Population Dynamics: Mathematic Models of Population, Development, and Natural Resources

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Abstract

Whereas interactions of population and natural resource growth have generally been modeled using large-scale numerical simulation studies, we review small-scale models that permit partially analytical results and can capture some of the salient features observed in history. This article refers only to models that concentrate on renewable resources since these are the most interesting and least understood as regards changes in population structures and dynamics. It starts by reviewing models of population and resource dynamics that refer to subsistence economies. Within this class of models it is possible to investigate how the equilibrium between the resource and population stock changes, dependent on the functional relations that govern the dynamics of population and resources. But as societies become less bound to the land, more urbanized, and more technological, resources might still be at risk, albeit no longer from positive population growth but rather from the environmental costs of consumption and production. To capture the impact of population growth on the environment, demographic impact models have been developed aimed at decomposing the effect on the environment from population on the one hand and that from consumption and technology on the other. The article concludes our review with a look at models of environmental influences on population dynamics.

Although the importance of the links between population and environment is widely appreciated, there is little agreement in the literature about the nature of these links.

The dynamic link between population and natural resources – influences are never entirely unidirectional or constant over time – constitutes the main difficulty in assessing formal models and unified theories. To complicate matters further, this interrelationship depends on the level and type of economic activities, technological development, institutional settings, and cultural systems. Even the variables themselves are not uniquely defined, but depend rather on the level and purpose of the analysis.

This article does not survey numerical simulation models of demographic/economic/environmental interactions (see Sanderson, 1994 for a review), of which the World 3 Model (Meadows et al., 1972) is the most popular. Instead, it looks at some simple mathematical models that capture stylized facts of the link between population and natural resource dynamics. Such 'mathematical cartoons' help us to explain and understand how various population and environmental characteristics might affect each other, and they can teach us how to respond most effectively to various demographic and environmental developments.

Although it was exhaustible resources that first received theoretical attention, this article concentrates on renewable resources since these are the most interesting and least understood as regards changes in population structures and dynamics. In contrast to nonrenewable resources, the use of which is controlled largely by market prices, renewable ones are very often open-access resources. The overuse of resources if property rights are absent or poorly defined is called the 'first tragedy of the commons' (Hardin, 1968) and can be corrected by restricting access to the resource. But as emphasized by Lee (1990), if the population is not fixed – as is presupposed in the models presented in this article – free access through reproduction constitutes the 'second tragedy of the commons'. More recently the externality of childbearing in relation to pollution externality has been studied in Harford (1997, 1998) and Schou (2002).

Malthusian Population Dynamics and Natural Resources

The study of interactions between population and resources has a long history. According to Malthus, population growth reduces material welfare due to diminishing returns to labor on a fixed supply of land. On the other hand the higher the level of material welfare the higher the population growth rate will be. The Malthusian model predicts that "population will equilibrate with resources at some level mediated by technology and a conventional standard of living" (Lee, 1986). Improvements in technology will be offset in the long run by increases in the size of the population, but the standard of living will not be related to the level of technology. As such, the Malthusian model provides a description of a rather primitive society with incomes not too far above the subsistence level and where local renewable resources are an important part of the economic production process.

Renewable resources (agricultural land, forests, lakes, etc.) are not in fixed supply as Malthus assumed. Renewable resources regenerate, but if the rate of utilization (harvest) exceeds the rate of regeneration, a renewable resource will be depleted or, in the extreme case, irretrievably exhausted. By adding the dynamics of renewable resource growth to the dynamics of population growth, the Malthusian model is capable of explaining patterns of population growth and resource degradation that do not necessarily end up in a single

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equilibrium (Malthusian trap) (see Brander and Taylor, 1998; Prskawetz et al., 1994).

The structure of these models can best be described in terms of prey–predator dynamics, with the resources, R, being the prey and the population, P, acting as the predator. The dynamics of renewable resources (eqn [1]) is commonly described by the standard model of mathematical bioeconomics, where the net growth of the renewable resource, $\mathrm{d}R(t)/\mathrm{d}t$, is affected by two counteracting factors: indigenous biological growth, $g[R(t)]$, and the harvest, $H[R(t), P(t)]$, which depends on the stock of resources available to be harvested and the number of people who are harvesting. Indigenous resource growth is modeled by the logistic growth function $g[R(t)] = aR(t)[K - R(t)]$, where the coefficient K determines the saturation level (carrying capacity) of the resource stock (i.e., K is the stationary solution of R if the resource is not degraded) and parameter a determines the speed at which the resource regenerates. The functional form of the harvest function is determined by the prevailing economic structure, and it establishes the link between the stock of resources and population. The population growth rate, $(\mathrm{d}P(t)/\mathrm{d}t)/P(t)$ (eqn [2]), is modeled as an increasing function of material welfare $y(t) = y[P(t), H(t)]$, which is determined by the level of the harvest and will be reduced by population growth. Whenever material welfare falls below the subsistence level, the population will decline. These Malthusian population dynamics imply that population growth may well adapt to resource constraints in contrast to models with exogenous positive population growth, where the economy collapses if resources do not regenerate quickly enough.

