Making Long-Term Economic Growth Sustainable? Evaluating the Costs and Benefits

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ANALYSIS

Making long-term economic growth more sustainable: evaluating the costs and benefits

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Abstract

Currently, traditional development issues such as economic stagnation, poverty, hunger, and illness as well as newer challenges like environmental degradation and globalisation demand attention. Sustainable development, including its economic, environmental and social elements, is a key goal of decisionmakers. Optimal economic growth has also been a crucial goal of both development theorists and practitioners. This paper examines the conditions under which optimal growth might be sustainable, by assessing the costs and benefits of growth. Key environmental and social aspects are considered. The Ecol-Opt-Growth-1 model analyses economic–ecological interactions, including resource depletion, pollution, irreversibility, other environmental effects, and uncertainty. It addresses some important issues, including savings, investment, technical progress, substitutability of productive factors, intergenerational efficiency, equity, and policies to make economic growth more sustainable—a basic element of the sustainomics framework. The empirical results support growing concerns that costs of growth may outweigh its benefits, resulting in unsustainability. Basically, in a wide range of circumstances, long term economic growth is unsustainable due to increasing environmental damage. Nevertheless, the model has many options that can be explored by policy makers, to make the development path more sustainable, as advocated by sustainomics. One example suggests that government supported abatement programs are needed to move towards sustainable development, since the model runs without abatement were infeasible. The optimal rate of abatement increases over time. Abatement of pollution is necessary to improve ecosystem viability and increase sustainability. Further research is necessary to seek conditions under which alternative economic growth paths are likely to become sustainable.

Keywords: Costs and benefits; Economic growth; Sustainability

1. Introduction

At the dawn of the 21st century, humankind is facing many critical problems. Traditional development issues such as economic stagnation, persistent poverty, hunger, malnutrition, and illness as well as newer challenges such as worsening environmental degradation and accelerating globalisation demand attention. One key approach that has received growing attention is based on the concept of sustainable development or ‘development which lasts’ (WCED, 1987). Following the 1992 Earth Summit in Rio de

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Janeiro and the adoption of the United Nations' Agenda 21, the concept of sustainable development has become well accepted worldwide (United Nations, 1993).

While no universally acceptable practical definition of sustainable development exists as yet, the concept has evolved to encompass three major points of view: economic, social and environmental (see for example, Munasinghe, 1992). Each viewpoint corresponds to a domain (and system) that has its own distinct driving forces and objectives (Dopfler, 1979). The economy is geared mainly towards improving human welfare, primarily through increases in the consumption of goods and services. The environmental domain focuses on protection of the integrity and resilience of ecological systems. The social domain emphasises the enrichment of human relationships and achievement of individual and group aspirations. Recent work has sought to analyse these economic, social and environmental dimensions in a balanced manner.

At the same time, economic growth has long been pursued as a major objective in most countries, e.g. to improve human welfare and eradicate poverty. In particular, economic growth indicators like GNP are in common use to assess the success of national policies (World Bank, 2001). Traditional development based on growth theory has relied heavily on the paradigm of economic efficiency and optimality (in the dynamic sense).

One key question that follows is whether optimal economic growth can also be sustainable. In this context, appropriate indicators of economic, social and environmental development play a key role. Starting from sustainable development viewpoint, progress has been made in assessing the sustainability of the three types of indicators, but this approach does not provide insights as to whether the development path is optimal (i.e. maximum economic growth). By contrast, growth modelling optimises economic output, but is unable to guarantee sustainability (especially in the environmental and social dimensions).

The precise definition of sustainable development remains an ideal, elusive (and perhaps unreachable) goal. A more realistic framework called "sustainomics" was proposed, with a less ambitious, but more focused and feasible strategy that would merely seek to 'make development more sustainable' (Munasinghe, 1992, 2002). Such an incremental method is more practical, because many unsustainable activities can be recognised and eliminated. This approach seeks continuing improvements in the present quality of life at a lower intensity of resource use, hopefully, leaving behind for future generations an undiminished stock of productive assets—manufactured, natural and social capital—that will enhance opportunities for improving their quality of life.

In this paper, we pursue a more practical approach along the above lines, to analyse the optimality–sustainability issue. We will seek to value all costs and benefits of growth (including environmental and social aspects) to the extent possible, and maximise the resultant net benefits (i.e. benefits minus costs) within a conventional cost–benefit analysis (CBA) framework. Side constraints would be imposed, especially to ensure ecological sustainability. In this context, the links between macroeconomic policies and the environment are especially important (Munasinghe and Cruz, 1994).

Our analysis is carried out using a quantitative ecological growth model that comprehensively assesses the long run prospects of sustainable economic growth (Islam, 1998). More specifically, we will: (1) argue for the need for the consideration of social and environmental costs and benefits in evaluating growth strategies; (2) present a model in which the social and environment costs and benefits are operationally embedded; (3) demonstrate how the results of such an optimal growth model can be meaningfully utilised for (a) preparing and evaluating alternative growth strategies in terms of economic welfare and sustainability; (b) to investigate whether or not optimal growth is always sustainable growth (Islam and Craven, 2003); and (4) explore policy options to make growth more sustainable.

The next section of this paper surveys selected issues concerning economic growth and sustainability. Section 3 summarises and applies a model developed by Islam (1998); Islam (2001a,b). Finally, the results and their implications for sustainability, as well as some conclusions are provided in Section 4. To summarise, the quantitative modelling in this paper indicates that concern about the unsustainability of perpetual economic growth is justified.

2. Economic and non-economic costs and benefits of growth

There are several limitations of existing literature within this area. First, most studies investigate these issues qualitatively rather than in quantitative form (Mishan, 1971). Few studies exist, focussing on costs and benefits within an ecological model (Islam, 1998). Second, when economic costs and benefits are discussed, their impacts on the three domains are generally not distinguished. The costs and benefits of economic growth can affect the social or environmental domains in rather different ways. The question of sustainability is largely dependent on which type of costs and benefits are considered (Mishan, 1971; Daly and Cobb, 1990; Cobb and Cobb, 1994).

Some recent studies suggest that the costs of economic growth are higher than its benefits (Daly and Cobb, 1990; Jackson and Marks, 1994; Diefenbacher, 1994; Rosenberg and Oegema, 1995; Hamilton, 1998; Islam, 1998), but others disagree (Beckerman, 1994; Dodds, 1997; Gylfason, 1999). Therefore, economic growth models, which include the calculation and consideration of costs and benefits in a sound operational model, are needed. Although the possibility of economy wide planning on the basis of CBA has been proposed (Malinvaud, 1979), it has not been widely implemented (see Van den Bergh, 1991, 1996; Islam, 1998).

