Sustainable Development: A Dynamic Systems Perspective

Kerry Krutilla*
Associate Professor
School of Public and Environmental Affairs
Indiana University
Bloomington Indiana 47405
krutilla@indiana.edu

Rafael Reuveny*
Assistant Professor
School of Public and Environmental Affairs
Indiana University
Bloomington Indiana 47405
rreuveny@indiana.edu

* authorship shared equally.

Sustainable Development: A Dynamic Systems Perspective

Abstract

This paper describes a dynamic systems model consistent with a broadly-defined quality of life measure, and uses this framework to taxonomize a number of strands of research that explicitly, or implicitly, bear on the topic of sustainable development. The review is based on a selective group of "representative" articles from each literature that convey their central modeling components, research questions, and sustainability implications. We then judge what synthetic insights are missing from the accretion of information embodied in these separate literatures, and attempt to assess what the "bigger picture" dynamic frame of reference suggests about the need for additional research.

1. Introduction

This paper describes a dynamic systems model consistent with a broadly-defined quality of life measure, and uses this framework to taxonomize a number of strands of research that explicitly, or implicitly, bear on the topic of sustainable development. The specific objectives are to place the contributions of the individual literatures within the context of a larger systems picture; to consider the insights individual literatures offer with respect to understanding sustainable development; to attempt to judge what synthetic insights may be missing from the accretion of information embodied in separate literatures; and to assess what the "bigger picture" frame of reference suggests about the need for additional research.

There is considerable disagreement about what constitutes the appropriate policy target for gauging sustainable development. Several alternatives have been put forward, among them: non-declining utility (Toman et al., 1998; Brutland 1987) and undiscounted utility maximization (Heal 1998). The choice among such alternatives is an inherently philosophical issue, and therefore not likely to be resolved in the near future. Notwithstanding this debate, it is clear that the sustainability concept ultimately has to be linked to a quality of life measure. Consequently, we take the definition of a quality of life measure as the starting point. The quality of life concept defined is broad enough to include any public good about which there is mainstream consensus e.g., democratic political process, peace and security, environmental quality. The next step is to develop a conceptual model that is logically consistent with the broadly-defined quality of life measure. The resulting model is essentially a dynamic economic growth model with an augmented set of stocks and flows. This conceptual model is used to organize a review of different literatures, which are subcomponents of the larger model, based on the stock and flow variables found in their representative models.

Notwithstanding the objective to broaden the frame of reference, the "larger" conceptual model itself embodies a number of abstractions and is useful principally as an organizational device/thought experiment. The focus is more macroeconomic than microeconomic or sector-based, and the literature synthesis is based on a selective set of "representative" articles from each literature to convey the central modeling components, research questions, and sustainability implications. The review is thus in the form of a snapshot of representative models from different literatures, an approach designed to highlight the comparative aspects of research agendas and implications for the larger systems picture. Research implications follow from what is found in the picture, and what is left out of the picture.

The reviewed literatures are described in Table 1, and fall in two basic groups. "Economic Growth Models without the Environment" includes neoclassical and endogenous growth models, and studies in population growth. "Economic Growth and Environment Models" include research addressing possible limits to economic growth, ecosystem resiliency, and the implications of natural resource and/or environmental stocks in economic growth models. Some of this literature is not framed explicitly in terms of the concept "sustainable development," but all the reviewed models are components of a larger system that ultimately determines the quality of life.

[Insert Table 1 here]

The balance of the paper is as follows. Section 2 first defines a broad-based quality of life measure and then develops a logically consistent systems model. Sections 3 and 4 review the relevant literatures that embody parts of this model, in the order specified in Table 1. Section 5 discusses the potential significance of several topics not emphasized in the reviewed literatures; specifically, political economy and the potential consequences of complex system behavior with technology change. Section 6 briefly concludes the paper.

2. Quality of Life Measure and Associated Systems Model

The future path of utility affords the broadest measure for indicating sustainable development. Utility is assumed to be a function of consumption in most neoclassical models. Some studies in the resource economics literature have broadened this measure to include environmental stocks (Barrett, 1992; Krautkramer, 1985). In general, however, the utility measures of conventional economic growth models are substantially narrower than those discussed in the quality of life literature.[1] The quality of life measure and the associated system's model described below capture the essential features of the broader picture while keeping the logically-implied systems model as simple as possible. This model encompasses all the models discusses in Sections 3 and 4 of the paper in the sense that each of those models in principal could be carved out of the big model as a subset. It is important to note that these models ignore political economy. We relax this assumption subsequently, introducing political economy in Section 5.

As is in the conventional studies reviewed in this paper, we assume that there are N similar individuals in the economy at any given time that can be thought of as household-production units. At each moment t, the quality of life of a representative agent, U, is modeled as a flow:

(1) $U=U(c, k_{\beta}, l_{\beta}, h, t_{\beta}, e, s)$

Note that the time subscripts (t) are suppressed in the entire presentation for notational convenience, and that lower case variables denote per capita terms and upper case variables denote societal aggregates (e.g., c=C/N, where C denotes consumption).

Welfare (U) in (1) is positively related to each of the listed arguments. The variable c denotes per capita consumption; it could be regarded as an aggregate that includes goods as well as services such as utilities and medical assistance. The variable k_{β} refers to household capital services (e.g., the benefits of housing and home appliances). Leisure (l_{β}) is total available time less time devoted to work and education, while human capital stocks (h) includes existing knowledge and experience. The variable (t_{β}) denotes technology stocks embodied in household capital. The environment enters utility as a flow

[1] There is a large and controversial literature on the measurement of the quality of life that could be a subject in its own right. See, for example, the World Bank (1990, 1992).

service (e), while the flow benefits from society's social structure (s) represent a service aggregate that is positively related to such institutional features as the level of democracy and freedom from external security threats.

Although the quality of life depiction in equation (1) is itself an abstract simplification, a logically consistent conceptual model is comparatively complex. We now turn to the task of describing such a model. Note that the model variables are listed in Table 2.

[Insert Table 2 here]

The production of society's aggregated output is given by the function:

(2) $Q=Q(K_{\alpha}, L_{\alpha}, T_{\alpha}, NR, R, S, H, E_{\alpha})$,

where, the flow of output (Q) is a positive function the stocks of industry-specific capital (K_{α}), time allocated for labor (L_{α}), production technology (T_{α}), non renewable resources (NR), renewable resources (R), the benefits from societal social structure (S), human capital H, and the flow of pollution generated by the production process (E_{α}). Production depends on S because, for example, S affects the security of property rights and contract enforcement.[2]

Output is directly consumed or saved and invested:

(3) $Q=C+I$,

where, I is the flow of investment.

Societal investment is divided to six channels:

(4) $I=I_H+I_K+I_{T\alpha}+I_{T\beta}+I_R+I_N$,

where, I_H is investment to increase human capital, I_K to increase physical capital, $I_{T\alpha}$ to increase production technology, $I_{T\beta}$ to increase household technology, I_R is investment to maintain and improve natural resources, and I_P is investment in population planning (which may either increase or shrink

[2] Pollution is modeled as an input of production: the more pollution there is, the less production resources are allocated to abatement and the more resources are allocated to production.

population).

The stocks of technology (T) and capital (K) are allocated among production (denoted by α) and household use (denoted by β).

