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Modelling sustainable development: systems dynamic and input–ouput approaches

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Abstract

This paper discusses alternative approaches to modelling economy–environment systems from the perspective of sustainable development. We distinguish between systems' dynamic methods and economic approaches, including input–output (I/O) models. We then discuss the structure of two models constructed for Scotland. Firstly, a hierarchical, dynamic model is used to look at long-term trends in population, resource use and pollution. Secondly, an environmentally extended I/O model is used to estimate the effects of economic policy and structural change on pollution levels and output. We conclude with some comments on the possible future developments in modelling sustainable development. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Sustainable development has become an important part of international and national approaches to integrating economic, environmental, social and ethical considerations so that a good quality of life can be enjoyed by current and future generations for as long as possible. The broad concept of sustainable development gained prominence after the publication of the so-called Brundtland Report 'Our Common Future' (WCED, 1987). At the Earth Summit meeting held in Rio de Janeiro in 1992 many national governments pledged themselves to making development sustainable by the early years of the new millennium. Over the last decade numerous governments have pledged themselves to make this concept operational in national and local planning. The Australian Federal Government has developed an Ecologically Sustainable Development strategy (ESD, 1991; Moffatt, 1992) and similarly UK has adopted and revised a national strategy (HMSO, 1994).

Research has produced numerous indicators of sustainable development so that it is possible to gain some insight into whether or not an area or region or nation is on a trajectory of sustainable development (Moffatt, 1996; Hanley et al., 1998). Amongst the measures developed to indicate sustainability have been economic measures such as genuine savings; ecological measures such as human appropriation of Net Primary Production (NPP), ecological footprints and environmental space; and socio-political measures such as the Index of Sustainable Economic Welfare (ISEW) and quality of life indicators. These different measures can give different messages to policy makers and others interested in measuring sustainable development but, because of their essentially empirical approach, they are unable to inform policy makers about *long-term* changes to a nation owing to the changing exogenous or endogenous factors, and the consequent implications for the sustainability of its trajectory. One obvious way to explore these complex and long-term changes is to construct quantitative models of sustainable development.

This paper presents two models of sustainable development based on research recently completed in Scotland. In Section 2 we describe some of the approaches to modelling sustainable development. This review is not exhaustive but indicates the breadth of different approaches that have been developed, and that are still being developed to contribute to our understanding of the processes which make development sustainable. In Section 3 we describe a novel approach to modelling sustainable development using system dynamics which

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involves inter-connecting a global and a national model in a dynamic, hierarchical approach. Section 4 describes a more conventional static approach to modelling sustainable development using an environmentally adjusted input–output (I/O) model. In both we set out illustrative results from a recently completed preliminary study of Scotland. Finally, some of the weaknesses in these two approaches are described, together with avenues for further research.

2. Modelling sustainable development

An early attempt to model sustainable development was undertaken by Forester and co-workers at MIT in their infamous Limits to Growth models (Forrester, 1971; Meadows et al. 1972, 1974). These models attempted to examine the impact of population growth, and pollution and resource use on planet. The neo- Malthusian conclusion of this early set of models was stated as "the limits to growth on this planet will be reached somewhere within the next one hundred years…even the most optimistic estimation of the benefits of technology in the model…did not in any case postpone the collapse beyond the year 2100" (Meadows et al., 1972, pp. 23 and 145).

There were of course numerous criticisms on these early models. Some suggested that these early models were models of doom (Clark et al., 1975). Others suggested that social feedback loops added to the model could prevent the doomster conclusion reached in this set of models (Oerlemans et al., 1972). Economists were very unhappy about the ways in which scarcity was handled in these models and in particular about the lack of a price mechanism in the allocation of scarce resources to different uses (Cole et al., 1973) Others suggested that some basic aspects of model building methodology, e.g. parameter sensitivity testing were ignored (Moffatt, 1983). Despite these numerous criticisms the system dynamics methodology can be used to build models of sustainable development — although it is very disappointing to find the *same* models being repeated using STELLA rather than taking on board the many serious criticisms aimed at this approach. (Meadows et al., 1992). While many of the criticisms aimed at the Limits-to-Growth models were correct it is fair to say that these early models represented a welcome antidote to the unduly static models which had dominated this area of research into global problems as seen in Leontieff's well known global I/O model (Leontief, 1977).

The systems dynamic approach to modelling sustainable development has followed two different paths, although both based on the same methodology of difference equations represented as a set of interacting feedback loops. The first approach has been developed by Slesser (1990) as an set of Enhanced Carrying Capacity Option models (ECCO) (Moffatt and Slesser, 1989). These models attempt to define some measure of sustainablity and then construct a model of economy such as Kenya or Mozambique, and by a series of simulations show how business as usual scenarios are not sustainable. By a judicious use of negative feedback loops the models are then able to simulate policy options so that a more sustainable form of development can be achieved. Some of the research using this form of ECCO model is shown in Table 1 where simulations for Australia and the UK are indicated.