2.1. Issues relating to costs and benefits of economic growth

2.1.1. Evolution of the growth debate

The crucial role of natural resources in limiting growth was recognised as far back as Malthus (1798) who analysed impoverishment due to agricultural land constraints and exponential population growth. Subsequently, Ricardo (1817) explained how diminishing returns to land would impose checks on wealth and population. More recently, Koopmans (1973) sought to combine the natural capital in the 'cake eating' problem with manufactured capital, within a typical Ramsey growth model. The exploration of the links between pollution, natural capital and growth has continued ever since (Leontieff, 1970; Stiglitz, 1974; Solow, 1993; England, 2000). Other researchers have attempted to set out broader macroeconomic frameworks or models which explicitly include environmental variables in the analysis (Daly, 1991; Girma, 1992; Maler and Munasinghe, 1996; Conrad, 1999; Islam, 2001b). Munasinghe et al. (2001) provides a comprehensive review.

Following the second World War, economic growth was considered vital for improving both individual and collective welfare (Eltis, 1966; United Nations, 1972; Beckerman, 1974, 1992, 1993; Hufschmidt et al., 1983; Dodds, 1997; Manning and De Jonge, 1996; Gylfason, 1999). The benefits of higher incomes and material prosperity appeared to overshadow environmental and social concerns like pollution, natural resource exhaustion, and income inequality.

Some analysts used the environmental Kuznets curve (EKC) argument. While pollution might increase with growth, once society became richer and pollution reached unacceptable levels, additional resources would be expended to reduce pollution (Beckerman, 1992; Gylfason, 1999; World Bank, 1992). Likewise, as resources became scarcer, market prices would increase to prevent natural resource exhaustion—by encouraging shifts to substitutes or through technological improvements that increased resource supply or reduced levels of equilibrium usage. Even if the price mechanism failed, previous predictions of resource exhaustion had proven incorrect, and so any future predictions would also be incorrect.

The alternative view was that total costs of economic growth outweigh benefits, resulting in uneconomic growth (Daly, 2000) or impoverishing growth (Islam and Jolley, 1996). Other researchers have reported that the environmental and social benefits of growth accrued to richer groups whilst costs fell mainly on the poor (Adelman and Morris, 1973; Ahluwalia, 1975; Duloy, 1975; Fields, 1995; Munasinghe, 2002). Therefore, despite recent continually high periods of economic growth world wide, over one billion people now live in absolute poverty—the greatest number in human history (Pinstrup-Anderson, 1996).

Ayres (1996, 1998) and Grossman (1995) dispute the use of the EKC, arguing that current world pollution levels are low because developing countries world (75% of world population) have not fully industrialised, and, therefore, are not polluting at western levels. Also, beyond certain pollution thresholds, very rapid increases in damages occur (Osberg, 1992). The inverted-U curve is applicable mainly to local pollutants and not to globally significant pollutants like CFCs and other greenhouse gases (Ayres, 1996, 1998). Finally, it is not prudent to wait for the economy to 'self-correct', because survival depends on a constantly functioning environmental domain. Thus, environmental costs and benefits are also closely linked to sustainability.

Several recent reviews examine the environmental and social impacts of structural adjustment and other economy wide interventions that have been applied during the past two decades, especially in the developing countries (Munasinghe and Cruz, 1994; Munasinghe, 1996, 2002; Opschoor and Jongma, 1996; Panayotou and Hupe, 1996; Kessler and Van Dorp, 1998). On the positive side, liberalising policies have benefited both the economy and the environment. However, some growth inducing economy wide policies have increased environmental and social damage. In general, the remedy does not require reversal of the original reforms, but rather the implementation of additional complementary measures (both economic and non-economic) that reduce the negative impacts (Munasinghe and Cruz, 1994).

2.2. Linking sustainability and growth

2.2.1. Basic concepts of sustainable development

The Brundtland Commission first defined sustainable development as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED, 1987). A variety of descriptions have emerged subsequently (Pearce and Turner, 1989; Pezzey, 1992; Cesar, 1994; Faucheux et al., 1996). One recent definition states that sustainable development is "a process for improving the range of opportunities that will enable individual human beings and communities to achieve their aspirations and full potential over a sustained period of time, while maintaining the resilience of economic, social and environmental systems" (Munasinghe, 1994).

It is useful to compare the economic, environmental and social concepts of sustainability. Economic progress is evaluated mainly in terms of welfare (or utility)—measured as willingness to pay for goods and services consumed. Economic sustainability seeks to maximise the flow of income or consumption that could be generated while at least maintaining the stock of assets (or capital) which yield these beneficial outputs (Hicks, 1946; Solow, 1986; Maler, 1990). Economic efficiency plays a key role in ensuring both efficient allocation of resources in production, and efficient consumption choices that maximise utility. Problems arise in the valuation of non-market outputs (especially social and ecological services), while issues like uncertainty, irreversibility and catastrophic collapse pose additional difficulties (Pearce and Turner, 1990).

Environmental sustainability focuses on the overall viability and health of ecological systems—defined in terms of a comprehensive, multiscale, dynamic, hierarchical measure of resilience, vigour and organisation. Natural resource degradation, pollution and loss of biodiversity are detrimental because they increase vulnerability, undermine system health, and reduce resilience (Perrings and Opschoor, 1994; Munasinghe and Shearer, 1995). The notion of a "safe threshold" (and the related concept of "carrying capacity") are important, e.g. to avoid catastrophic ecosystem collapse (Holling, 1986).

Social sustainability seeks to reduce vulnerability and maintain the health (i.e. resilience, vigour and organisation) of social and cultural systems, and their ability to withstand shocks (Chambers, 1989; Bohle et al., 1994; Ribot et al., 1996). Strengthening social values and institutions (like trust and behavioural norms), and enhancing human capital (through education) will increase social capital—typically, the accumulation of capabilities for individuals and groups of people to work together to achieve shared objectives. This process will improve governance and the resilience of social systems. Preserving cultural diversity and cultural capital, strengthening social cohesion and networks of relationships, and reducing destructive conflicts, are integral elements of this approach. In summary, for both ecological and socio-economic systems, the emphasis is on improving system health and its dynamic ability to adapt to change across a range of spatial and temporal scales, rather than the conservation of some 'ideal' static state.