(5) $T=T_\alpha+T_\beta$

(6) $K=K_\alpha+K_\beta$,

where, T_α is the technology level embodied in existing industry capital stock, and T_β is the technology level embodied in existing household capital stock, K_β is capital accumulation in household specific capital (housing, durable appliances), and K_α is physical capital used in production.

Agent's available time (L) is allocated among labor (L_α), leisure (L_β) and education (L_σ).

(7) $L=L_\alpha+L_\beta+L_\sigma$.

L is given by a linear transformation of population (N), and ψ is a positive parameter.

(8) $L=\psi N$

The model's stocks evolve in time. We abstract from the possibility of depreciation for T, K, and H but allow for resource and environmental depreciation. The growth rate of physical capital is given by society's investment in this capital.

(9) $dK/dt=I_K$

The growth rate of technology (δ) depends on investments in technology and the stocks of human capital and technology.

(10) $dT/dt=\delta(I_T, H, T)$

The growth rate of population (n) depends on the level of income, the stock of human capital, and investment in population planning (I_P).

(11) $dN/dt= n(Q, H, I_P)\cdot P$

The growth rate of human capital (ξ) depends on the investment in human capital (I_H), the stock of human capital and the allocation of time to acquire human capital (L_σ).

(12) $dH/dt = \xi(L_\sigma, H, I_H)\cdot H$

The growth rate of social structure - a non sector specific public good - (Λ) depends on the stocks of social structure, human capital, and technology.

(13) $dS/dt = \Lambda(S, H, T)$

The growth rate of the non renewable resource stock (NR) depends on its harvesting flow (H_N), where NR may be thought of as a mix of publicly and privately owned good.

(14) $dNR/dt = -H_N$

The growth rate of the renewable resource stock is given as the difference between its intrinsic growth rate (ν), which depends on the renewable resource stock and the investment in renewable resources, and its harvesting flow (H_R). Again, R may be thought of as a mix of publicly and privately owned good.

(15) $dR/dt = \nu(R, I_R) - H_R$

The growth rate of environmental quality, a public good, is given by the difference its own intrinsic growth rate (μ), and the depreciation generated by both the industry or household sectors, E_α and E_β, respectively (i.e., an air space which is polluted by both industrial pollution and private automobiles).

(16) $dE/dt = \mu(E) - E_\alpha - E_\beta$

Within the equation system described in (1)-(16) a subset of the varialbes are assumed to be control variables that agents, or decisions makers, can influenced. These variables include the agent's time allocations to labor (L_α), learning (L_σ), and leisure (L_β,) the level of consumption (c), the harvesting rates of the non-renewable (H_N) and renewable resources (H_R), the investment allocations among accumulating physical capital (I_K), human capital (I_H), production technology ($I_{T\alpha}$), household technology ($I_{T\beta}$), improving renewable resources (I_R), and population planning (I_N).

Beyond the specification of control variables, a number of a explicit assumptions would be needed to solve the described system. First, a solution concept is needed. The standard solution concept in neoclassical economics is net-present value maximization of the representative agents' welfare, in many cases constrained by the mathematical requirement that the model generates steady state levels of stock variables, i.e., the assumption that transversality conditions hold. Undiscounted utility maximization is a special case of this criterion. The common sustainability criterion that welfare not decline over time is a fundamentally different solution concept. One way of modeling it would be to maximize net-present value subject to a non-declining utility side constraint (Toman et al., 1992). Adding heterogenous agents and political competition to the model would necessitate another type of solution concept derived from dynamic game theory, e.g., Markov perfect equilibrium.

At this juncture, we abstract from the implications of the solution concept, and simply use the stocks and flows identified in the system in (1) - (16) as a taxonomic devise for circumscribing the domains of the literature reviewed in the following two sections. (These literatures typically employ net-present value maximization as the solution concept.) However, we return to the implication of the solution concept in Section 5, because the dynamic behavior of the system importantly reflects the solution concept, and the system's dynamic behavior is an important issue for sustainable development.

The property rights structure and assumptions about policy transactions costs are two other issues that would have to be decided in the model's formalization. In most conventional economic modeling, the property rights are either costlessly present or costlessly assignable if missing in some sphere of economic activity. Alternatively, government regulation can be costlessly implemented to address the missing markets problem. These are the assumptions of the formal models reviewed in Sections 3 and 4. We return to the implications of these assumptions in Section 5.

We now turn to a review of a wide range of studies bearing implicitly, or explicitly on the topic of sustainable development. As noted, these studies emphasize subsets of the above relatively large system's model. Table 3 summarizes the utility, stock variables, flow variables and the sustainability concepts employed (explicitly or implicitly) by each of the literatures reviewed in the following sections. It is important to note that Table 3 lists variables that are used in *a wide variety of studies* belonging to the literature in question. The reviewed studies are "representative models" that use a smaller set of variables than those listed in Table 3. As such, the reviewed studies may themselves be thought of as a partial representation of a literature which itself is part of the larger model (described in (1)-(16) whose variables are defined in Table 2.

[Insert Table 3 here]

It is important to point out in advance that the term "sustainable development" is used in several, sometimes inconsistent ways in this literature and, in fact, that much of the reviewed literature in Table 3 does not use the term explicitly. There are several alternative interpretations in those cases where the term is implicit. The "sustainable development" concept can sometimes be construed as the attainment of steady states for stocks used as inputs. The satisfaction of the transversality conditions in a standard optimal control framework is the necessary condition for achieving this kind of "sustainable" outcome. For example, the "sustained yield" concept in resource management, or the existence of steady states for per capita capital stock in neoclassical economic growth models, represent "sustainable" outcomes in this sense. The term "sustainable" can also be construed as a condition applying to the output side of the economy. Here, a 'static" and "dynamic" concept" can be distinguished. "Static" sustainability on the output side would refer to steady states for consumption, output, or utility, while the "dynamic" criterion would require non-declining growth paths for consumption, output, or utility.

The various (implied) concepts of sustainability are not necessarily consistent; for example, steady states on the input side do not necessarily imply steady states on the output side, and visa versa. In fact, maintaining a steady states on the input side is neither always necessary or always sufficient to achieve such policy targets as maintaining a non-declining level of a broadly-defined quality of life measure like that in Equation 1. Moreover, the steady state reference point does not deal with the welfare implications of a parametric change that moves a system from a higher welfare steady state to a lower welfare steady state. Thus, one conclusion which emerges in advance is that the steady state analysis alone is not adequate for drawing conclusions about sustainable development.

We now turn to the literature review in Sections 3 and 4. This review lays the foundation for the qualifications and research extensions described in Sections 5 and 6.

3. Economic Growth without the Environment

Economic growth models without environmental factors do not explicitly use the term sustainable development. In this literature, sustainability implies a non-declining consumption or utility.

3.1 Neoclassical and Endogenous Growth

The neoclassical growth model predicts that in the absence of technological progress, an economy whose population grows at some given constant rate will converge on a constant consumption per capita (Cass, 1965). Using a constant return to scale production function and operating in competitive markets, individuals save a portion of the produced output in order to produce more capital. Population growth implies a need to spread capital over more workers. Therefore, the steady state consumption per capita declines with a rise in the rate of population growth, and high population growth can be unsustainable once consumption per capita falls below subsistence level, ceteris paribus. Yet consumption per capita may grow in steady state in the presence of technological progress in production.