The second route which practitioners of systems dynamics have taken is to develop macro structures by simulating micro-world processes. This approach has been developed by Allen and the so-called Brussels School of modelling working under the idea of Prigogine's far from equilibrium approach of self-organisation. (Allen and Sanglier, 1981; Prigogine and Stengers, 1982). In a recent text (Clark et al., 1995) this approach to modelling sustainable development has been undertaken with reference to case studies in Crete and Senegal to illustrate the ways in which it is possible to model sustainable development by examining underlying behavioural decisions rather than mechanistic inter-linkages at the aggregate level of major sectors. The major weakness in this approach at present is the lack of empirical research to support the models behavioural assumptions.

One of the most innovative approaches to modelling sustainable development at a sub-national or regional scale has been developed in US by Costanza et al. (1990, 1997a) who have developed a set of system dynamic models which are interconnected to a geographical information system (GIS) to simulate through space and time the changes in wetlands surrounding the Chesapeake estuary. This integration of spatio-temporal processes by interfacing dynamic modelling with GIS represents the cutting edge of such modelling. This approach can be further enhanced by including intelligent or quasi-intelligent front ends or Decision Support Systems (DSS) to the system. These DSS can include optimisation approaches as well as neural networks.

For the economist concerned with modelling sustainable development, several aspects are important (Faucheux et al., 1997). Firstly, analysts often want to know how environmental policy will impact on macro variables, such as the level of output in an economy. Secondly, how impacts are distributed across different sectors of the economy: e.g whether employment effects are more severe in manufacturing than in services. Thirdly, the inter-connectedness of the economy, in terms of firms producing inputs which are in turn used by other firms to produce outputs, and where both have implications for resource use and emissions of pollutants, should be recognized. Finally, we want to know how changes in policy, for example, impact on the long-

Table 1
Unsustainable and sustainable simulations for Australia and Scotland, 1980–2020

Major state variables	Unsustainable trajectory (U)			Sustainable trajectory (S)		
	Parameter	1980	2020	Parameter	1980	2020
Australia						
Population growth	0.02	100	221	0.00	100	111
Sustainable population	–	100	93	–	100	113
Investment	0.24	100	–	0.50	100	–
Energy self-sufficiency	0.21	100	0	1.00	100	464
Food self-sufficiency	1.00	100	42	1.00	100	102
Interest rate	0.50	100	100	0.50	100	100
Imports	–	100	315 000	–	100	58
Standard of living	–	100	19	–	100	89
Scotland						
Population growth	0.02	100	200	0.00	100	111
Sustainable population	–	100	110	–	100	113
Investment	0.24	100	–	0.50	100	–
Energy self-sufficiency	0.21	100	380	1.00	100	474
Food self-sufficiency	1.00	100	99	1.00	100	102
Interest rate	0.50	100	100	0.05	100	100
Imports	–	100	128	–	100	58
Standard of living	–	100	19	–	100	54

term growth rate of the economy. Two modelling approaches meet these needs and are widely used: Computable General Equilibrium modelling (CGE); and I/O analysis.

CGE models have been used fairly intensively to study the economic implications of environmental policy. An earlier paper is that of Hazilla and Kopp (1990), who used a 36-sector model of the US economy to estimate the social costs of compliance with the Clean Air and Clean Water Acts. Their objective was to compare costs derived from a CGE model with engineering cost-of-compliance estimates presented by the US EPA. Hazilla and Kopp's main findings are that CGE cost estimates are substantially lower than engineering cost estimates, and that the Acts produced a 6% fall in GNP by 1990, and a 6% rise in the consumer price index. Production is most affected in 'dirty' sectors, such as motor vehicles, but some effects are noted in all sectors. Jorgenson and Wilcoxon (1990a,b) present a similar analysis, using a 35-sector dynamic CGE model of the US. Their main aim was to investigate the long run effects on growth of environmental regulation during the period 1974–1985. In the model, households and firms both optimize over time, and both can substitute away from pollution-intensive products. Productivity growth is endogenous in the model, and occurs through energy price effects. Jorgenson and Wilcoxon find that environmental regulation reduces the GNP growth rate by 0.19%, resulting in a 2.59% fall in GNP by the end of the period. Again, sectoral effects vary, with motor vehicles and coal mining amongst the worst affected. The costs of environmental regulation have also been estimated by Conrad and Schroder (1993) and Nestor and Pasurka (1995a,b) for Germany, and by Boyd and Uri (1991) for the US.