2.2.2. Sustainability of growth

Within a growth model, a simplified approach would be to value all costs and benefits (including environmental and social aspects), and optimise the resultant net benefits (i.e. benefits minus costs) within a conventional CBA framework. Side constraints would ensure sustainability, based on critical variables like the rate of non-renewable resource depletion, rate of net harvesting of renewable resources over their regeneration rate, polluting emissions, pollution reducing technologies, and the capacity to assimilate such technical progress. Although beyond the scope of this model, we note that where environmental and social assets cannot be monetarily valued, it may be easier to measure them in non-monetary units. Furthermore, such non-monetary indicators (which are not directly comparable), could be assessed using techniques like multicriteria analysis (MCA) (Munasinghe, 1992).

One view (among many) of sustainability requires non-negative net environmental degradation in the economy. Others have defined sustainability in terms of non-declining income, consumption or welfare (Islam, 2001a). Basically, such sustainability criteria require that an economic–ecological system remains viable enough to support the needs and economic activities of current and future generations. A key question is whether there is an absolute limit on economic growth imposed by ecological (and social) constraints (Islam, 1998). If so, sustainability is highly dependent on social and environmental costs and benefits.

In our growth model, we adopt a more limited view of social costs and benefits. It is difficult to include the broader concept of social capital. Instead, only social costs and benefits which can be readily valued in monetary units, are considered. Typical costs include the problems of urbanisation, worsening income distribution, commuting and ugly cities, whereas the benefits include improved transport, communications, and standards of living. If costs exceed benefits and growth becomes unsustainable, it would be desirable to restructure growth, to make net benefits positive (Munasinghe, 1992).

The second set of costs and benefits are environmental. Costs include pollution, and reduction of natural resources and bio-diversity, while benefits include technological innovation and less damaging resource extraction, substitution away from scarce natural resources, and pollution abatement. Pollution may fall if EKC-type mechanisms apply (Beckerman, 1992; Munasinghe, 1999; Panayotou, 2000). Growth accompanied by reduced pollution and increased substitution away from natural resources is likely to be sustainable. Alternatively, if environmental costs of economic growth exceed benefits (Meadows et al., 1972; Islam, 1998), the outcome is both unsustainable and impoverishing (Islam and Jolley, 1996).

Physical laws dictate that matter can neither be created nor destroyed, and our environment is self contained. Thus, the earth's resources are finite (Georgescu-Roegen, 1971, 1981; Boulding, 1992). Resources are not used but transformed into waste that must be absorbed by the environment. Many argue that perpetual, material-intensive growth is unsustainable (Daly, 1971; Meadows et al., 1972; Daly and Cobb, 1990; Cobb and Cobb, 1994; Kendall and Pimento, 1994; Brown, 1996; Ayres, 1998; Brown, 1998).

3. Modelling environmental and economic costs and benefits of growth

The remainder of this paper empirically tests the possibility of sustainable long term economic growth using a dynamic optimisational growth model with ecological constraints (Islam, 2001b). The model considers both social and environmental costs and benefits of economic growth, with greater emphasis on environmental aspects.

3.1. Ecol-Opt-Growth-1 model

The Ecol-Opt-Growth-1 model (first developed in Islam, 2001b) is a dynamic optimal growth model with ecological constraints (Cesar, 1994; Faucheux et al., 1996; Kolstad and Krautkraemer, 1993; Pearce and Turner, 1989; Pezzey 1992). It analyses relationships between the long-term costs and benefits of economic growth, with emphasis on sustainability imposed by ecological constraints to growth (see Appendix A). The model is developed within the structure of optimal planning theory by embedding the elements of an optimal growth program (Chakravarty, 1969; Heal, 1973).

It is assumed in the model that social welfare at a given point in time is a function of consumption and environment quality. In the optimal growth framework, the social planner maximises intertemporal social utility by choosing the optimal trajectories of consumption, investment and pollution abatement variables. The model finds optimal growth paths for resource extraction, environmental quality and consumption that maximise the objective function subject to the ecological–economic constraints.

Economic equations of the Ecol-Opt-Growth-1 model (see full model in Appendix A) define major aggregate economic equations and ratios of the economy, such as aggregate production per capita, consumption of GDP, capital accumulation, technical progress, population growth, interest rate, saving rate, etc. The ecological constraints are based on the following principles: natural resources are exhaustible, cumulative waste emissions degrade the environment, environmental quality affects economic activities, and investments in capital, R&D, pollution control and recycling are beneficial. These equations apply under various resource extraction regimes and sustainability conditions. Social constraints are represented through simple sustainability rules and indicators focusing on excess waste accumulation rates, resource shortage indicators and total damage indicators. In addition, there are policy and cost-benefit analysis equations focusing on waste abatement and appropriate abatement rates. A growth path is deemed unsustainable if the costs outweigh the benefits, e.g. this may involve monotonically rising pollution levels and declining stocks of non-renewable resources.

Thus, the model highlights both social and environmental aspects of economic growth by establishing a crucial relationship between social welfare, consumption of goods and services, capital accumulation, technical progress, ecology and economic growth in a growth maximising framework. Eleven models runs are shown. Runs 1–9 are optimising ones, with different objective, production and investment functions (see Table 1). Model runs 10 and 11 are forecasts without an objective function. The growth process of the economy is determined by: (a) capital; (b) technical progress resulting from government expenditure for R&D; education, learning by doing and accumulation of knowledge in the private sector; (c) population; and (d) environmental quality that is affected by pollution, government expenditure for environmental control, and resource use.

3.2. Methodology

Ecol-Opt-Growth-1 is numerically implemented as a discrete dynamic optimisation problem by using GAMS (Brooke et al., 1997). The Ecol-Opt-Growth-1 model has been specified and solved for finite planning horizon of eight periods/decades (finite vs. infinite horizons are discussed in Chakravarty, 1969).