The neoclassical growth model is extended in various ways, including adding endogenous generating of technology, environmental factors and endogenous population processes. These extensions are discussed below and in Sub-Section 3.2 and Section 4. One extension which yields a completely different dynamic behavior from the base model is that of Kurz (1968). He adds the capital stock to agents utility, representing wealth effects. The model thus modified can yield multiple steady states, which alternate in their stability properties between saddle point stable and unstable nodes. Subsequent research in the growth field has largely ignored this result and continued with the standard utility formulation. We return to this point in Section 5.

The neoclassical model does not explain the source of technological progress. In endogenous growth models, technological progress is modeled to be determined by economic agents. These models generally include three stock variables: physical capital, human capital, and technology. The flow variables are consumption, investment, and output. Population is assumed to be constant. Models which assume imperfect competition also include the flows of innovations and profits.

There are three types of endogenous growth models. In the first type (e.g., King and Rebelo, 1990; Rebelo, 1991; Jones and Manuelli, 1990), a production function is posited under which the marginal product of capital, while diminishing with capital, never declines below the discount rate. Since investment is always profitable, agents continue to accumulate capital, enabling steady state economic growth. In the second type of model, steady state consumption growth comes from external economies in production in competitive markets due to accumulation of human capital or production technology. In Romer (1986), as production technological knowledge rises, firms become more productive. In Lucas (1988), human capital creates positive external economies in production. In a third type of model, economic growth is driven by monopoly rent-motivated innovation (Schumpeter, 1961; Grossman and Helpman, 1991; Aghion and Howitt, 1992), implying that economic growth requires well-defined property rights institutions.

3.2 Population Growth

Above, population was assumed to grow at a given rate or not grow at all, but its effects are mostly not studied. As noted, the neoclassical growth model implies that without (exogenous) technological progress, steady state consumption per capita declines with population growth. However, the effect of population growth on economic growth is generally debated. Many studies argue the effect is negative, due to various forces, including capital thinning, diminishing returns to labor, unemployment, diseconomies of scale, and reduced investments due to the need to support more retirees (Kelley, 1988; Heerink, 1994; Razin and Sadka, 1995). In a smaller number of studies, population growth is the main driver of consumption growth. In Boserup (1981) and Lee (1988), higher population density stimulates innovations, raises the efficiency of transportation and communication, and stimulates specialization. Simon (1986) argues that a larger population raises the demand for innovations (through necessity) and the supply of innovation (through specialization and economies of scale), resulting in consumption growth. A similar conclusion is reached by Kremer (1993). These models do not include natural resources. Simon, in particular, argues that innovations rise faster than the decline in resources, and the latter do not play a special role in growth.

In two other type of studies, population growth is taken to be endogenous. In one type, a social planner chooses the rate of population growth to maximize society's utility (Dasgupta, 1969; Pitchford, 1974, Neumann, 1988). In these models, sustainable development implies attaining a steady state consumption by controlling the number of people in the system. A second type of model assumes that population growth rate depends on income per capita. Empirically, below some threshold of income per capita, fertility grows with income per capita, but above it fertility falls with income per capita (Heerink, 1994). Sato and Davis (1971) extend the neoclassical growth model by assuming that population growth depends positively on per capita income and conclude that the optimal program has the same qualitative features as the neoclassical model. However, Krutilla and Reuveny (1999c) show that endogenous population growth could generate multiple steady states that differ in income per capita and stability, demonstrating the inherent complexity associated with introducing endogenous population growth into economic growth theory.

4. Economic Growth with the Environment

A growing number of studies considers the effects of environmental variables on economic growth, an approach which originating with Malthus and Ricardo. Some of these studies are more qualitative in nature or do not employ an explicit optimizing framework.

4.1 Limits to Growth

In his famous study, Malthus (1798) discussed the reality of diminishing returns to labor in an economy without technologic change, with economic convergence to a state of subsistence and political breakdown as the ultimate natural check on population growth. Ricardo (1817) introduced resource heterogeneity into the model, with diminishing returns resulting from the use of lower quality resources. In these classical works, per capita consumption is unsustainable, declining overtime.

Partly as a reaction to these predictions, economists emphasize technological progress as the source of perpetual economic growth (See Section 4.2). Recent years, however, have seen some revision of opinions as scholars returned to the basic Malthusian-Ricardian question "are there limits for economic growth?" Meadows et al. (1972), simulated the modern implications of population growth and finiteness of non-renewable resources, predicting a sharp global economic decline sometime in the twenty-first century, implying that continuous economic growth is unsustainable due to physical limits.[3] Many authors rejected these predictions noting that Meadows et al. did not allow for substitution of declining natural resources by other materials, proven resource reserves should not be used for long term trajectories since historically they always proved to be bad predictors of actual reserves, and the model did not allow for technological progress and did not consider the negative effects of economic growth on population growth (Page, 1973).

Georgescu-Roegen (1971) argues the second law of thermodynamics imposes a biophysical limit

[3] See also Meadows et al. (1992).

to growth. Economic activities accelerate entropy growth (a measure of non useful energy), implying limits to growth due to declining natural resources, the environment's ability to absorb waste and heat, and the limited ability to recycle waist. The economy must reach a steady state. While even this cannot last forever (as entropy must grow), a goal of perpetual economic growth will accelerate the failure (Hardin, 1974; Daly, 1977, 1997; Young, 1991). In contrast, Solow (1997), Stiglitz (1997) and others argue natural resources can be substituted by man made capital, recycling does not pose a limitation, earth is not a closed system and solar energy is practically infinite.

Hirsch (1977) argues that there are social limits to growth. Once a consumption threshold is met, agents utility increasingly depends on others' consumption and relative social positions. In particular, as their level of education rises, agent's material gain from education declines. At some point, agents' spending will not translate into aggregate improvement, questioning the ability of education or technological progress to sustain long run economic growth.

Ecosystem threshold models provide another perspective on growth constraints. In this literature, resilience is defined as the capacity of the system to withstand shocks. The economy is treated as a black box; the stock variables are renewable resources, non renewable resources, environmental quality and population. The flow variables are economically motivated, not fully specified interventions or shocks, which adversely affect the ecosystem (e.g., resource harvesting, pollution). The emphasis is on defining physical indicators that measure ecosystem diversity, since the ability of the system to withstand these shocks is assumed to be positively related to ecosystem diversity.

Policy must ensure that economic activity does not cause ecosystem diversity to fall beneath a certain threshold, thereby destabilizing the system. Certain natural resource stocks are argued to be critical to diversity (Holling, 1986; Common and Perring, 1992). It is necessary to keep these stocks from declining to allow for future generations to maintain current welfare. Hence, "sustainability" requires a non-declining welfare, which requires maintaining critical natural stocks above some threshold assuring ecosystem diversity. How to identify such critical stocks? Pearce and Turner (1990) and Klaasen and Opschoor (1991) distinguish between man made capital and natural resources and argue that the substitution between the two is limited. Natural resources that provide non-substitutable services to the economy (e.g., atmospheric integrity, nutrition cycles) are termed *keystone processes* and constitute critical resources. Pearce et al. (1990) attach a monetary value for environmental impacts and argue that sustainable development requires that the discounted sum of environmental benefits from any economic intervention in the ecosystem not be larger than the discounted sum of the appropriate costs. A stronger form of this requirement requires that environmental benefits be larger than costs in each point of time.