I/O models incorporating pollution generation and pollution abatement sectors were widely used in the late 1970s and early 1980s (Forsund, 1985; James, 1985; Ketkar, 1984). Miller and Blair (1985) identify three main types of environmental I/O models: generalised I/O; economic-ecological models; and commodity-by-industry models. In the first of these, emissions of pollutants and abatement activities are included by adding additional rows and columns to a standard I/O matrix. Ecological-economic models specify ecological inputs to production as flows from environmental assets which are in turn affected by emissions from economic activity (in feedback loops). Pearson (1989) notes that such models require an understanding of economy–ecology interactions which is, in the main, absent. The final approach is also known as the Victor approach (Victor, 1972), and involves broadening the generalised model, by adding ecological inputs and outputs to the standard commodity-by-industry model. As Pearson (1989) points out, most applications in the literature are of the generalised model, owing to data limitations in addition to the knowledge gap referred to above.

On the whole, environmental I/O models have been used to study changes in the level and composition of final demand, requirements for emission reductions, technological changes, and energy conservation. Other issues studied include changes in the spatial location of discharges and regional impacts of non-uniformly mixed pollutants (Pearson, op cit). Typically, environmental I/O models incorporate common air pollutants, such as SO_x, NO_x and particulates, and may be highly disaggregated, with up to 190 industrial sectors (Hafkamp, 1991). The 'energy crisis' of the 1970s produced a shift towards detailed modelling of the energy sector (see Casler and Wilbur, 1984 for a survey), while Muller (1979) extended the framework to include regional-level analysis. The SEAS (Strategic Environmental Assessment System) project in the USA, and the RIM project in the Netherlands, both attempted to combine very detailed energy conversion, supply and demand models with a national I/O framework (Ratick and Lakshmanan, 1983; Vos et al., 1983). Other recent I–O work includes that of Schafer and Stahmer (1989), Nestor and Pasurka (1995a,b) and Proops et al. (1992).

Both CGE and I–O models share some important abilities. These include the ability to disaggregate impacts into a relatively large number of sectors, and to consider knock-on (indirect) effects of policies on, say, output shares. Disaggregation is very important given the fact that different sectors of the economy may be expected to be dis-proportionately effected by environmental policy. Comparing general equilibrium with partial equilibrium approaches, Boyd and Uri (1991) note that, in addition, CGE models are consistent with utility maximising behaviour by all agents (both statically and inter-temporally), that all markets clear at equilibrium prices, and that interactions between all sectors and markets in the model are taken into account. On the down side, CGE models assume that all markets clear instantly under conditions of perfect competition (so that they cannot model adjustment processes), take no account of transactions costs, and no account of technological innovation (although this is not true in all CGE models: see Jorgenson and Wilcoxon, 1990b). In addition, CGE models are extremely data-intensive, both in terms of the social accounting matrix on which they are based, but also in terms of the elasticities and parameters of the production and utility functions specified. Whilst sensitivity analysis of parameters and elasticities is routinely undertaken, this does not fully address all the difficulties in meeting data needs.

I/O models are clearly less comprehensive than CGE models, and also rely on fixed coefficient production functions. Marginal pollution abatement costs are typically constant, and emissions produced through fixed emissions coefficients per unit of output. Problems over infinitely elastic factor supplies must be got around by, e.g., extending the model using mathematical programming, an approach which also allows I–O to be set in an optimizing framework (Muller, 1979; Ma et al., 1997). However, I–O models do capture the interdependencies of the productive sector of the economy, and allow a large degree of dis-aggregation. In addition, pollution emission and pollution abatement matrices can be used to supplement traditional I–O models. Pollution intensity indices, incorporating both direct and indirect emissions, can be calculated for products or by income class of household (Pearson, 1984). I–O model outputs could perhaps be considered as medium term forecasts of the effects of environmental policy, with CGE models being used as long term effect forecasts.

Finally, a different approach to both economic and system dynamics methods is one that compares a conventional development scenario with alternatives by means of a sophisticated data base approach (POLESTAR). This method identifies a set of global constraints and then allocates feasible scenarios within this region. The model user sets up the criteria for 'sustainable development' and then alters several of the parameters in the database model to discover if the nation is sustainable (Raskin et al., 1996).

While the development of models of sustainable development is still in its infancy it is clear that several theoretically interesting and empirically derived approaches are being examined to give a better understanding of the ways in which current socio-economic activities can be altered to make development sustainable. At present there is no one preferred modelling approach. Each approach has its merits and limitations. In the following sections we describe two approaches to contribute to the research into modelling sustainable development. The first approach in Section 3 is an hierarchical approach using system dynamics; while Section 4 develops an orthodox I/O model to address problems of environmental quality in a dis-aggregated economic environmental model.