Table 1
Different model specifications/runs

Model run	Model type	Objective function (see Appendix A)	Investment function (see Appendix A)	Investment function/ variable	Pure time preference rate (%)
Run 1	Optimisation	1(a)	2(a)	Sectoral/aggregate	3
Run 2	Optimisation	1(b)	2(a)	Sectoral/aggregate	3
Run 3	Optimisation	1(a)	2(b)	Aggregate investment as a control variable	3
Run 4	Optimisation	1(c)	2(a)	Sectoral/aggregate	3
Run 5	Optimisation	1(d)	2(a)	Sectoral/aggregate	3
Run 6	Optimisation	1(d)	2(b)	Aggregate investment as a control variable	3
Run 7	Optimisation	1(a)	2(a)	Sectoral/aggregate	0
Run 8	Optimisation with non-declining constraints on environmental quality	1(a)	2(a)	Sectoral/aggregate	3
Run 9	Optimisation with abatement=0	1(a)	2(a)	Sectoral/aggregate	3
Run 10	Forecasting	–	2(a)	Sectoral/aggregate	–
Run 11	Forecasting without abatement	–	2(a)	Sectoral/aggregate	–

The essential characteristics of the model may be summarised as follows:

1. it is a multi-sectoral global (total ecosystem) growth model;
2. it is an optimisation growth model, based on a holistic approach to economic development including elements of social choice, ethics, and political economic issues (see Dopfler, 1979);
3. the model is specified for a generic economic system rather than for defending any particular type of growth theory (Burmeister and Dobell, 1970);
4. the ecosystem is in equilibrium initially, but the trajectory can lead to disequilibrium depending on the growth process;
5. it includes economic and ecological constraints and feedbacks, based on the thermodynamic laws of the ecosystem;
6. all the crucial variables are determined endogenously in the model; and
7. issues of intertemporal equity are modelled through specification of the social discount rate and values of the perceived variables and parameters.

3.2.1. Model specification: data, boundary conditions and transversality

Ecol-Opt-Growth-1 was solved for 11 sets of specifications. In the following sections, the results of these different models are reported. Each model spans eight periods, each of 10 years duration. The major differences arise from variations in their objective functions, production functions, time preference rate, etc. (see Table 1 for the different model specifications).

Table 2
Parameter values

a_B	500	N_{crit}	15 000
α	0.098	P_{crit}	450
a_P	0.5	R	0.05
A_{Pop}	5.0	ρ	0.03
A_{rec}	0.8	s_1	0.5
A_{wa}	0.95	s_2	0.5
b_I	550	K_I	1.0
b_{crit}	100	p_N	1
B_{wa}	18	p_S	1
C_n	30 000	κ	100
C_{wa}	1.2	θ_2	2
d	1	θ_1	0.00144
δ	0.025	b_1	0.0686
ε	0.096	b_2	2.887
E_{crit}	0.8	α_1	0.3
μ	0.1	β_1	0.5
		γ_1	0.1
		δ_1	0.1

Table 3
Initial conditions

$K_Q(0)=43.0$	$K_i(0)=3.6$	$K_{wa}(0)=5.0$
$Krec(0)=5.0$	$K_N(0)=30.0$	$K_S(0)=30.0$
$Pop(0)=100.0$	$T_{rd}(0)=100.0$	$R_{sup}(0)=300.0$
$N(0)=10\,000.0$	$S(0)=3000.0$	$P(0)=100.0$
$Z(0)=Q(0)+I(0)$		

Following the mainstream view on the social discount rate, a pure time preference value of 3% was used. The present model was also solved with zero social discount rate in model run 7. The data for the model was largely obtained from Van den Bergh (1991), except for data related to the objective function and transversality conditions (see Islam, 2001b). Table 2 shows the data adopted in Ecol-Opt-Growth-1 Model.

In addition, the initial and the terminal values of the variables are also adopted from Van den Bergh (1991). The boundary conditions on the state and control variables applied are shown in Table 3.

4. Results

4.1. Costs and benefits of economic growth and sustainability

In the basic Ecol-Opt-Growth 1 model, the key problem is to find the optimal trajectories of various economic and ecological variables concerned with sustainability. The results have generated various scenarios for the eco-system over the planning period, which satisfy the static and dynamic efficiency conditions of resource allocation numerically determined by the modal algorithm. The path of the major economic (GDP) and sustainability (pollution and stock of non-renewable resources) variables are discussed below (see Appendix A for further details).

The model results on optimal values of different variables and parameters have been determined by a set of complex, interrelated and integrated factors, such as time, different optimality criteria, modelling factors (forms of various equations, solution algorithm, computer programming, etc.), and the nature of (economic, ecological, socio-political) systems incorporated in the model, which reflect differing social preferences and perceptions about systems, intertemporal allocation and equity. Since the above factors vary in different model runs, the optimal solutions or the values of the variables also change. One of these variations (across time, systems and social preferences) is the possibility of an economy generating negative net benefits with shifting patterns switching between benefits and costs over time. A discussion of these differences in modelling and results is provided below.

The results show the basic unsustainability arising from the infeasible model solutions, as shown in the alternative model runs summarised in Table 1. The outcomes (see Figs. 1–3) show a progressive tendency towards unsustainability in the economy, with deteriorating environmental quality, stronger ecological impacts, increasing resource shortages, and an increasing trend for both the waste indicator and the total pollution damage, over the planning period. The paths of resource use and extraction for different model runs vary substantially. All runs show increases in the use and extraction of natural resources to meet resource needs for optimal economic growth. As the economy grows the ecological economy generates progressively higher amounts of pollution, according to the specified pollution function.

The greatest increase in GDP, over all simulation periods, is found in model run 4 where the growth objective is the maximisation of output. However, growth in non-renewable levels also accelerates and ends at the lowest level among all model runs. During this run, pollution increases steadily. Similar results exist for run 10 which is in the forecasting mode. Accelerated growth in GDP occurs simultaneously with extraction of non-renewable resources. As with model run 4, there are steady increases in pollution levels.