A related approach emphasizes the role of uncertainty (Ciriacy-Wantrup, 1952; Bishop, 1978; Tisdell, 1990; Randall and Farmer, 1995, Arrow et al. (1995), arguing that economic activities are sustainable only if life supporting ecosystems continue to function. The maintenance of ecosystem diversity is important to reduce uncertainties associated with the effects of economic activity on the environment, which are not well understood (e.g., loss of biological productivity, irreversible natural changes). Maintaining natural resource stocks constant is therefore risk minimizing, and requires identifying safe minimum standard thresholds (SMS), in physical units.[4]

4.2 Growth with Environmental Stocks

Several studies add environmental stocks and flows to the neoclassical and endogenous growth framework. Population is either constant or grows at an exogenous rate, utility generally depends on consumption (in some models also on natural resource stock) and the (implied) concept of sustainability is non declining consumption.

---

[4] Turner (1993) also identifies crucial *keystone species.* Van Pelt (1993) suggests setting different thresholds for each category (e.g., pollution, non-renewable resources, renewable resources). For specific SMS levels see, Hanley et al. (1991). For a critique of ecological threshold approaches, see Hanley and Spash (1993).

One type of models studies the effect of natural resources on economic growth. Dasgupta and Hill (1974) consider an agent extracting a non-renewable resource. In the long run, consumption and the resource vanish. Krautkraemer (1985) adds technological progress in utilizing the resource to this model and finds that if technological progress grows at a rate higher than the discount rate, consumption may grow forever. Stiglitz (1974) extends the neoclassical production function to use a nonrenewable resource input, while population is growing in a given rate. Dasgupta and Hill (1974) consider a similar framework (with a different functional form) for production and constant population. Both papers conclude that if the resource can be substituted by capital, a growing consumption path is feasible. Hartwick (1977) uses a Cobb Douglas production function with a larger output share of capital than of resource, constant population, and no technological progress. He concludes that a path of constant consumption is feasible provided the value of the extracted resource is invested in capital accumulation, keeping the value of capital plus resource constant.[5] Krautkraemer (1985) adds a nonrenewable resource to utility in Dasgupta and Hill's (1974) model. Resource preservation is optimal if capital is always productive, society is not myopic, the initial capital stock is high, society values the resource, capital is highly substitutable for the recourse in production and the resource is highly substitutable for consumption in utility.

A second type of models adds pollution to the neoclassical model (e.g., Heal, 1982). Pollution is either a stock or flow, generates disutility, increases production, or both, and is controlled by abatement or by choosing production processes (Klassen and Opschoor, 1991). Without technological progress, models generate a steady state consumption (i.e., growing consumption is not feasible). Some models generate multiple equilibria with different pollution stocks (Heal, 1982). When substitution of dirty technologies for clean ones is possible, this dichotomy disappears (Tahvonen and Kuuluvainen, 1993). A related issue is the inverted U-shape according to which pollution grows (falls) with income when

[5] For criticism of the Hartwick approach see Dixit et al. (1980) and Asheim (1994).

income is low (high). The empirical validity of this claim is controversial. Nevertheless, it implies that growth could improve the environment (Selden and Song, 1994; Grossman and Krueger, 1995), the effect operating through more education and political participation, shifts toward cleaner industries and being able to care for more than immediate livelihood (World Development Report, 1992). Others argue that in the long run environmental damage must rise with growth, and the damage may rise more than income (Common, 1995).

A third type of model extends endogenous growth frameworks.[6] Model's structure vary. The stock variables include pollution, capital, innovations, human capital and natural resources. Utility rises with consumption and environmental quality. Production rises with capital, human capital, innovations, natural resources and pollution. Population is constant. The control variables include consumption, natural resource extraction, pollution abatement, knowledge and innovation efforts, and production "dirtiness."

In Michel and Rotilon (1995), for example, knowledge grows with capital and exerts a positive externality on production, pollution stock rises with production, and utility declines with pollution and rises with consumption. When the marginal utility of consumption declines with pollution, consumption growth is not optimal, otherwise, growth is possible, but with more pollution. In Verdier (1995), permanent growth is induced by the number of product varieties, and environmental quality is enhanced by assuming that cleaner varieties exhibit increasing returns to scale. In Bovenberg and Smulders (1996), utility rises with consumption of a renewable resource and environmental quality, which is depleted by pollution. Capital substitutes for natural resources, and production rises with capital and pollution. Consumption growth with constant pollution and resources is possible when capital can substitute for resources and human capital generates cleaner technologies. In Stokey (1998), production rises with capital and technology dirtiness, environmental quality declines with technology dirtiness, utility rises

[6] The literature is relatively small. For a survey see Carraro (1998).

with consumption and environmental quality, and agents choose consumption and technology dirtiness. Without exogenous technological progress, consumption growth is not feasible since technology dirtiness declines along the optimal path. Using a similar model, Aghion and Hewitt (1998) allow for the decline in capital productivity due to the decline in technological dirtiness to be by cleaner innovations, which enable a growing consumption. Innovations which are less nonrenewable resource-intensive than output also make growing consumption feasible in the presence of a decline nonrenewable stock.

5. Discussion

The reviewed literature offers the benefits of a tightly focused query of particular parameters and policies that influence the behavior of the sub-modules encapsulated by the bigger systems model. Taken together, economic growth models imply that increasing consumption per capita is possible when population is growing and without unbounded environmental degradation *if* technological progress results in increasing returns to scale, lower emission per unit production, there are increasing returns in producing cleaner products and abatement, and the elasticity of substitution between natural resources and man-made capital is relatively high. Pessimistic conclusions about these parameters, concerns about the stability of functional forms, and the possibility of adverse ecosystem shocks provide a temporizing view. Above all, the welfare measures of the reviewed literature are not broad enough to capture the distinction at the heart of the emergence of the independent study of sustainable development: the focus on development, rather than growth, per se.

There are number of implications of the welfare measures used in the literature reviewed beyond the fact that the growth policy target is too narrow to fully reflect welfare. First, the derivative policy prescriptions have the natural tendency to focus on the stocks and flows incorporated in the particular model under study. Historically, at least, economists have tended to emphasize investments in technology, physical capital, or human capital, and, in the context of growth modeling, have focused on particular kinds of technology change, e.g., Hicks-neutral technical change that increases the productivity of all production factors proportionately, or Harrod-neutral technical change that increases the productivity of labor. Demographers have quite naturally emphasized population planning, while environmentalists have tended to emphasize resource conservation and ecosystem protection and recovery. Yet, it is not theoretically obvious which, or what combination, of these policies is most likely to improve the future quality of life, or whether other investments – for example, in conflict resolution, or institution building -- would yield even better returns. Moreover, some threshold level of investment may be needed to maintain the stability of ecosystems, as well as society's basic institutions. Comparative information is needed to judge investment priorities beyond these critical thresholds, information lacking in models having the narrower quality-of-life focus.

The narrower quality of life measure also has dynamical implications. A one-argument utility function yields one steady state in economic growth models without technology change, or one balanced growth path for per capita consumption and capital in models with technology change. Augmenting the utility function to include just one stock beyond consumption in relatively simple general equilibrium growth model significantly increases dynamic complexity, i.e., produces multiple equilibria, or multiple growth paths. The dynamic consequences of more stocks operating directly on utility in a more complex systems model like that described in (1)-(16) are likely to be even greater. In general, the dynamic behavior of the actual system that supports human welfare is extraordinarily complex. Uncertainties associated with dynamic complexity may reinforce the conclusions of the ecosystem reliance literature that risk premia in the form of additional margins-of-safety for stocks of nature, or more generally, lower growth policies, may be a rational social insurance policy.