3. A dynamic global/national hierarchical model

One of the messages brought across from the Limits to Growth types of models is that if we are to consider sustainable development then we have to model globally *and* locally. As many people are aware individual nations cannot stop major changes to the environment although some nations contribute more toward damaging the environment than others. Similarly, several researchers have noted that it may be possible to have sustainable development in the context of one nation but such 'sustainability' would be at the expense of other people (Faucheux et al., 1997). Clearly, from an ethical perspective this is unacceptable yet it is with dismay that we find some economists still arguing that they need to disregard fundamental issues of global resource scarcity by assuming that prices and interests rates are constant in order to simplify the analysis (Brekke, 1997, p. 62). Further, such arid economics leads to the rather obvious conclusions that a resource rich national economy depletes its resources at a rate which maximises wealth in the belief that whatever the economy would need of this resource in the future can be bought on the world market. If all resource rich economies behaved in a similar manner, the world economy would eventually face resource scarcity (Brekke, 1997). Such simplification rules out many fundamental questions of sustainable development. Hence, if we are to avoid self-delusion by oversimplifying our analysis then it is vital that any realistic model of the transition to a sustainable world needs to examine the *global* resource constraints which operate.

3.1. A global model

One of the problems of modelling sustainable development is to recognise that any one country is part of the global economic system. Whilst an individual country's impact on the world environment may be small it is not negligible (adding up numerous small impacts produces a global impact), but the impact of global changes will have an impact on many nations. Hence, if we are to realistically model sustainable development for Scotland, Australia or any nation it has to be set in the context of the global economic-ecological system. This of course poses immense problems for any model builder, as it is difficult to model the macroeconomy–ecology of a nation let alone place the nation in its global setting. The approach adopted here is to first develop a simple global model which captures some but not all of the interactions implicit in the WCED definition of sustainable development, and then sets a national model in this context.

The global model is designed to be relatively simple and focuses on environmental impacts globally of resource use and population change. The generic structure of the hierarchical model is shown in Fig. 1. The upper level represents the global ecosphere and the lower layer represents one country within the global system (Scotland). The global model structure consists of three sectors: population; primary productivity; and non-renewable materials. The population sector is sub-divided into two groups representing the wealthy people in the developed world with the other group as the less developed countries. It is assumed that as material levels of wealth increase there is a non-linear relationship with declining vital rates. The populations appropriate Net Primary Productivity in the form of food and fibre and also use other areas of land indirectly for supporting themselves.

The world model simulates the global environmental impact of population and resource changes. The model runs for three hundred years simulated time and solves the equations for every year. At its simplest the model is divided into three sectors — a demographic group, a 'biosphere' and a materials sector. The demographic sector divides the worlds' total population crudely into a rich 20% and a poor 80%. Both demographic sectors change by rates of birth and death. The major difference in the structure of the two demographic groups is that the rich groups experience a falling birth rate as their wealth expands. This is consistent with the observations of several rich nations as captured in the demographic transition model. In the poor South sector birth rates are high as poverty causes individual families to produce more children even though the chances of survival are lessened per child. Both population groups are supported by food taken as a minimum to represent the FAO kilocalories per person per day converted into tonnes of Net Primary Productivity (NPP) per person per year, but the rich group can consume more than this as they have the purchasing power to do so.

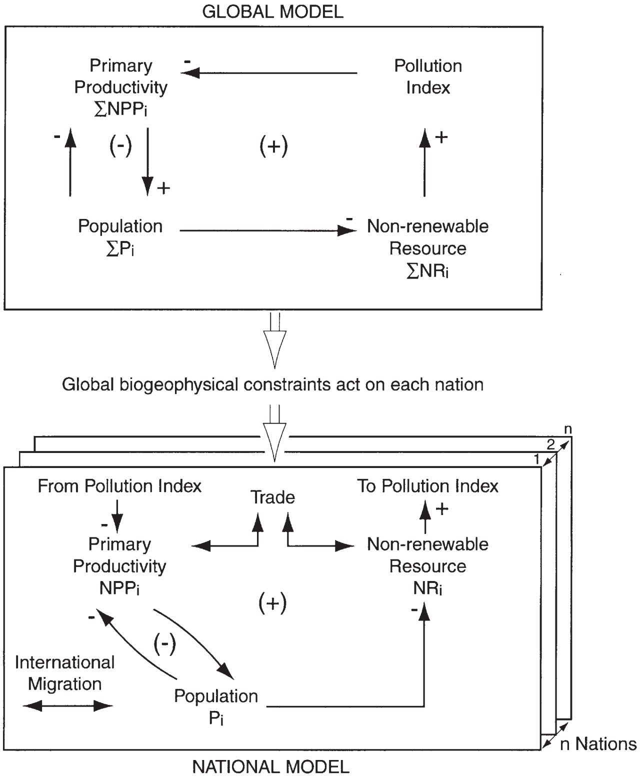

Fig. 1. Caption

It is well known that any society needs to derive its sustenance at least partly from the use of renewable resources. In the model the renewable resources or ' food supply' is taken from the Net Primary Productivity (NPP) of the globe. Vitousek et al. (1986) suggested that current human consumption of NPP accounted for 40% of this total and noted that two further doublings of the world population would, on current trends, would be physically impossible to achieve. In the model we constrain the human appropriation of NPP by an upper limit of 50% although this, like any other parameter, can be changed. The NPP sector remains in a state of dynamic equilibrium and attempts to compensate for human appropriation of energy from this level. It should be noted that NPP represents the total food supply of the planet that includes the food supply for *all* life forms.