$$\frac{\mathrm{d}R(t)}{\mathrm{d}t} = g[R(t)] - H[R(t), P(t)] \quad [1]$$

$$\frac{\mathrm{d}P(t)}{\mathrm{d}t} = n[y(t)]P(t) \quad [2]$$

Within this class of models it is possible to investigate how the equilibrium between resources and population stock changes, dependent on the functional relations that govern the dynamics of population and resources. For instance, the efficiency of harvest technology, the degree of substitution between labor and resources, the indigenous rate of resource growth, and the carrying capacity of the resource stock will have an effect on material welfare and hence on population growth. In turn, fertility and mortality will affect the resource dynamics via the input of changing labor stocks in the harvest. An empirical calibration of the model for the case of the small Pacific Easter Island characterized by pronounced population fluctuations was carried out by Brander and Taylor (1998) in the framework of a general-equilibrium model.

During the last decade, the model by Brandner and Taylor has been extended in several directions. Dalton and Coats (2000) studied the introduction of different structures of property rights (common access vs personal ownership of resources) as represented by alternative specifications of the link between the dynamics of natural resources and population growth. Their results indicate that the steady-state solutions for population and resources are unaffected by the institutional setup, whereas the transition toward the long-run equilibrium will depend on the prevailing institutional setup exhibiting less (more) fluctuations in the dynamics of population and resources under private (common) property resources. These results will change if institutions also affect other parameters and functional forms of the model such as technology, preferences, fertility, and mortality (e.g., D'Alessandro, 2007). Institutional settings are also discussed in Anderies (2000); both for the Brandner and Taylor model of Easter Island as well as the model of the Tsembaga society of New Guinea (Anderies, 1998). The Tsembaga people is provided as an example, where institutional settings, such as a ritual cycle in which pigs are killed and warfare is initiated, serve to reestablish a sustainable equilibrium of population and resource stocks. Modifying the original Brandner and Taylor model by introducing a subsistence level of consumption, Anderies (2000) shows that changes in population and resources are more rapid as compared to the original Brandner and Taylor model. Anderies then argues that these sudden changes – that fit the historical evidence quite well – did not allow for institutional adaption. Explicit conservation policies (a consumption tax and quotas on total resource harvest, total harvest effort, and per capita harvest effort) are introduced in Pezzey and Anderies (2003). These policies may counteract the destabilizing effect of a larger subsistence level in consumption although their implementation and control may indeed be rather difficult. Besides institutional reforms, several authors have also studied the role of technological progress to prevent the collapse of population and resources in Easter Island. Reuveny and Decker (2000) assume that the growth rate of resources and their carrying capacity, as well as the productivity of harvesting positively depends on technological development. However, as technological progress may allow for faster population growth, it may thereby even foster the collapse of the resource stock and population.

An alternative explanation of the dynamics of population and resources in primitive societies such as Easter Island was proposed by Maxwell and Reuveny (2000). The authors refer to recent research on resource scarcity as it may initiate conflict in developing countries and extend this causal link by studying the repercussion of conflict situations on resource and population dynamics. A variant of the model by Maxwell and Reuveny can be found in Prskawetz et al. (2003). Instead of assuming two separate models that present either a conflict or no-conflict situation, they postulate that changes in the labor force participation rate, the death rate, and the growth rate of resources are 'smooth' functions of the prevailing level of per capita resources. Most recently de la Croix and Dottori (2008) explain the history of Easter Island by introducing a model of noncooperative bargaining between two competing groups where population growth acts as a means to gain power. Fertility behavior between both groups is therefore guided by strategic complementarities – a new motive to explain population dynamics. The authors discuss the conditions under which a population race may set in, which ultimately results in resource degradation and the collapse of the society. A recent review of the various extensions of the Brandner and Taylor model is presented in Nagase and Uehara (2011).