The political economy dimensions of sustainable development are also relatively under studied in the dynamic general equilibrium context. The bulk of the reviewed literature is based on a representative agent formulation, thereby ignoring heterogeneities that motivate political activity. These models are consistent with what McGuire and Olson (1996) have described as a “consensual democracy”: a society in which there is total unanimity about decision making. Although the consequences of political activity for economic growth are beginning to be addressed (e.g., Tornell and Lane, 1999) there is as yet no systematic study of the role of political economy in affecting the goal of sustainable development.

Political economy is potentially significant for a variety of reasons. First, political economy is likely to inject frictions that dissipate gains. Such frictions have the potential to attenuate the propitious impacts of technology change and/or undermine investment policy. Second, political economy has the potential to further increase dynamic complexity, since introducing agent heterogeneity into the basic model converts the formulation into a dynamic game. In this context, trigger strategies, in which agents base behavior on past history, can support virtually any equilibrium with high enough discount rates. Unique outcomes under Markov Perfect equilibrium strategy are not assured in a model of the complexity of (1)-(16). Finally, models lacking a political economy component cannot offer any perspective about which combination of investment profiles is likely to be politically feasible for the current generation -- an important determinant of whether sustainable development is practically achievable. Conceivably, some investments might be politically feasible (e.g., human capital investments that benefit current generation) and others might not be feasible (e.g., restricting current consumption to increase social investment).

We now turn in more detail to the political economy issue, and then give fuller discussion to the issue of dynamic complexity associated with a systems model like that in Equations (1)-(16).

5.1 Political Economy

Three aspects of political economy would seem to have particular salience for the study of sustainable development: collective action constraints on policy making, rent seeking, and violent conflict.

5.1.1 Collective Action: If sustainable development does not arise endogenously from the actions of the current generation, the task of passing on a non-declining quality of life to future generations may pose a significant collective action challenge, involving both the need for a broad-based consensus about intergenerational equity and overcoming the coordination issues underlying requisite policy action.

Self-interested policies of the current generation do not necessarily diminish future generation welfare. Investments in human capital, technology, and institution building, or reducing population growth rate, pollution, and supporting biodiversity may benefit both current and future generations due to long-term lag effects.[7] But because the manifestation of the effects is lagged, the payoffs to future generations from current policies may be less than equitable. Some degree of inter-generational difference in interest is likely to arise even over the level of policies with propitious cross-generational lag effects – not to mention such policies as resource depletion with negative cross-generational effects.

One possibility is that the current generation cares directly about its offspring, a possibility explored in overlapping generation models e.g., Babu, et. al., (1997). This structure would minimize cross-generational differences for private goods stocks. However, even in this class of models, suboptimal provision of public goods, due to free-rider problems emerges as a potential issues (Babu, et. al., 1997). Indeed, even in the case where "intergenerational equity" is broadly construed as a public good, provision by the current generation can be suboptimal from the perspective of even *current generation* welfare.

A second possibility involves a repeated game in which the cooperative strategy to endogenously arise (Taylor, 1987). Game payoffs also can be altered by institutional design (Ostrom,1994). The successful negotiation of the Montreal Protocol and the attempt to restrain $C0_2$ emissions through the Kyoto Accord are examples of the second mechanism. Notwithstanding these efforts, the collective

---

[7] For an example, see the literature on "no-regrets" energy conservation (e.g., Boyd et al., 1996).

action dimension of addressing such large issues as climate control or reducing biodiversity loss are likely to be significant, in light of transactions costs, information imperfections, and free-riding.

5.1.2. Rent-Seeking: Investment policy is an important aspect of achieving sustainable development.[8] The literature on Hartwick's rule suggests ways for reinvesting resource rents to maintain non-declining capital (Hartwick 1997) or investment policy specifically to maintain renewable resource stocks. The availability of economic rents to support such investments is an important issue for sustainable development.

It is well known that agents in a representative democracy dissipate rents through political activity (Tollison, R. and Congelton, eds., 1995). A large portion of the world's natural resources are publicly-owned and/or managed, and how resource rents are utilized is therefore a political issue. Beyond this issue, the level of taxation and the disbursement of tax revenues in democracies are usually subject to political competition. The transactions costs of political activity invariably consume some of these rents (Tollison, R. and Congelton, eds., 1995), reducing the rent available for investment policy.

The impact of rent-seeking has begun to be explored in the dynamic general equilibrium setting. Using a dynamic game formulation, Tornell and Lane (1999) show that the economic cost of rent-seeking more than offsets the economic benefits of positive terms-of-trade changes, i.e., conventionally-measured economic growth declines after a positive terms of trade change. Privileged rent-seekers are able to lobby to increase their tax share, and the social cost of the associated capital reallocation always dominates the benefits of the positive terms of trade change. This result raises the question as to whether the gains of other positive economic shocks (e.g., technology breakthrough) could also be dissipated in political competition, or again, the rents needed for reinvestment policy. These kinds of possibilities have obvious implications for sustainable development.

[8] Investments in this context is construed in its broadest sense, e.g., to include such policies as resource conservation and pollution control.

5.1.3. Violent Conflict. Throughout history, violent conflicts have been a significant factor in disrupting human populations and undermining on the quality of life throughout history. Indeed, the intensity of wars has grown over time. Although there is an emerging economics literature in the area of power and conflict (Skaperdas, 1992), war is mostly studied in the political science field. There are competing theories, each receiving some empirical support (Cashman, 1993).

As reviewed by Gleditch (1998) and others, many empirical studies have recently linked political conflict with environmental degradation and resource scarcity through four channels, essentially charted by Malthus: (1) economic decline and dwindling of natural resources per capita; (2) population migration or displacement due to economic decline; (3) existing social problems (e.g., ethnic tension, unequal distribution of wealth) aggravated by environmental scarcities; and (4) weakening governments due to economic decline which result in disrupted institutions and the rule of law.[9]

Another set of studies links economic growth and war. Choucri and North (1975) argue that economic growth in Europe intensified competition over natural resources in the form of colonial lands, which heightened arms races and ultimately lead to World War I. Other studies claim that economic downturns push leaders to expand the economy by intensifying the competition for world markets and/or investing in a war-economy. In times of economic downturn, leaders may also attempt to divert public attention from internal problems by blaming other countries (Ostrom and Job, 1986; Russet, 1990). Other studies argue that the likelihood of war rises in economic upturns. According to this view, wars are fought when nations can afford them (Blainey, 1973; Goldstein, 1988).

A third approach investigates the link between wars and long waves of economic growth (roughly 50 years at length), which were first observed by Kondratieff (1928), and later by Schumpeter (1961) and Lewis (1984). The cause(s), timing, and existence of these waves are controversial. In this

[9] For reviews of empirical cases see Myars (1993) and Homer-Dixon and Percival (1996).

view, long waves are a future of a world market economy and can be found in series of price, production, investment, wage, innovation etc., going back (in some studies) to the tenth century. Most economists would not challenge that the global economy went through long periods of rapid and slow growth, but they disagree that they represent a systematic phenomenon (Samuelson, 1980; Maddison, 1982).