Economic growth and development is also predicated upon the use of non-renewable resources. The conventional view is to make a distinction between non-renewable energy resources (oil, natural gas and uranium) and other non-renewables (metallic minerals, aggregates etc.). In this model all the material in the Earth's crust is potentially available for use as materials inputs into the economy. This includes all known non-renewable energy resources and other minerals. Obviously not all of the Earth's crust could be used but it represents another finite amount of materials taken as the total amount of rock down to the 45 km below sea level. The model assumes that the two populations groups have differential access to the per capita consumption of these materials set at 2 and 8 ton per person per year for inhabitants of the poor and rich nations, respectively. Again, current patterns of (unfair?) trade are assumed to keep this differential access to the use of non-renewable resources unless policy changes are made to the terms of trade. The pollution generated by the use of non-renewable resources is given a conservative figure of 50% of the material consumed per person per year, some of which is emitted as CO_2. It should be noted that the pollution generated in the model only impacts directly onto the life support system of the biosphere: as the pollution index increases then the rate of NPP decreases.

The Net Primary Production sector uses a logistic equation to increase this stock subject to human demands. Obviously, there are natural limits to the regenerative and reproductive capacity of primary production. As the human population grows then the demands for primary production increase and when demand exceeds supply then a feedback loop drives down the population by increasing the death rates. Under conditions of a stable global population — estimated at by the UN at 10 billion people by 2020 (Pearce, 1998) — the population is able to support itself on the available NPP but the 50% constraint has to be relaxed. It is also hypothesised that the growth rate of primary production is affected by CO_2 concentrations. The literature on the impact of an increased CO_2 on plant growth is inconsistent. One group of researchers suggest that CO_2 is good for plant growth whilst others suggest that an increased CO_2 would slow down plant growth and therefore reduce the amount of NPP available. In this model several hypotheses are explored. Even under a stable population the growth in CO_2 can cross a critical threshold and cause the population to fall as NPP is diminished. The environmental impact (I) is the same as used by Erhlich and Holdren (1971) but in an index form. An index has to be used as different forms of pollution and environmental degradation are measured in different units and cannot be combined.

3.2. The national model

Compared to the rest of the world Scotland is a small nation. Its population circa 1970 was 5 million in an area of 78,829 km^2. These figures represent some 0.1 and 0.015% of the 1970 global figures used in the world model. The population of Scotland has remained quite stable at 5 million since 1970. It is clear that Scotland's impact on the globe will not be as strong as the impact of the global environmental and economic changes on Scotland. Therefore, it is necessary to imbed a model of Scotland within a global framework.

The dynamic model developed in this study is therefore hierarchical in that it attempts to ensure that any nation remains well within the bounds of the ecologically possible renewable resources of the biosphere. The upper level of the model then allows every lower level area (nations) to allocate resources in terms of trade and other economic activity. The national model is again initialised on 1970 data and run for 500 years, with the global constraints noted below.

There are four main differences between the national model and the global model. First, the demographic sector includes in and out migration. Next, an employment sector is incorporated, along with a production function with labour, natural resources (both renewable and non-renewable) and man-made capital as inputs. Third, changes in world prices are included rather than purely material flows. Fourth, different land use categories (representing important aspects of renewable resources) can be incorporated. Obviously, the model can be further dis-aggregated to reflect the details of any national economic and environmental statistics. It is important that the dis-aggregation does not mask the three main aspects of the models structure which are non-renewable and renewable resources and demographic interactions. Global constraints must be observed as the summation of all nations resource use will add up to total global net primary production and non-renewable resource use and increased CO_2 levels.

The most important set of global constraints in the model are:

- A constraint on the global CO_2 burden.
- An adequate supply of potable water.
- A constraint on human population growth via a wealth effect, which effects resource consumption.
- A constraint on global NPP appropriation to ensure that the ecosystem services can provide all the food required for human consumption as well as maintaining biodiversity and other the essential services — even if the latter cannot be brought into the market.

The complete details of the dissagregated model are described elsewhere (Moffatt et al., 2001).

3.3. Results from the global and national models

The global and the national models were initialised for 1950 and both were run for 500 years simulated time.