Not all the model runs produce the same results. Within model runs 3 and 5, GDP growth rates are low, extraction rates of non-renewable resources only fall slowly and growth in pollution is also slow. The important factors which are present in these two versions of the model are the concerns for terminal capital and environmental quality. These two factors appear in the objective function of the models. Following the incremental approach towards sustainable development advocated by sustainomics, the model

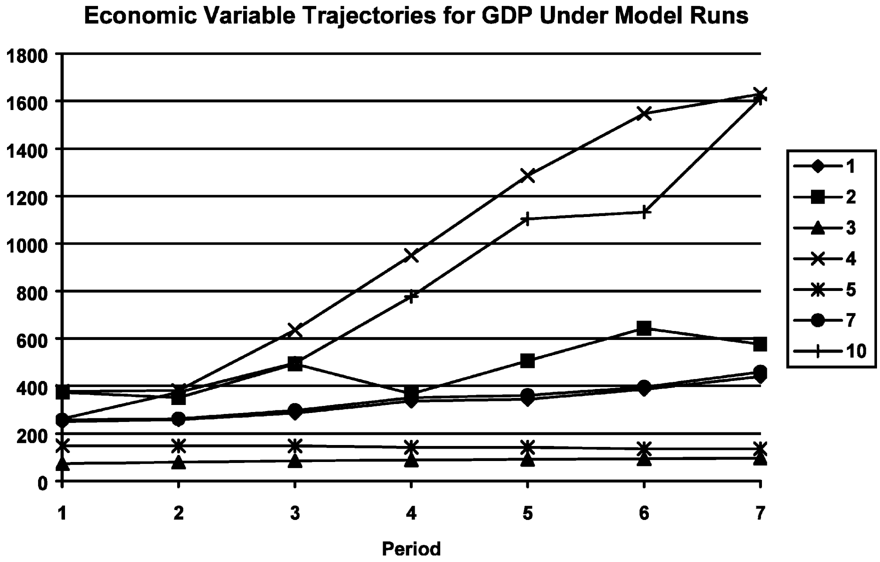

Fig. 1. Economic variable trajectories for GDP under model runs.

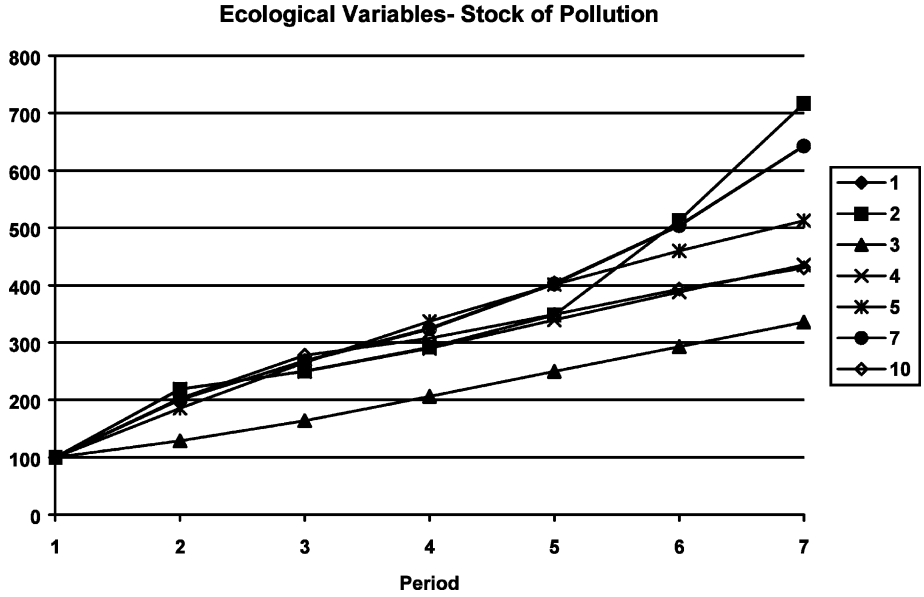

Fig. 2. Ecological variables—stock of pollution.

shows that social concerns for increasing environmental quality and higher capital base help to make economic growth more sustainable.

Table 4 shows the impacts of economic growth. We have specified the values of costs and benefits as included in the model, as well as the values of consumption and total damage (as alternative indicators of benefits and costs). Both measures show a steady increase in the costs of growth relative to benefits, over time. Table 4 also shows optimal abatement policies, and costs and benefits of abatement policies in the various model runs. It is evident

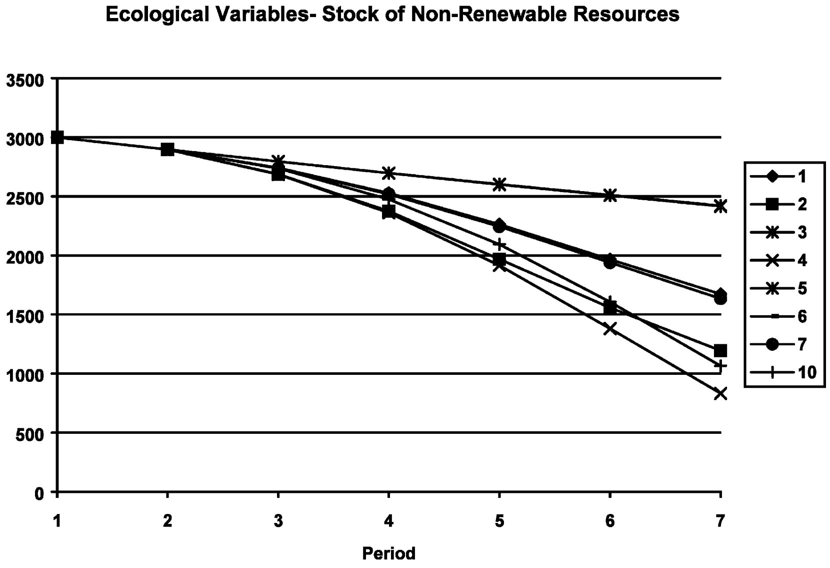

Fig. 3. Ecological variables—stock of non-renewable resources.