Many researchers have investigated the link between long waves, the rise and fall of major powers and major wars. While a periodicity of war and economic growth is identified in many studies, the causal theories vary (see Modelski and Thompson, 1996 and Neumann, 1996 for reviews). Modelski and Thompson (1996) argue that long waves are the result of technological innovation in leading economic sectors and is endogenous to the system. At first, it is spatially and temporally centered in a leading economy. As the new knowledge diffuses, the relative position of the leader deteriorates.[10] Economic leadership is associated with political leadership and, historically, with a large navy as a means of projecting power. A period of concentrated leadership is associated with peace. A period with leadership relative decline is associated with a global war, historically roughly every 100 years (every other long wave), which serves as an endogenous mechanism on deciding on the next system leader.

The literature on war implies that sustainable development is also an international political issue, not only economic or biological. Periods of economic decline or growth associated with scarcity of natural resources are dangerous. Capitalistic development seems to progress in short and long term waves. Periods of fast economic change in which a world leader is in decline while a challenger is rising are particularly dangerous. All this does not mean that similar future periods must end in a war. In the same way that economic agents learn, political agents can develop peaceful conflict resolution mechanisms.

5.2 Dynamic Complexity and Technology Change

The dynamic system underlying the development of human welfare is extremely complex; even

[10] For a similar interpretation but without war see Brezis et. al. (1993).

the highly aggregated model in equations (1) -(16) cannot be analytically solved under any of the commonly-used solution concepts for representative agent models. Multiple dynamic paths are likely to be a feature of simulated solutions, since the possibility of multiple equilibria and multiple growth paths emerge in any principal-agent model one step more complex than the standard neo-classical Ramsey model (Krutilla and Reuveny 1999a, 1999b, 1999c). As indicated before, agent heterogeneity introduces a strategic element that increases dynamic complexity.

Implications of dynamic complexity for system behavior is suggested by a principal of systems engineering in which complex systems behave in ways not predictable by observing the behavior of each of the component parts in isolation. For example, once engineers integrate the component parts of complex system such as a space shuttle or a large super computer, they may find that the behavior of the system's components change when interacting with the other parts due to a pathway not taken into account, or not arising in a particular subsystem alone. The new behavior may not be predictable in advance.

These insights can be applied to the role of technology change in a systems model like that in (1)-(16). Technology advance increases welfare in standard economic models by increasing the scope for resource substitution, and the rate of social return on scarce production factors, and stimulating the accumulation of physical capital (Barnett and Morse, 1963; Simon 1986; Toman et al. 1998). Exogenous technological advance in a simple general equilibrium setting is sufficient to overcome a resource constraint on production in the sense that per capita consumption and capital both grow in the long-run at the rate of technological progress (See Section 4.2.)

However, technology can also have negative welfare effects, even in simple partial equilibrium model of renewable resource extraction. For example, if the equilibrium is to the right of the maximum sustained yield (MSY) level in a model with costly resource extraction, technology change that improves the efficiency of resource extraction will shift the cost curve down. To the right of the MSY, this downward shift increases the resource stock level and lowers the catch rate. Welfare drops when the catch rate declines in the simple model in which welfare is monotonically increasing in consumption

This basic result carries over into a dynamic general equilibrium setting. A renewable resource-based economic growth model can have undefined dynamical properties in the case where resource harvest is a function of labor and the resource stock, and labor-productivity enhancing technologic advance is evenly distributed across economic sectors. Given this, the possibility of a negative relationship between technological advance and welfare cannot be ruled out (Krutilla and Reuveny, 1999a). Using Cobb-Douglas functional forms and restricting parameters to assure a unique equilibrium, welfare can initially decline along the dynamic transition path but ultimately increases. However, the rate of welfare increase is less than the rate of technologic progress (a result similar to that of Stokey, 1998). Thus, the propitious effect of technological progress is attenuated relative to the standard case in which technical change does not affect resource extraction efficiency.

These models represent a small part of the bigger model presented in Section 2. It seems highly likely that the varying pattern of technology effects that begin to emerge in these relatively minor departures from the standard neo-classical model would become more pronounced in more complex settings. One candidate for such additional complexity is the resource regeneration functions for renewable resources and environmental sinks, which are likely to be significantly more complicated than such defaults as the simple logistic growth equation. Nonconvexities in resource regeneration functions have dynamic consequences in partial equilibrium models (Clark, 1990). To our knowledge, the relationship between technological advance, welfare, and non-convexities in resource and environmental regeneration functions has not been investigated in the dynamic general equilibrium framework.

It also seems likely that the welfare effects of technology may depend on the type of technological change. Technology change that increases resource extraction efficiency is less beneficial than the usually-assumed type of technical change that increases the efficiency of other production inputs. Technological advance in weaponry obviously has the potential to decrease welfare. These factors suggest a relatively cautious perspective is warranted with respect to the role of technology development, particularly within the context of a complex dynamic systems model.

6. Conclusion

Ultimately, an integrated systems model is the best way to fully understand the behavior of complex dynamic system underlying human welfare. In principle, the behavior of such a model could be investigated in a dynamic simulation. The different parts of the system would be modeled separately, and then put together to interact with each other. This is the standard process for systems simulation in the engineering field. However, the results of such simulations would be sensitive to calibration, and calibration would be a formidable empirical problem. It is thus not surprising that model building of this scope cannot now be found in the literature.

Given this fact, it is reasonable to ask what presumptive conclusions can now be drawn from conceptual theorizing based on the larger systems perspective. Four primary issues emerge. First, an attempt at an assessment of a broader range of policy options, based on the full range of relevant stock and flow variables in the larger systems framework, would be worthy research goal. Secondly, political factors are likely to inject frictions that attenuate gains and otherwise waste resource, suggesting that assumptions about the propitious impacts of technology change and/or investment policy in principle agent models may be overly optimistic. This area deserves further research. Thirdly, institutional design that minimizes the possibility for rent-seeking, as well as war and conflict, may be a crucial aspect of sustainable development. Finally, the dynamic behavior of the actual system that supports human welfare is likely to be extraordinarily complex and, to a degree unpredictable. This fact reinforces the conclusions of the ecosystem reliance literature that risk premia in the form of additional margins-of-safety for stocks of nature, or more generally, lower growth policies, may be prudent as part of an overall strategy for achieving sustainable development.

References

Arrow et. al , (1995). Economic-growth, carrying-capacity, and the environment, Science 268: 520-521.

Aghion, P. and Peter H. (1992), Model of growth through creative destruction, Econometrica 60:323-51.

Aghion, P. and P. Hewitt (1998), Endogenous Growth Theory, Cambridge: The MIT Press.

Asheim, G. B. (1994), Net national product as an indicator of sustainability, Scandinavian Journal of Economics, 96: 257-265.

Babu, P. Guruswamy, K., Kavi, K.S, and Murthy (1997) N.S., An overlapping generations model with exhaustible resources and stock pollution, Ecological Economics (21) 35-43.

Barbier, E.B., and A. Markandya (1990), The conditions for achieving environmental sustainable development, European Economic Review 34: 659-669.

Barnett, H. And C. Morse (1963), Scarcity and Growth, Baltimore, MD: John Hopkins Press.

Barrett, S. (1992), Economic growth and environmental preservation, Journal of Environmental Economics and Management 23: 289-300.

Bishop, R.C. (1978) Endangered species and uncertainty: The economics of a safe minimum standard, American Journal of Agricultural Economics, 60: 10-18.

Blainey, Geoffrey (1973), The Causes of War. New York: Free Press.