Some of the results of this base run simulation are presented in Table 2. It will be observed that the global concentrations of CO_2 in parts per million by volume (ppmv) begin at 250 ppmv and rise steadily to a maximum at the year 2150 and then return to 240 ppmv — which represents an estimate of the pre-industrial concentration of atmospheric carbon dioxide. The global population also rises from an initial value of 2.51 to 14.16 billion before an ecological damage to the Net Primary Productivity causes the world human population to crash to extinction. In this sense the global model's output is similar to the early limits to growth but it is based upon a more realistic, but still highly simplified, set of biogeophysical and economic processes. The world Gross National Product in the model rises from 2.4 trillion dollars in 1950 to 20.9 trillion in 1990 while the value of the world's ecosystem services and natural capital (most of which is outside the market) grows from an estimated 1950 value of 45.8 trillion dollars to 59.6 trillion by the year 1990. Recent controversial estimates of the value of the ecosphere are approximately 18 trillion dollars for global GNP and between 16–54 trillion dollars for the entire biosphere (Costanza et al., 1997b). It is readily admitted that we need better data for some of these global estimates but the model's predictions are very similar in direction and magnitude to the current estimates. This would give some confidence that we are working along the right lines.

The national model based on Scotland operates well within the global constraints. Again the model is initialised for 1950 and runs for 500 simulated years. The population rises from 3.5 million estimated) to 5.68 in 2150. This rate of growth is not high but masks large movements of international in- and out-migration patterns throughout the period. As in the global model the population crashes when the human appropriation of Net Primary Productivity outstrips nature's pattern of reproduction. In both the national and global models non-renewable resources are not a hindrance for making development sustainable; it is renewable resources in the widest sense that are most constraining. Breaching the natural assimilative processes of environmental systems is not a sustainable strategy locally, nationally or globally.

Table 2
Results from the dynamic models

Year	Global CO2 (ppmv)	Global GNP (trillion$)	Global ecosystem value (trillion $)	Global population (billions)	Scottish population (millions)
1950	275	5.4	45.8	2.51	3.51
1960	335	8.9	48.2	3.53	4.73
1970	365	13.5	51.2	4.60	5.01
1980	397	24.6	62.5	5.77	5.34
1990	430	20.9	59.6	6.96	5.37
2000	462	22.4	65.1	8.09	5.41
2050	439	28.2	63.6	11.97	5.56
2100	605	30.6	51.9	13.14	5.68
2150	633	53.6	55.1	14.16	5.99
Onwards	240	na	na	0.00	0.00

3.4. Problems with the dynamic models

There are several problems with the hierarchical model as currently developed. Firstly, the national model is very sensitive to changes in migration flows. The latter are derived from the employment multiplier which compares employment/unemployment within a nation to the ratio for the globe. Secondly, it is set up as a very aggregated structure. Obviously, it is important to dis-aggregate the model so that finer sectors of the economy and ecology can be integrated in more detail. Here, we run up against the limits of using early versions of STELLA as a simulation language as it is unable to handle matrices. Other languages such as VENSIM can do so. Thirdly, the model needs to be integrated with GIS, and VENSIM can inter-link with ARCINFO if a suitable software interface is written. This would represent another round of detailed modelling spatio-temporal patterns of sustainable development (four-dimensional Modelling) similar to the work of Costanza et al. (1990). Fourthly, the allocation of some share of the global resources between competing users — a classic problem of economics — needs to be developed. Whether this relies purely upon free-trade or acts within a GATT-regulated framework is a moot point at present.

4. An I/O approach

An environmental I/O model was constructed, using as its basis I/O tables produced by the Scottish Office Industry Department for 1989 and industry-industry data for 1979 and 1993. We have aggregated data down to 28 sectors and limited our model to the following 12 pollution 'sectors': CO_2, SO_2, NO_x, black smoke, VOCs, methane, CO, waste, lead, and radioactive waste to air, land and water. Emission figures for all these pollutants except radioactive waste have been derived from the Digest of Environmental Protection and Water Statistics, 1994. Scotland's share of these UK figures have been based on the proportion, by sector, of the most appropriate population, output, vehicle kilometers, aircraft movements or GDP. Radioactive waste figures were taken directly from the Scottish Office Statistical Bulletin — Radioactive Waste Disposals from Nuclear Sites in Scotland, 1995. Data for the matrix of inputs to the pollution abatement sectors proved difficult to locate.

Our first model was a simplified version that excluded pollution abatement sectors and simply combines a pollution by industry matrix (in coefficient form) with the conventional I/O matrix as follows:

$$X=(I-A_a)^{-1}\times Y$$

and then

$$P=A_b\times X$$

where A_a and A_b are the standard inter-industry and the pollution by industry coefficients matrices, respectively. So given a final demand Y we can calculate the gross output X and from this find the vector of sectoral pollution P generated by that output.

An advantage of such a model is that if instead of using final demand we applied just the change in final demand (δY), we can calculate the change in pollution (δP) resulting from this change. This could be particularly useful if we want to assess the effects of a demand change, perhaps from electricity to gas. Table 3 is a sample output from this simple model which illustrates the effects on output and pollution emission levels of a switch from road to rail transport. (We have assumed a direct pound for pound transfer between sectors so that the total final demand remains unchanged.)