Table 4
CBA of economic growth

		Period						
	Run	1	2	3	4	5	6	7
The rate of abating of pollution	1	0.649	0.715	0.774	0.797	0.823	0.823	0.829
	2	0.649	0.748	0.816	0.846	0.858	0.859	0.860
	3	0.649	0.645	0.646	0.640	0.640	0.633	0.633
	4	0.649	0.762	0.828	0.862	0.891	0.907	0.918
	5	0.649	0.653	0.666	0.669	0.676	0.678	0.677
	7	0.649	0.718	0.778	0.801	0.827	0.828	0.834
	10	0.649	0.730	0.812	0.848	0.882	0.900	0.911
Benefit of abatement	1	21.458	23.760	29.590	43.575	48.015	64.558	82.282
	2	3658.399	3102.246	8785.608	4115.520	14 486.03	29 509.16	20 870.88
	3	32.825	44.683	58.407	66.251	71.871	75.811	80.565
	4	−1151.29	−1213.98	−1280.05	−1349.70	−1423.12	−1500.50	−1582.07
	5	317.641	309.024	293.614	257.721	242.112	211.223	204.040
	7	1325.921	1506.854	2265.578	4154.411	5021.287	7625.489	11 458.57
	10	1394.172	4034.998	8161.570	30 173.21	69 035.39	60 324.68	150 265.9
The total cost of abatement	1	4.934	6.713	9.369	12.008	13.466	15.086	17.603
	2	7.371	10.407	18.842	15.490	22.346	28.468	25.551
	3	1.447	1.542	1.669	1.683	1.738	1.720	1.763
	4	7.434	11.960	25.298	42.468	63.264	80.012	87.366
	5	2.928	2.966	3.135	3.056	3.147	3.047	3.034
	7	5.079	6.907	9.875	12.691	14.324	15.749	18.659
	10	5.175	10.314	18.680	33.127	52.734	57.303	84.604
Total benefits of growth	1	4.948	1.117	−5.015	46.031	97.073	138.977	155.390
	2	39.135	−366.702	−149.168	14.418	170.252	199.656	186.072
	3	−66.655	−48.974	−31.243	−27.913	−30.199	−34.102	−37.650
	4	−1151.29	−1213.98	−1280.05	−1349.70	−1423.12	−1500.50	−1582.07
	5	−1151.29	−1213.98	−1280.05	−1349.70	−1423.12	7.893	0.774
	7	0.066	−4.010	−7.643	45.306	98.743	141.921	160.545
	10	−547.061	−579.510	−1279.94	−1349.59	−1423.00	−1500.38	−145.155
Total costs of growth	1	13.065	103.312	153.660	200.626	237.792	288.016	343.818
	2	53.217	146.283	203.458	195.770	263.286	350.748	386.457
	3	−109.623	−77.088	−44.441	−14.672	12.164	34.636	55.878
	4	54.067	155.932	232.766	306.705	376.925	434.472	475.710
	5	−39.094	34.799	80.239	108.550	134.705	151.519	170.380
	7	15.970	105.448	157.301	204.512	242.792	290.882	349.019
	10	17.842	143.254	220.103	291.848	362.528	396.639	472.346
Net benefits of growth	1	−8.117	−102.195	−158.675	−154.595	−140.719	−149.039	−188.428
	2	−14.082	−512.985	−352.626	−181.352	−93.034	−151.092	−200.385
	3	42.968	28.114	13.198	−13.241	−42.363	−68.738	−93.528
	4	−1205.36	−1369.91	−1512.82	−1656.41	−1800.05	−1934.97	−2057.78
	5	−1112.2	−1248.78	−1360.29	−1458.25	−1557.83	−143.626	−169.606
	7	−15.904	−109.458	−164.944	−159.206	−144.049	−148.961	−188.474
	10	−564.903	−722.764	−1500.04	−1641.44	−1785.53	−1897.02	−617.501

that the benefits of the abatement are substantially higher than its costs.

4.2. Concluding remarks

Sustainable development, including its economic, environmental and social elements, is a key goal of decision makers. Optimal economic growth has also been a crucial goal of both development theorists and practitioners. This paper has examined whether optimal economic growth is sustainable, and the conditions under which this might or might not be the case, by assessing the costs and benefits of growth under different scenarios.

The Ecol-Opt-Growth-1 model analyses key interactions between the economic and ecological systems, including resource depletion, pollution, irreversibility, other environmental effects, and uncertainty. It addresses important economic issues, including savings, investment, technical progress, substitutability of factors of production, and policies to make economic growth more sustainable—a basic element of the sustainomics framework. It also examines efficiency and fairness in intertemporal allocation of natural, environmental and physical resources, the contradictory effects of the social discount rate on optimal growth and sustainability, and relative affects of key variables and parameters on growth. Key social and environmental aspects are considered.

The empirical results support growing concerns that the costs of economic growth may outweigh its benefits, resulting in unsustainability. Environmental costs and benefits have more impact on sustainability, although economic costs and benefits are also important. Basically, it has been determined that in a wide range of circumstances, long term economic growth is unsustainable due to increasing environmental costs.

This paper adds to the growing evidence indicating that perpetual economic growth is unsustainable. Nevertheless, the Ecol-Opt-Growth-1 model has many degrees of freedom and variables that can be explored by policy makers, to make the development path more sustainable, as advocated by sustainomics. One example suggests that government supported abatement programs are needed to move towards sustainable development, since the model runs without abatement were infeasible. In most runs, the optimal rate of abatement increases over time. Therefore, abatement of pollution is necessary to improve ecosystem viability and make development more sustainable.

The modelling experiments, therefore, confirm the view that optimal economic growth may not always be sustainable (see Munasinghe et al., 2001; Islam and Craven, 2003). Further research is necessary to seek specific conditions under which alternative economic growth paths are likely to become sustainable.

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Appendix A

The model is adapted from Islam (2001b). The complete model including objective functions and constraints (economic, ecological and social), is presented below.

(A) Social Welfare Function

To study the sustainability implications of numerical economic-ecological growth models, a number of different growth objectives embedded in various social welfare objective functions are specified (Equations 1a to 1f):

1) The objective function maximises the sum of discounted social utilities:

$$\sum_{t=1}^{t_T} (1+\rho) - t\{U[c(t),\ Pop(t)] + \kappa K(t)\} \qquad (1a)$$

The utility function has the logarithmic functional form:

$$U[c(t),\ Pop(t)] = Pop(t)\log c(t) \qquad (1c)$$

2) An alternative utility function in Cobb–Douglas form was also specified:

$$\max \sum_{t} (1+\rho)^{-t}(C(t)^{0.8}E(t)^{0.2} + \kappa K(T)) \qquad (1d)$$

3) In another case, the objective maximised environmental quality:

$$\max \sum_{t} (1+\rho)^{-t}(E(t) + \kappa K(T)) \qquad (1e)$$

4) The fourth type of social welfare function involved the maximisation of output:

$$\max \sum_{t} (1+\rho)^{-t}(Y(t) + \kappa K(T)) \qquad (1f)$$

(B) Economic Constraints

Economic equations of the model define major economic aggregates and ratios of the economy.