Boserup Ester (1981), Population and Technological Change: a Study of Long Term Trends, Chicago : Chicago University Press.

Bovenberg, L. and S. Smulders (1996) Environmental quality and pollution augmenting technological change in a two sector endogenous growth model, Journal of Public Economics, 57: 369-391.

Boyd, K. R.G., Krutilla, and W. K. Viscusi (1995), Energy taxation as a policy instrument to reduce CO_2 emissions; A net benefit analysis. Journal of Environmental Economics and Management *29:1-24.*

Brezis, E. S., P. R. Krugman, and D. Tsiddon (1993), Leapfrogging in International Competition: A Theory of Cycles in National Technological Leadership, American Economic Review 83: 1211-1219.

Brutland (1987) , Our Common Future, U.N. Commission on Environment and Development.

Carraro, C. (1998), New economic theories, Environmental and Resource Economics, 11: 365-381.

Cashman, Greg (1993), What Causes War? An Introduction to Theories of International Conflict, New York: Lexington.

Cass, D. (1965) Optimum growth in aggregate model of capital accumulation, Review of Economic

Studies 32: 233-40.

Choucri, Nazli and Robert C. North (1975), Nations in Conflict: National Growth and International Violence, San Francisco: Freeman.

Ciriacy-Wantrup, S. (1952) Resource Conservation: Economics and Policy, Berkeley: University of California Press.

Clark, C. (1990), Mathematical Bioeconomics, New York: Wiley.

Common, M. S. (1995) Sustainability and Policy: Limits to Economics, Cambridge: Cambridge University Press.

Common M. and C. Perring (1992) Towards an ecological economics of sustainability, Ecological Economics, 6: 7-34.

Daly, Herman. E. (1977), Steady State Economics: The Economics of Biophysical Equilibrium and Moral Growth, San Francisco: Freeman.

Daly, Herman E. (1997) Georgescu-Roegen, versus Solow/Stigliz, Ecological Economics 22, 261-266.

Daly, Herman. E. (1987), The Economic Growth Debate: What Some Economists Have Learned, but Many Have Not, Journal of Environmental Economics and Management, December, 14: 323-361.

Dasgupta, P. S. (1969), On the concept of optimum population, Review of Economic Studies 36: 28-49.

Dasgupta, P. S. and G. M. Heal (1974), The optimal depletion of exhaustible resources, Review of Economic Studies: Symposium , 41: 3-28.

Dixit, A., P. Hammond M. Hoel (1980), "On Hartwick's rule for regular maximin paths of capital accumulation and resource depletion, Review of Economic Studies, 47: 551-556.

Georgescu-Roegen, Nicholas (1971), The Entropy Law and The Economic Process, Cambridge, MA: Harvard University Press.

Gleditsch N. P., (1998), Armed conflict and the environment: A critique of the literature, Journal of Peace Research 35: 381-400.

Goldstein, Joshua (1988), Long Waves in War, Production, Prices, and Wages, Journal of Conflict Resolution, 31: 573-600.

Grossman, Gene M. and Elhanan Helpman (1991), Innovation and Growth in the Global Economy. Cambridge: MIT Press..

Grossman, G. M. and A. B. Krueger (1995), "Economic growth and the environment," Quarterly Journal of Economics, 110: 353-377.

Hanley, N., A. Munro, D. Jamieson and D. Ghosh (1991) Environmental Economics and Sustainable

Development in Nature Conservation, Peterborough: NCC.

Hanley, N. and C. Spash (1993) Cost-Benefit Analysis and the Environment, Aldershot: Elgar.

Hardin, Garrett (1974), Living on a lifeboat, Bio Science, 24: 564.

Hartwick, J. M. (1977), "Intergenerational equity and the investing of rents from exhaustible Resources," American Economic Review, 67: 972-974.

Heal, G., (1998) Interpreting Sustainability, in G. Chichilnisky et. al. Eds. Sustainability: Dynamics and Uncertainty, Amsterdam: Kluwer.

Heal G. (1982), The use of common property resources," in V. K. Smith and J. V. Krutilla (eds.) Explorations in Natural Resource Economics, Baltimore: Johns Hopkins University Press, 78-99.

Heerink, N. (1994), Population Growth, Income Distribution, and Economic Development: Theory, Methodology, and Empirical Results, New York: Springer-Verlag.

Hirsch, F. (1977), Social Limits to Growth, London: Routledge & Kegan Paul.

Holling, C.S. (1986) The resilience of terrestrial ecosystems, in W.C. Clark and R.E. Munn (eds), Sustainable Development of the Biosphere, Cambridge: Cambridge University Press.

Homer-Dixon, F. Thomas, and Valerie Percival (1996), Environmental Scarcity and Violent Conflict: briefing book, Toronto: University of Toronto.

Jones, Larry E. and Rodolfo Manuelli (1990), A convex model of equilibrium growth, Journal of Political Economy, 98: 1008-1038.

Kelley, Allen C. (1988), Population pressures, saving, and investment in the Third World: some puzzles, Economic Development and Cultural Change, 36: 449-64.

King, Robert G., and Sergio Rebelo (1990), Public policy and economic growth: Developing neoclassical implications, Journal of Political Economy 98: 125-50.

Klaasen, G. and H. Opschoor (1991), Economics of sustainability of the sustainability of economics, Ecological Economics, 4: 83-92.

Kondratieff, Nikolai D. (1928), The Long Wave Cycle, New York: Richardson and Snyder.

Krautkraemer, J. (1985) Optimal growth, resource amenities and the preservation of natural environments, Review of Economic Studies 52: 153-70.

Kremer, Michael (1993), Population growth and technological change: One million B.C. to 1990, Quarterly Journal of Economics, 108: 681-716.

Krutilla, K. and R. Reuveny (1999a), A renewable resource-based Ramsey model with resource amenity value, Working Paper, School of Public and Environmental Affairs, Indiana University.

Krutilla, K. and R. Reuveny (1999b), A Renewable resource-based Ramsey Model with harvest costs, Working Paper, School of Public and Environmental Affairs, Indiana University.

Krutilla, K. and R. Reuveny (1999c), A Ramsey Model with endogenous population growth, Working Paper, School of Public and Environmental Affairs, Indiana University.

Kurz, M. (1968), Optimal economic growth and wealth effects, International Economic Review, 9: 348-357.

Lee, Demos Ronald (1988), Induced population growth and induced technological progress: Their Interaction in the accelerating stage, Mathematical Population Studies, 1: 265-288.

Lewis, W. A. (1984), The Rate of Growth of the World Economy, Taipei: The Institute of Economics.

Lucas, Robert E., Jr. (1988), On the mechanics of economic development, Journal of Monetary Economics 22: 3-42.

Maddison, Angus (1982), Phases of Capitalist Development, New York: Oxford University Press.

Malthus, Thomas (1798), An Essay on the Principle of Population, Homewood, IL: Irwin [1963].

McGuire, M. C. and M. Jr. Olson (1996), The economics of autocracy and majority rule: The invisible hand and the use of force, Journal of Economic Literature(34): 72-96.

Meadows, Donella H., Dennis L. Meadows, Jorgen Randers, and William W. Behrens III (1972), The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind, New York: Universe Books.

Meadows, Donella H., Dennis L. Meadows, and Jorgen Randers (1992), Beyond the Limits: Confronting Global Collapse, Envisioning a Sustainable Future, Post Hills, VT: Chelsea Green.