As can be seen there have been positive and negative impacts in sectoral outputs and pollutant volumes. Besides, although only a few sectors were directly affected by our simulation, we can see that nearly all sectors have felt some impact. Carbon dioxide and monoxide emissions fall, as do levels of black smoke, VOCs and lead. These changes in emissions come about in two ways: (i) owing to the relative emissions associated with road and rail travel (on the whole, lower for rail); and (ii) changes in emissions from other industries, whose outputs are affected by the change from road to rail (e.g. electricity and oil refining).

In Table 4, we show results from a similar simulation, which this time looks at a shift in energy policy, which replaces £150 million worth of electricity output with gas output. Again, there are changes in both industrial outputs and emissions; SO_2 emissions fall by 9%, while $N0_x$ emissions fall by 4%. Finally, Table 5 shows the effects of a change in the structure of the economy over time, with a 25% fall in manufacturing sector outputs, and a 25% increase in financial and business sector outputs. As might be expected, this produces a large range of reductions in emissions of almost all pollutants in the model, as the financial and service sector produces less (direct) emissions than the manufacturing sector.

Including abatement sectors into the model showed up some interesting results which illustrate a problem with simple I–O designs. Abatement sectors were added for all pollutants except CO, lead and methane. These sectors use purchased inputs and fixed technology to reduce emissions of, e.g. SO_2. However, as input supplies are unconstrained in the I–O model, and as prices are fixed, progressively increasing restrictions on emissions produce increases in total output, as the abatement sector's output rises to meet pollution reduction targets. This implies no trade-offs between pollution control and economic growth.

In order to solve this problem, a linear programming model of the economy, with the I/O matrix as a set of constraints, was constructed. In this case, total output is constrained not to rise when emission targets are made more strict (for details, see Ma et al., 1997). We also report there on versions of the model which allow pollution taxes to be simulated.

5. Conclusions

This paper has described some of the ways in which sustainable development can be modelled. In particular it has described two alternatives: a systems dynamics model, and an I/O model. The first approach is characterised by being both dynamic and hierarchical. The model shows how individual countries cannot be divorced from the rest of the world's resource-consuming activities which impact on the nation, and how renewable resources, in the widest sense, may impose a stricter limit than non-renewable resources (a contrast with the central message of the Limits to Growth team. Globally, renewable resource limits due to declining NPP are more likely to be felt in poorer countries that are curently over-exploiting their resource base due to poverty. The dynamic nature of the model indicates the long-term horizons over which sustainable development has to be managed: the emphasis is long-term, rather than short or medium term (unlike the economic model). Two major weaknesses in this dynamic model are that it fails, at present, to interlink temporal considerations with spatial information. Second, it does not incorporate a highly dis-aggregated sectoral breakdown of the ecological and economic systems which have to interact in a sustainable manner. This latter problem has been partly overcome by dis-aggregating the Scottish economy into finer subdivisions and then re-examining their impact, in terms of pollutants and resource use, in the I/O model. The I/O model suffers from the usual restrictions of such models (such as fixed technologies and perfectly elastic factor supplies), although the developments reported by Ma et al. (1997) do address this latter problem. However, in constructing the model the main obstacle proved to be severe data shortages, especially on pollution abatement. In both models we were able to make reasonable inferences about the environmental implications of current patterns of development. We are also able to hint at some of the effects of polices which might be put into place in the real world in an attempt to contribute to making development sustainable.

Despite the considerable progress in modelling sustainable development that has been made since the publi-

Table 3
Change in outputs and emissions due to a change in transport policy

	Sector	Output			
		Current demand (£m)	Change in demand (£m)	Change in output×£m	% Change
1	Agriculture	292.3	0.00	−0.04	−0.00
2	Forestry	53.4	0.00	0.01	0.01
3	Fishing	172.7	0.00	−0.01	−0.00
4	Coal	38.3	0.00	0.17	0.09
5	Oil/gas	696.3	0.00	0.47	0.04
6	Oil refining	1486.0	0.00	3.01	0.13
7	Electric	746.2	0.00	5.19	0.37
8	Gas supply	383.2	0.00	0.06	0.01
9	Water supply	88.6	0.00	0.19	0.11
10	Metal manufacture	742.7	0.00	1.65	0.13
11	Mineral extraction and processing	405.6	0.00	0.63	0.07
12	Chemical and fibre manufacture	1454.5	0.00	0.18	0.01
13	Metal goods	415.1	0.00	0.74	0.10
14	Instrument engineering	6693.0	0.00	1.26	0.02
15	Transport equipment	1392.6	0.00	0.44	0.03
16	Food, drink and tobacco	5094.3	0.00	−0.07	−0.00
17	Textiles	1498.3	0.00	0.38	0.02
18	Paper and publishing	1208.3	0.00	−0.48	−0.02
19	Other manufacturing	923.0	0.00	0.35	0.02
20	Construction	2767.3	0.00	−0.25	−0.01
21	Distribution	6630.3	0.00	−3.24	−0.04
22	Railways	160.3	100.00	99.82	37.51
23	Road	685.5	−100.00	−100.11	−7.48
24	Sea	378.4	0.00	0.03	0.01
25	Air	503.2	0.00	−0.09	−0.01
26	Finance and business	3134.7	0.00	−11.59	−0.18
27	Other services	910.5	0.00	−1.52	−0.11
28	Public and admin. services	9710.4	0.00	−0.02	−0.00