Contrary to the Malthusian predictions, increasing population densities might be beneficial, as argued by Boserup (1981), and could well increase the human carrying capacity of the earth. Higher population densities will initiate technological innovations in agriculture, thereby increasing the yields so that the natural environment can support a larger population without reducing the level of welfare. Similar positive feedback mechanisms are captured in a simple mathematical cartoon of the interdependence between the growth in population $P(t)$ and carrying capacity $K(t)$ (expressed in numbers of individuals) by Cohen (1995) as

$$\frac{\mathrm{d}P(t)}{\mathrm{d}t} = rP(t)[K(t) - P(t)] \quad [3]$$

$$\frac{\mathrm{d}K(t)}{\mathrm{d}t} = c\left[\frac{\mathrm{d}P(t)}{\mathrm{d}t}\right] \quad [4]$$

with $r > 0$ and c either negative, zero, or positive. The parameter c, which captures the effect of an increment of population on the carrying capacity, determines the long-term population dynamics, and it can represent technological innovation. When $c = 1$ population size grows exponentially (Euler, eighteenth century); when $c < 1$ population grows logistically (Verhulst, nineteenth century); and when $c > 1$ population grows faster than exponentially (Forester and coworkers, twentieth century). The positive correlation between population growth and technological progress is taken up by Dalton et al. (2005) who extend the model by Reuveny and Decker (2000) allowing for endogenous technological progress. Whether long-term economic growth with positive levels of populations and resources is viable depends on the division of technological progress between being 'resource-depleting' (by increasing the efficiency of harvest) or 'resource-conserving' (by increasing the growth rate of resources) (Dalton et al., 2005: p. 36).

Malthusian results (in the sense that population will grow to the point where material welfare matches subsistence demand) can be further undermined by allowing population growth to be a choice variable. Zero population growth may well be the optimal choice for individuals in the economy. Since environmental changes are often slow over the course of an individual life span, and since environmental damage may outlive its perpetrators, overlapping generation models (Eckstein et al., 1988) provide an appropriate demographic structure. Intra- as well as intergenerational conflicts can be modeled in such a framework, taking account of the effects of increases in population and resource exploitation on the future population's quality.

Economic Development and the Environment

The models presented in Section Malthusian Population Dynamics and Natural Resources represent traditional societies in which populations derive their living from primary occupations (agriculture, hunting, fishing, etc.) that depend on the availability of resources. But as societies become less bound to the land, more urbanized and more technological, they not only use the environment as a source of natural resources but also as a dump for waste products arising from human activity. Furthermore, an economy's production possibilities are no longer determined by the maximum sustainable yield of renewable resources. Improvements in technology can increase the sustainable yields or reduce the resource stock required for production, and economic growth will allow for the use of artificial capital in place of natural resources. In open economies with trade, technological change, and economic growth, there is no simple and direct relationship between population growth on the one hand and the environment on the other hand. The paper by Lehmijoki and Palokangas (2010) nicely demonstrates – based on a stylized dynamic optimization model – how gains from trade in developing countries may first increase and then decrease environmental pollution and population growth, thereby replicating the time path of the environmental Kuznets curve.

Resources might still be at risk, albeit no longer by positive population growth alone. The risk can stem from the environmental costs of consumption and production. It is therefore of great importance to understand how these environmental impacts depend on different population structures.

An interesting contribution that considers the role of consumption for environmental quality but also allows for investment to increase environmental quality is presented in John and Pecchenino (1994). Based on an overlapping generations model, where the utility of households depends on consumption and environmental quality, they study the link between economic growth and the environment. The short-lived agents may be better-off if a long-lived social planner takes into account the externalities of consumption and maintenance of the environmental quality. The model is extended to allow for population growth in John et al. (1995). Lower population growth together with lower levels of consumption are shown to imply higher levels of environmental quality and economic output in the steady state. Similar to John and Pecchenino (1994) the authors show that a social planner who has a lifetime similar to the environment may internalize the externalities that are not taken into account by short-lived individual households.

The role of preferences and technology in the relation between population size and environmental quality is studied in Cronshaw and Requate (1997) within a static framework, where agents' utility also depends on the aggregate emissions of the economy. The very long-term relation between energy use and economic development, allowing for endogenous population development, is studied in Fröling (2011) within the framework of the unified growth theory.