Investment Functions

1) Final goods sector investment

$$I_Q(t) = 0.04K_Q(t) + [I(t) - 0.04K_Q(t) - \delta_K(K(t) - K_Q(t))]K_Q(t)/K(t)$$

2) Capital goods sector investment

$$I_i(t) = \delta_K K_i(t) + [I(t) - 0.04K_Q(t) - \delta_K(K(t) - K_Q(t))]K_i(t)/K(t),$$

3) Aggregation of capital goods sectoral investment

$$I(t) = \sum_{i \in K} I_i(t)$$

Capital Accumulation

1) Capital accumulation in the final goods sector

$$K_Q(t+1) = K_Q(t) + I_Q(t) - 0.04K_Q(t)$$

2) Investment sectoral capital equations

$$K_i(t+1) = K_i(t) + I_i(t) - \delta_K K_i(t), \quad i \in \{i,\ wa,\ rec,\ N,\ S,\}$$

3) Aggregation of investment sectoral capital

$$K(t) = \sum_{i \in K} K_i(t) \tag{2b}$$

4) Total capital stock

$$K(t) = \sum_{j \in K+Q} K_j(t)$$

Technological Progress: Framework of Knowledge Economy

1) Technological growth rate equation

$$T_{rd}(t+1) = T_{rd}(t) + (0.1 - \alpha e_e)I(t) + (0.1 - \varepsilon e_e) \times [O_{rd}(t) + 0.5 + Q(t) + I(t) - Y(t)]$$

2) The technological growth lag equation

$$Y(t+1) = Q(t) + I(t)$$

Economic Ratios

1) Savings rate

$$s(t) = I(t)/Y(t)$$

2) Capital output ratio

$$ky(t) = K(t)/Y(t)$$

3) Capital labour ratio

$$kl(t) = K(t)/Pop(t)$$

4) Interest rate

$$R(t) = \alpha_1 Y(t)/K(t)$$

5) Aggregate wage rate/share

$$W(t) = \beta_1 Y(t)/L(t)$$

Population Growth

Population growth is endogenously determined consumption and population growth rate.

$$Pop(t+1) = Pop(t) + 0.01(a_{pop}Pop(t) - C(t))$$

(C) Ecological Constraints and Conditions

The following principles apply: natural resources are exhaustible, cumulative waste emissions degrade the environment, environmental quality affects economic activities, and investments in capital, R&D, pollution control and recycling are beneficial.

Resource Extraction

Supply equations for three major resources are:

1) Renewable resource extraction rate

$$R_n(t) = \min\{1.8K_n(t)^{0.8}(N(t)E(t))^{0.2},\ R_{nperv}(t)\}$$

2) Non-renewable resource extraction rate

$$R_s(t) = \min\{0.9K_s(t)^{0.7}S(t)^{0.3},\ R_{sperv}(t)\}$$

3) Recycled resource supply

$$R_{rec}(t) = a_{rec}\,\frac{T_{rd}(t)}{T_{rd}(t)+107}\,\frac{K_{rec}(t)}{K_{rec}(t)+8}\,W_{rec}(t)$$

Supply and Stock of Natural Resources

Equations governing major resources are:

1) Change in the stock of renewable resources

$$\begin{aligned}N(t+1) = {} & N(t) + rN(t(\min\{E(t)/E_{crit},\ 1\} \\ & - N(t)/C_N) - R_N(t)\end{aligned}$$

2) Change in stock of slowly renewing resource

$$\begin{aligned}B(t+1) = {} & \{B(t) + 10^{-5}[a_B + \min\{E(t)/E_{crit},\ 1\} \\ & - 5I(t) + 0.2K_Q(t) + 5\delta_K(K(t) \\ & - K_Q(t)) - 0.1(a_{pop} - C(t) \\ & /Pop(t))Pop(t) - 10R_N(t) \\ & - 4R_S(t)B(t)]\}\end{aligned}$$

3) Change in stock of non-renewable resources

$$S(t+1) = S(t) - R_S$$

4) Change in the total supply of resources

$$\begin{aligned}R_{sup}(t+1) = {} & R_{sup}(t) + R_N(t) + R_s(t) - R_{rec}(t) \\ & - \frac{T_{rd}(t)+600}{T_{rd}(t)+400}\,Q(t) \\ & + \frac{T_{rd}(t)+550}{T_{rd}(t)+400}\,I(t)\end{aligned}$$

5) Required extraction rate of resources

$$R_{new}(t) = \frac{(T_{rd}(t)+600)5K_Q(t)\min\left\{\frac{E(t)+2.2}{E_{crit}+2.2},\ 1\right\} + (T_{rd}(t)+b_l)k_lK_l}{T_{rd}(t)+400} - K_{rec}(t)$$

Waste and Pollution Accumulation

1) Waste and pollution accumulation functions are:

$$\begin{aligned}W_{em}(t) = {} & (W_{Q,I}(t) - R_{wa}(t)) + (1 - s_2) \\ & \times (W_{rec}(t) - R_{rec}(t))\end{aligned}$$

$$\begin{aligned}P(t+1) = {} & P(t) - a_P P(t)^{0.9}\min\{E(t)/E_{crit},\ 1\} \\ & + W_{em}(t)\end{aligned}$$

2) Gross waste from final goods and investments sector

$$W_{Q,I}(t) = \frac{200Q(t) + (b_l - 400)I(t)}{T_{rd}(t)+400}$$

3) Change in the stock of stored waste

$$\begin{aligned}S_w(t+1) = {} & S_w(t) + S_w(t)R_{wa}(t)(W_{rec}(t) \\ & - R_{rec}(t))\end{aligned}$$

4) Waste amenable for recycling

$$\begin{aligned}W_{rec}(t) = {} & Q(t) + 0.04K_Q(t) + \delta_K(K(t) - K_Q(t)) \\ & + (1 - s_1)R_{wa}(t)\end{aligned}$$

5) Material balance condition

$$G(N,\ E)(t) = M(P,\ E)(t)$$

Social Constraints (Concerns and Conditions)

Perceived social value judgements and preferences about the ecosystem, the economy and sustainability enter into the model (Tinter and Sengupta, 1969):

Sustainability Indicators and Constraints

Some simple sustainability rules and indicators are:

1) Excess waste accumulation rate

$$W_{TOO}(t) = \min\left\{1,\ \frac{a_P P(t)^{0.9}\min\{E(t)/E_{crit},\ 1\}}{W_{em}(t)}\right\}$$

