientists have identified a number of important factors that jointly determine pollutant emissions, including the familiar elements of the IPAT identity—population, affluence, and technology as reflected in energy and emissions intensities (132). Selden et al. (133) analyzed the reduction of U.S. major air pollution emissions from 1970 to 1990 and found that changes in economic scale, economic composition, energy mix, energy intensity, and emissions intensity all played important roles. In quantifying the impacts of population on air pollution, researchers have reached different conclusions depending on which pollutants are under study, in which locations, at what scale, and for which time periods. For instance, a study of California counties shows that population size significantly contributes to the increase of the reactive organic gases NO_x and CO and has little impact on PM_{10} and SO_x, which are derived more from production activities (134). Population size shows no significant relation to ground-level ozone because ozone is very difficult to measure at specific sites owing to its nature as a diffuse secondary pollutant (135). In research using national-level data, researchers found an almost linear positive correlation between population size and CO_2 emissions (128, 132, 136, 137) and an inverted U-shaped curve for SO_2 (136). However, a more recent study of Canadian provinces over the period 1970–2000 suggests that population size has an inverted U-shaped curve with CO_2 emissions as well, which is at odds with previous literature investigating these variables for other regions and time periods (138). The different patterns of impacts may reflect the nature of complicated interactions between different pollutants and regional geographic/climatic conditions (139, 140), income, and technological levels (139, 141).

The same inconsistencies in the relationship between population size and emissions of various pollutants are in evidence when examining other population-related variables. Cramer (134) in his study of California counties and Cole & Neumayer (136) in their cross-national studies found that other variables such as the percent of population that are migrants, age composition, household size, and level of urbanization have the same basic relationship as overall population size on emission levels of each of the pollutants they studied. However, caution should be used in interpreting these results because the studies only cover short time periods (10 to 20 years) in which there were only small changes in the demographic variables.

Because of the complexity of population interactions as well as political issues, population issues were not considered in formulation of the Kyoto Protocol (142) and have also been largely excluded from the Intergovernmental Panel on Climate Change (IPCC) assessment reports (143), although population projections are an integral part of the *Special Report on Emissions Scenarios* (SRES) (144). The original emissions scenarios were constructed in 1996 using population projections with a base year of 1990. Although the projections used in the SRES were largely consistent with actual population sizes for the 1990–2005 period, the projections to 2050 and beyond were higher than more recent projections (see the text, above, on global trends in population and consumption) (11, 145, 146). Therefore, even though the 1996 scenarios continue to serve as a primary basis for assessing future climate change and possible response strategies, the Fourth Assessment Report of the IPCC is based on slightly lower population projections than the Third Assessment Report under the A2 scenario, which describes an economically divided world with slow technological progress and high population growth. Consideration of demographic factors beyond population size, such as changes in age structure, urbanization, and living arrangements, which as discussed above are important in modeling future energy use, are not accounted in the SRES population assumptions. Making progress in this area requires a better understanding of the scope for future demographic change as well as methods for including demographic heterogeneity within energy-economic growth models used for emissions scenario development.

Simultaneous and consistent projections of population, urbanization, and households are a challenging demographic tasks (147). Recently, Dalton et al. (148) introduced heterogeneous households into a general equilibrium population-environment-technology model of the U.S. economy. Because different types of households have unique demands for goods, capital stock, and labor supply, and these characteristics have direct and indirect implications for energy demand, they were incorporated into cohorts by age groups (or “dynasties”). These dynamics and other relationships implied by household projections create nonlinear interacting effects that influence each dynasty’s future saving and consumption decisions. Their research shows that including age heterogeneity among U.S. households reduces emissions by almost 40% in the low-population scenarios by year 2050, and effects of aging on emissions can be as large as, or larger than, effects of technical change in some cases. Those effects are believed to be much larger for the developing world, where more significant demographic changes such as population growth, aging, household nuclearization, and urbanization are occurring.

CONCLUSION

One of the reasons natural scientists have found population to be so appealing as a human dimension of environmental change is that data are readily available (in contrast to other human variables such as values, culture, and institutions), projections are reasonably reliable (149), and population can be treated in models in a manner that is analogous to all the other quantitative variables. This has promoted something of a reductionist view of population-environment interactions. Fortunately, a growing number of natural scientists are beginning to appreciate that humans interact with the environment in more ways than their raw numbers often imply. Populations are composed of people who collectively form societies, and people and societies cannot easily be reduced to food and material demands that result in some aggregate impact on the environment.[5] This makes human societies at once messy for modeling and fascinating to study. The new understanding builds on the concept of coupled human-environment systems, which are more than the sum of their parts (150, 151).