Besides the mere number or growth of the population, its age structure will be an important variable for long-term economic growth and the environment. Dalton et al. (2008) introduce population age structure into an energy-economic growth model. Calibrating their model to the US shows that population aging reduces long-term emissions and the effect may be similar to the role of technological change.

The Impact of Population on the Environment

In a seminal paper, Ehrlich and Holdren (1971) express the impact on the environment, I (e.g., the value of some pollutant), as the product of population, P, and per capita impact, $F(P)$:

$$I = PF(P) \quad [5]$$

Depending on whether diminishing returns or economies of scale are dominant, per capita impact can be increasing or decreasing in the total population. The most familiar form of such a demographic impact model is the so-called I-PAT identity, which divides per capita impact $F(P)$ into affluence A, and technology T. The accounting model I-PAT stands for the environmental Impact decomposed into Population size P, Affluence A, and Technology T. Affluence can be measured as Gross National Product (GNP) per capita, and technology represents the mean impact of an extra dollar of production (impact/GNP). The latter variable encompasses the cleanliness of technology, the effects of institutions, and other factors that can alter the impact efficiency of production.

Demographic impact models (Wexler, 1996) constitute multiplicative identities aimed at decomposing the effect on the environment of population on the one hand and that of consumption and technology on the other. The number of variables on the right-hand side of eqn [5] can be any number greater than two. Although these models are commonly used, they face several criticisms. They suppress any feedback relation between the variables on the right-hand side; their implications are highly sensitive to the choice of decomposition variables; and the method of decomposition and the role of institutions and culture are ignored. Recent research on the I-PAT identity has dealt with some of these problems. Expressing the identity in terms of variances rather than means (Preston, 1996) allows one to incorporate the links between the decomposition variables. Considering households instead of individuals as the unit of consumption (MacKellar et al., 1995) highlights the effect of economies of scale as household size increases. Typical results of such analyses are that the population has a much stronger impact on the environment in developing countries than in developed countries. In the case of environmental hazards produced by industrial processes, population growth plays a minor role both in developing and in developed countries. A stochastic version of the I-PAT identity (STIRPAT) and a discussion among the alternative variants of measuring the impact on the environment are presented in York et al. (2003). STIRPAT constitutes a stochastic model and stands for Stochastic Impact by Regression on Population, Affluence, and Technology.

Milik et al. (1996) embed the I-PAT identity into a dynamic model where population P, affluence A, and technology T influence each other and vary over time. Pollution I reduces the regenerative capacity of natural resources, which in turn influences the dynamics of population and affluence. The model highlights the fact that understanding and monitoring the impact of pollution on the environment is important even when outward signs of damage (as a reduction in the resource stock) are not yet visible. Ecosystems often absorb stresses over long periods of time and then eventually reach a disruption level at which the cumulative consequences of stress appear in critical proportions. A policy of waiting until the first signs of environmental deterioration are observed before actions are taken to reduce the impact on the environment may well prove to be disastrous. When action is initiated, the impact on the environment might already be irreversible. Mathematically, these systems can best be described in terms of 'slow–fast' dynamics, where during certain periods some variables vary much more rapidly than others. While population and economic variables can be regarded as slow-moving variables, the environment changes most rapidly once the system has absorbed too much stress. For instance, the emission of carbon dioxide occurred almost unobserved for several decades before any attention was paid to the impact of greenhouse gases on global warming.

It becomes difficult to quantify the impact of population on the environment if the demand for local resources is not related to local population growth and if institutional environments are not stable. In fact, "commercialisation by converting a limited and inelastic subsistence demand to a limitless and elastic export demand (from the standpoint of the region, at least) can lead to much more rapid rates of exploitation than would be implied by population growth alone" (Repetto and Holmes, 1983).

Modeling Environmental Influences on Population Dynamics

Existing models of environmental influences on population exhibit two shortcomings. First, they generally do not distinguish between the separate effects the environment may have on fertility and mortality. Second, the environmental impact on population growth is commonly modeled to work only through the economic and social variables of the model. There are only few examples in the literature that model the direct effect of environmental stress on fertility and mortality.