2) Ecological effect indicator

$$E(t) = \max\{0.2,\ \min\{1,\ N(t)/N_{crit}\}\min\{1,\ B(t)/B_{crit}\}\min\{1,\ P_{crit}/(P(t)+1)\}\}$$

3) Resource shortage indicator

$$R_{short}(t) = \min\{1,\ R_{perc}(t)/R_{new}(t)\}$$

4) Total damage indicator

$$DM(t) = Y(t)\theta_1(t)P(t)^{\theta_2}$$

Perceived or Subjective Rate of Resource Extraction

1) Perceived rate of renewable resource extraction

$$R_{N,perc}(t) = \max\left\{0,\ dp_N N(t) + (1-d)\min\{E(t)/E_{crit},\ 1\}rN(t) \times \left(1 - \frac{N(t)}{\min\{E(t)/E_{crit},\ 1\}C_N}\right)\right\}$$

2) Perceived rate of non-renewable resource extraction

$$R_{S,perc}(t) = p_s S(t)$$

3) Total subjective rate of resource extraction

$$R_{perc}(t) = R_{N,perc}(t) + R_{S,perc}(t)$$

(E) Policy and Cost-Benefit Analysis Equations: Waste Abatement and its Rate

1) Waste abatement

$$R_{wa}(t) = a_{wa}\,\frac{K_{wa}(t)}{K_{wa}(t)+1.2}\,\frac{T_{rd}(t)}{T_{rd}(t)+18}\,W_{Q,I}(t)$$

2) Abatement rate

$$ar(t) = R_{wa}(t)/W_{Q,I}(t)$$

Abatement Costs and Benefits

Following work by Nordhaus (1994) and others, relevant abatement equations are:

1) Benefits of abatement

$$BN(t) = Y(t)\theta_1 R_{wa}(t)^{\theta_2}$$

2) Abatement costs

$$ac(t) = Y(t)b_1 ar(t)^{b_2}$$

Costs and Benefits of Economic Growth

1) Benefit of growth

$$BG(t) = Pop(t)[\log\,(C(t)/Pop(t))]$$

2) Cost of growth

$$CG(t) = Pop(t)[\log(DM(t)(t)/Pop(t))]$$

3) Net benefit = BG(t)−CG(t)

(F) Other Conditions: Boundary and Transversality Conditions

1. Initial values of variables and parameters. Given
2. Terminal constraint on capital

$$(1+\rho)^{-T}K(T) = I(T)$$

3. Transversality function(term active in the objective function in the terminal period)

$$(1+\rho)^{-T}\kappa K(T)$$

(G) Model Notations

The definitions of parameters, variables and functions are:

Parameters

α_1, β_1, γ_1, δ_1	elasticities of output with respect to different inputs
b_1	fraction of output per unit emissions control
b_2	exponent of control cost
ρ	pure time preference
D	dummy for basing resource availability on stock or sustainable flow

p_N	part of stock of renewables that is regarded as available for use now
p_S	part of stock of non-renewables that is regarded as available for use now
s_1	part of treated waste going into storage, useless waste
s_2	part of waste after recycling going into storage, useless waste
δ	production increase parameter in technology formation equations
θ_1	fraction of output per degrees c squared
θ_2	exponent of damage function
a_p	pollution assimilative coefficient
a_b	slowly regenerative resource generation coefficient
γ	renewable resource use coefficients
a_{wa}	waste abatement coefficient
E_{crit}, B_{crit}, P_{crit}	critical levels of environmental quality, slowly renewable resources and pollution
k_1	coefficient for resource demand by investment capital

Flow variables

C	consumption
E	indicator for overall environmental quality
e_e	ecological effect indicator for technical progress
I	total investment in replacement and new capital
$I_i(i\varepsilon K)$	investment in sector i
K_{occ}	used economic capital
L_D	employment (jobs)
L_S	labour force
O_{rd}	social investment in research and development
Q	output of final goods sector
R_{dem}	total productive and consumptive demand for resources
R_n	renewable resource extraction
R_{nperc}	subjective/perceived availability (rate) of all resources
R_s	non-renewable resource extraction
R_{nperv}	subjective/perceived availability (rate) of renewable resources
R_{sperc}	subjective/perceived availability (rate) of non-renewable resources
R_{short}	perceived shortage of resource supply to demand
R_{wa}	abated/treated waste
R_{new}	demand for new resources
U	long term labour market unbalance (unemployment)
W_{em}	emitted waste
$W_{Q,I}$	gross waste from final and investment goods sectors
W_{rec}	waste amenable for recycling
W_{too}	indicator for unsustainability of waste emission

Stock variables

B	a slowly renewable resource (soil, land, water)
K	total economic capital
K_Q	productive sector capital
K_I	investment sector capital
K_{wa}	waste abatement/treatment capital
K_{rec}	recycling capital
K_n	renewable resource extraction capital
K_s	non-renewable resource extraction capital
C_n	available maximum amount of renewable resources
N	the stock of renewable resources
P	stock of pollution in natural mediums or organisms
Pop	human population level
R_{sup}	total availability (supply) of natural resource materials in inventory
S	the stock of non-renewable resources
S_{wa}	the stock of useless, stored waste
T_{rd}	progress indicator of environmental technology
Y	total ‘real’ output/GDP
R_{rec}	recycling resources

Economic and ecological functions

α	general investment effect parameter on technology
A	assimilation function
ac	abatement cost
ar	abatement rate
BG	benefit of growth

b_i ($i = 1 \ldots 5$)	regeneration and damage functions of slowly renewable resources
CG	cost of growth
c_Q	ratio of resource input to material output in final goods sector
c_I	ratio of resource input to material output in investment goods sector
$D_i(i \varepsilon K)$	discarded capital
DM	total damage
dv	damage avoided by control
ε	effect of social R&D investment and part of production increase on technology
F_Q	unrestricted production function final goods sector
F_I	unrestricted production function investment goods sector
F_N	unrestricted production function renewable resource extraction sector
F_S	unrestricted production function non-renewable resource extraction sector
F_i^{-1}($i = 1 \ldots 6$)	determine for each sector used capital
f_{wa}	part of production waste that is abated/treated
f_{rec}	part of waste amenable for recycling that is recycled
G	regeneration function of renewable resource capacity
G_o	regeneration function
H	environmental quality function
ky(t)	capital output ratio
kl(t)	capital labour ratio
M(t)	waste assimilation
s(t)	savings rate
R(t)	interest rate
W(t)	wage rate

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