In the human-environment system, the impacts are not unidirectional but reciprocal. For example, the environmental change impacts on morbidity and mortality are a growing area of interest, and some have sought to close the circle by looking at how environmentally induced mortality may affect population projections (2). There is also growing research on the health impacts of landscape or climatic changes on humans, in the one instance through the creation of mosquito breeding habitats that contribute to malaria (152), and in the other through heat stress or famine (153). Research on the human-environment system also takes advantage of new data sources (remote sensing, biophysical data, as well as georeferenced household surveys), new technologies (high-powered computers, geographic information systems, spatial statistics), and new models (agent-based, multilevel, and spatially explicit modeling). Much of the research reviewed in this chapter has sought to deconstruct population into its component parts and to understand how human social institutions in all their complexity (e.g., markets, policies, communities) mediate the impact of population variables on the use of resources, waste generation, and environmental impacts. Thus, they could be said to fit into this growing understanding of the human-environment system.

Much population-environment research, whether at the local or global scales, is motivated by a broader concern for sustainability. Underlying some of the research, and contributing to some of the controversy, has been a concern for distributional justice in two forms: that the 5.4 billion citizens of developing countries might be able to raise their living standards and hence their consumption levels from their previously low levels and that the costs of biodiversity conservation and climate change adaptation not be unfairly borne by the poorest. Whether research proves that population dynamics have a dominant or negligible effect on environmental outcomes in each of the domains we surveyed, it is still left to human societies to address these inequities in consumption and costs as well as to seek long-term solutions. Here, research on culture, consumption, values, institutions, and alternative industrial and food systems will add to what is known about the demographic dimension as societies seek to transition to sustainable systems (10, 154).

Although we have sought to objectively review the literature rather than take a normative stance concerning the environmental impacts associated with population dynamics, at the global scale there is no question that humanity faces significant challenges in the coming decades owing to the scale and pace of changes in human numbers, population distribution, and consumption patterns. To quote Cohen's definitive study on the global carrying capacity, "The Earth's human population has entered and rapidly moves deeper into a poorly charted zone where limits on human population size and well-being have been anticipated and may be encountered" (2, p. 11).

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[5] Clarke (160, p. 9) writes, "There is a danger in talking about populations as if they are just numbers rather than groups of peoples, who have never been so demographically, socially, economically or even politically diverse. Variations in the roles of women around the world. . .admirably exemplify this diversity."

In recent decades, scientists have increasingly warned of the potential to reach the upper limits of the planet's productive, absorptive, and recuperative capacities (155). A challenge for micro- and mesoscale researchers is to understand how changes at the local and national scale relate to global-scale changes and how, in turn, their research can inform policies and programs at these lower scales that will attenuate environmental impacts at all levels.

SUMMARY POINTS

1. There is more to population dynamics than population size and growth. Recent research has illuminated the ways in which a number of population variables–age and sex composition, household demographics, and the elements of the population balancing equation (fertility, mortality and migration)–are related to environmental change.
2. Most demographers and many other social scientists subscribe to a mediating variable theory, which states that population dynamics affect the environment through other variables such as culture, consumption levels, institutions, and technology.
3. Across the environmental issues covered in our review, population dynamics usually act in concert with other significant factors such as local institutions, policies, markets, and cultural change. Teasing out the relative contribution of each factor can often be difficult.
4. The scale of analysis can significantly affect findings concerning the role of population dynamics in environmental change.
5. Evidence for the impacts of population on land and resource degradation has been mixed in part because time series data at appropriate scales and measurements of appropriate variables are rare and because the population "signal" is often difficult to isolate from other signals.
6. Both freshwater resources and coastal and marine ecosystems are often managed as common property resources (CPRs); hence levels of resource degradation or depletion depend more on the existence of effective management systems than on population variables per se.
7. In research on population and energy use, the household has been found to be a more useful unit of analysis than the individual, and population-environment researchers have made major strides in understanding how household size, composition, and income are related (via energy use) to environmental impacts.
8. Emerging understanding of complex human-environment systems is informing work in the area of population and the environment, and vice versa.

FUTURE ISSUES

1. Greater exploration of the linkages between micro- (farm or household level) and macroscale (global) processes manifested at meso- (subnational) scales in population-environment research across the different issue areas is needed.
2. Careful microscale longitudinal studies measuring population variables, household consumption, biophysical variables, institutional arrangements, and technologies employed over time should be conducted.

3. Given the environmental footprints of urban areas on rural hinterlands, one unresolved issue relates to the impact of population spatial distribution. For example, what would environmental impacts be if the same population were spread more evenly across the landscape rather than concentrated in urban areas?
4. Population-environment researchers could contribute to better understanding current consumption levels and the effects of future aspirations of the growing middle classes of Asia and Latin America as they relate to the sustainability transition.
5. Advances in demographic modeling are needed to develop a new population/household model with moderate data requirements, manageable complexity, explicit representation of demographic events, and output that includes sufficient information for population-environment studies.
6. A new generation of IPAT modeling is needed that explicitly accounts for the interactions among the IPAT terms, including the reciprocal impacts of environmental changes on population dynamics, and that is made part of integrated assessment modeling.
7. Future research could explore the increase in human mobility and collapse of geographical space as it affects population-environment relationships.

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The authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

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