The first example (Nerlove, 1991) is based on the vicious circle of poverty, population growth, and environmental degradation as evidenced in small rural communities of sub-Saharan Africa. In these economies simple tasks like fetching water and collecting fodder and wood are mostly carried out by children. This means that children are not only valuable to parents for future income but also as a source of current income. Higher population growth leads to more resource depletion, which reduces the marginal productivity of the resource. To offset this effect families have more children, thus depleting the resource even more. In a short parable, Nerlove demonstrates that increasing the birthrate when the environment deteriorates will be the optimal choice for a household that maximizes per capita harvest when 'the perceived marginal product of an additional child increases as environment deteriorates'. In addition, in a system in which land rights are acquired through cultivation, a large number of children can imply increased claim to land ownership. This positive feedback between fertility and environmental degradation is in stark contrast to Malthusian dynamics, where population equilibrates with resources. Since the marginal private and social costs of reproduction are not the same, Nerlove then shows how social interventions in the form of taxes or subsidies can be used to induce a specific birthrate corresponding to a socially desirable stationary state.

The underlying mechanism of the above-mentioned vicious circle is neither population growth nor environmental degradation but poverty, which prevents the substitution of alternative fuel sources, and the low status of women and girls, which devalues the large amount of time and effort that they must devote to daily gathering activities. To escape this vicious circle one needs to alleviate poverty and educate women.

As suggested by Chu (1998), the increasing specialization and level of economic activity typical of advanced societies may also imply a substantial dependency of population dynamics on the state of the environment. Increasing the level of human activities destroys the earth's biodiversity, so that the ability of the environment to absorb negative shocks will decline, while increased specialization makes people less adaptive to environmental shocks. Chu suggests a simple mathematical model of the survival probability $f(\cdot,\cdot)$ to capture both effects:

$$\begin{aligned} f(m_t, x_t) &< f(m'_t, x_t) \quad \text{if } x_t > 0 \\ f(m_t, x_t) &\geq f(m'_t, x_t) \quad \text{if } x_t \leq 0 \end{aligned} \qquad [6]$$

where m_t denotes the logarithm of the number of intermediate goods (a measure of the division of labor) with $m_t < m'_t$ and x_t is a realization of the environment value X_t with the critical state $x_t = 0$. The mean and the variance of the random variable X_t will be increasing functions of m_t. By reducing the ability to adapt, increased specialization m'_t will decrease the survival probability if the environment is already in a disastrous state $x_t < 0$, while the opposite relation will hold if the environmental state is favorable $x_t > 0$. These considerations are integrated into a modern Malthusian theory in Chu and Tai (2001).

In a recent contribution Mariani et al. (2010) consider the role of environmental quality for life expectancy. Their model is based on previous work by John and Pecchenino (1994) but accounts for the empirically observed positive correlation between life expectancy and environmental quality. More specifically they assume an overlapping generation framework where individuals live for three periods. While survival into the first and second period is quite certain, the survival into the third period is uncertain and depends on environmental quality. During their second period of life, individuals choose consumption and environmental maintenance (given an exogenous wage rate) such as to maximize their utility – which positively depends on second-period consumption and third-period environmental quality – and taking into account the effect of consumption and environmental maintenance on the dynamics of environmental quality. The model is capable of capturing the stylized facts of the positive correlation between survival and environmental quality. In addition, the authors show that multiple equilibria are possible that represent environmental poverty traps with low life expectancy and low environmental quality as opposed to high-level equilibria with high life expectancy and high environmental quality. The results are robust toward the extension of endogenous human capital formation that spurs growth and also life expectancy.

Another recent contribution that endogenizes the role of pollution on mortality is Lehmijoki and Rovenskaya (2010). Based on a long-term consumer optimization model and the assumption that pollution as a by-product of production negatively affects survival, the authors study the role of economic growth for reduced pollution and lower mortality.

Concluding Assessment of the Literature

Although there is a growing awareness of the population/environment linkage, as evidenced by the increasing number of empirical (case) studies, research has only slowly progressed in the Malthusian spirit of modeling the complex interaction in simple mathematical cartoons. Often dynamic interactions between population and environment are neglected – or increasingly complex simulation models are set up where anything can happen.

Further research on this topic is needed. The concern should be shifted away from physical limits to growth toward the ability of social units to respond to environment/population linkages. Although they are more difficult to formalize, such models should also include organizational and institutional issues.

See also: Boserup, Ester (1910–99); Carrying Capacity of the Environment; Demographic Impact of Disasters; Environment and Development; Environment and Health; Human–Environment Interactions: Case Studies; Ipat (Impact, Population, Affluence, and Technology); Kuznets Curves; Limits to Growth; Local Economic Development; Malthus, Thomas Robert (1766–1834); Sustainable Agriculture; Sustainable Development: An Economic Perspective.

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