Michel, P. and G. Rotillon (1995), "Disutility of pollution and endogenous Growth," Environmental and Resource Economics, 6: 279-300.

Modelski, George and W. R. Thompson (1996), Leading Sectors and World Powers: The Coevolution of Global Economics and Politics. Columbia: University of South Carolina Press.

Neumann, Manford (1989), Technical progress and population growth, in K.S. Zimmermann (ed.,) Economic Theory of Optimal Population, Springer: Berlin, 67-74.

Neumann, Manfred (1996), The Rise and Fall of the Wealth of Nations: Long Waves in Economics and International Relations, Cheltenham, UK: Elgar.

Ostrom, E. (1994) Governing the Commons: The Evolution of Institutions for Collective Action, Cambridge, Cambridge University Press, 1994.

Ostrom, C.W., and B. L. Job (1986), The president and the political use of force, American Political

Science Review, 80: 819-42.

Page, W. (1973), The Non-renewable resources subsystem, in H. S. D. Cole, C. Freeman, M. Jahoda, and K. L. R. Pavitt eds., Thinking About the Future: A Critique of the Limits to Growth, London: Sussex University Press.

Pearce, D.W. and R.K. Turner (1990) Economics of Natural Resources and the Environment, Hemel Hempstead, Harvester-Wheatsheaf.

Pearce, D.W. and E. Barbier, A. Markandya (1990) Sustainable Development Economics and Environment in the Third World, Aldershot: Elgar.

Pitchford, John D. (1974), Population in Economic Growth, NY: American Elsevier.

Randall, A. and M. Farmer (1995) Benefits, costs, and the same minimum standard of conservation, in D. Bromley (ed.), The Handbook of Environmental Economics, Oxford: Blackwell.

Razin Assaf and Efraim Sadka (1995), Population Economics, Cambridge MA: MIT Press.

Rebelo, Sergio (1991) Long run policy analysis and long run growth, Journal of Political Economy 99:500-21.

Ricardo, David (1817), Principles of Political Economy and Taxation, London: Everyman [1926].

Romer, P. M. (1986), Increasing returns and long run growth, Journal of Political Economy 94:1002-37.

Russet, B. (1990), Economic decline, electoral pressure and the initiation of interstate conflict, pp. 123-40 in C. Gochman and A.N. Sabrosky (eds.) Prisoners of War? Nation-States in the Modern Era, Lexington MA: Lexington Books.

Samuelson, Paul A. (1980), Economics, New York: McGraw-Hill.

Sato, R. and E. G. Davis (1971), Optimal savings policy when labor grows endogenously," Econometrica, 39: 877-897.

Schumpeter, Joseph (1961), The Theory of Economic Development: An Inquiry into Profits, Capital, Credit, Interest, and the Business Cycle, New York: Oxford University Press.

Simon Julian L.(1986), Theory of Population and Economic Growth. NY: Basil Blackwell.

Skaperdas, S., (1992) Cooperation, conflict, and power in the absence of property rights American Economic Review 82(4):720-739.

Selden T. and D. Song (1994) "Environmental quality and development: Is there a Kuznets curve for air pollution emissions?" Journal of Environmental Economics and Management, 27: 147-162.

Solow, R., (1997) Reply, Ecological Economics Symposium 22, 267-268.

Stiglitz, J. (1974), Growth with exhaustible natural resources: Efficient and optimal growth path, Review of Economic Studies, Symposium, 41: 123:137

Stiglitz, J.(1997), Reply. Ecological Economics Symposium, 269-270.

Stokey, N. (1998), “Are there limits to growth?” International Economic Review, 39: 1-31.

Tahvonen, O. and J. Kuuluvainen (1993), “Economic growth, pollution and renewable Resources,” Journal of Environmental Economics and Management, 24: 101-118.

Tollison, R. and Congelton, eds. (1995), The Economic Analysis of Rent Seeking, Elgar Reference Collection. International Library of Critical Writings in Economics, vol. 49. Aldershot, U.K.: Elgar

Taylor, M. (1987), The Possibility of Cooperation, Cambridge: Cambridge University Press.

Tisdell, C. (1990) Economics and the debate about preservation of species, crop varieties and genetic diversity, Ecological Economics, 2, 77-90.

Toman, M., J. Pezzey, and J. Kratkraemer (1998), Neoclassical economic growth theory, and sustainability, in Daniel W. Bromley, ed., Handbook of Environmental Economics, Blackwell: Cambridge, MA 139-165.

Tornell, A. A and P. R. Lane (1999), The voracity effect, American Economic Review 89: 22-46

Turner, R.K. (1993) Sustainability principles and practice, R.K. Turner (ed.), Sustainable Environmental Economics and Management, London: Belhaven Press.

Van Pelt, M.J.F. (1993) Ecologically sustainable development and project appraisal in developing countries, Ecological Economics, 7: 19-42.

Verdier T. (1995), Environmental pollution and endogenous growth: a comparison between emission taxes and technological standards,” in C. Carraro and J. Fillar (eds.) Control and Game Theoretic Models of the Environment, New York: Birckauser, 120-143.

World Bank (1990, 1992) World Development Report, Washington: The World Bank.

Young, J. T. (1991), Is the entropy law relevant to the economics of natural resource scarcity? Journal of Environmental Economics and Management, 21 (2), 169-179.

Table 1: Reviewed Literature

Model Taxonomy	Paper Section
Economic Growth without the Environment	3.0
Neoclassical and Endogenous Growth	3.1
Population Growth	3.2
Economic Growth with the Environment	4.0
Limits to Growth	4.1
Ecosystem Resilience	4.2
Growth with Environmental Stocks	4.3

Table 2: Stocks, Flows and Control variables

Variable	Definition
Stocks	
K	Total capital (machinery)
K_α	Capital used in production
K_β	Capital used by households
T	Total technology
T_α	Technology used in production
T_β	Technology used by households
P	Population
L	Available time
L_α	Time allocated for labor
L_β	Time allocated for leisure
L_σ	Time allocated for learning
H	Human Capital
S	Social Structure
NR	Non-renewable resources
R	Renewable resources
E	Environmental quality
Flows	
U	Quality of life
Q	Income in output units
E_α	Pollution from consumption
E_β	Pollution from production
I	Total investment
Control Variables	
C	Total consumption
I_H	Investment to acquire human capital
I_K	Investment in capital
$I_{T\alpha}$	Investment in production technology
$I_{T\beta}$	Investment in household technology
I_R	Investment in renewable resources
I_N	Investment in population planning
H_N	Harvesting of non-renewable resources
H_R	Harvesting of renewable resources

Table 3: (Utility, Stocks, Flows, and Implied Sustainability Concept

(Variable Definitions in Table 2)

Model Type	**Utility**	**Stocks**	**Flows**	**Implied Sustainability Concept**
Neoclassical Growth	U(c)	K, N	Q, U, C, I_K	Steady State Consumption and Capital
Endogenous Growth	U(c)	K, H, T	Q, U, C, I_K, I_T , I_H	Increasing consumption growth
Population Growth	U(c)	K, N	Q, U, C, I_K, I_P	Steady State Consumption and Capital
Limits to Growth	U(C, H_N)	K, N, NR	Q, U, C, H_N	***Disequilibrium consumption decline
Ecosystem Resilience	U(c)	NR, R, N	U, C, H_N, H_R, E_α, E_β, Q	Biodiversity Resources threshold