Pollution Pollutant	Change in pollution	Total pollution	% Change
	000 ton		
CO2 (C weight)	−77.5	11663.7	−0.66
SO_2	0.9	360.1	0.24
Black smoke	−0.8	18.3	−4.39
NO_x	−4.9	224.8	−2.17
VOC	−3.9	179.3	−2.19
CO	−25.8	368.3	−7.01
Methane	0.0	419.3	0.00
Waste	21.1	36920.0	0.06
Lead	−0.0	0.1	−7.48
RA (air)	0.0	5.1	0.37
RA (water)	0.0	0.3	0.37
RA (solid)	0.3	233.3	0.14

cation of the Brundtland Report (WCED, 1987) it is clear that more research remains to be carried out. Several avenues for future research may be suggested for the research community involved in modelling sustainable development, for strategic environmental policy making and for computing technology. First, the current generation of sustainable development models are quite crude. Some at present are not capable of being used as forecasting tools; others are useable but lack a sound theoretical base. In particular the integration of the dynamic models with a three-dimensional geographical information system (GIS) needs further development. Costanza et al.'s work is probably the best development in this field but is used for simulating continuous vari-

Table 4
Effects on output and emissions from a change in energy demands

	Sector	Output			
		Current demand (£m)	Change in demand (£m)	Change in output×£m	% Change
1	Agriculture	292.3	0.00	−0.23	−0.02
2	Forestry	53.4	0.00	−0.04	−0.04
3	Fishing	172.7	0.00	−0.02	−0.01
4	Coal	38.3	0.00	−3.51	−1.85
5	Oil/gas	696.3	0.00	−2.77	−0.26
6	Oil refining	1486.0	0.00	−17.69	−0.79
7	Electric	746.2	−150.00	−163.31	−11.75
8	Gas supply	383.2	150.00	150.08	27.86
9	Water supply	88.6	0.00	−0.43	−0.24
10	Metal manufacture	742.7	0.00	−0.42	−0.03
11	Mineral extraction and processing	405.6	0.00	−0.58	−0.06
12	Chemical and fibre manufacture	1454.5	0.00	−0.32	−0.02
13	Metal goods	415.1	0.00	−0.17	−0.02
14	Instrument engineering	6693.0	0.00	−5.52	−0.07
15	Transport equipment	1392.6	0.00	−0.34	−0.02
16	Food, drink and tobacco	5094.3	0.00	−0.56	−0.01
17	Textiles	1498.3	0.00	−0.23	−0.01
18	Paper and publishing	1208.3	0.00	−1.96	−0.10
19	Other manufacturing	923.0	0.00	−0.57	−0.04
20	Construction	2767.3	0.00	−6.58	−0.18
21	Distribution	6630.3	0.00	−6.59	−0.08
22	Railways	160.3	0.00	−0.82	−0.31
23	Road	685.5	0.00	−0.55	−0.04
24	Sea	378.4	0.00	−0.38	−0.09
25	Air	503.2	0.00	−1.00	−0.13
26	Finance and business	3134.7	0.00	−39.76	−0.62
27	Other services	910.5	0.00	−5.51	−0.39
28	Public and admin. services	9710.4	0.00	−0.04	−0.00

Pollution Pollutant	Change in pollution	Total pollution	% Change
	000 ton		
CO_2 (C weight)	−646.0	11663.7	−5.54
SO_2	−32.7	360.1	−9.08
Black smoke	−0.3	18.3	−1.78
NO_x	−9.8	224.8	−4.34
VOC	−0.6	179.3	−0.35
CO	−0.8	368.3	−0.21
Methane	6.5	419.3	1.54
Waste	−289.5	36920.0	−0.78
Lead	−0.0	0.1	−0.04
RA (air)	−0.6	5.1	−11.74
RA (water)	−0.0	0.3	−11.75
RA (solid)	−10.6	233.3	−4.55

ables such as the spread of water and the spatio-temporal diffusion of pollutants in an estuary. In cases where discrete parcels of land use are being planned then more sophisticated solutions have to be devised yet. The integration of three-dimensional dynamic models to address the problems of discrete and continuous variables within the one model framework would appear to be the next step in this research toward modelling sustainable development.

From discussions with policy makers in Australia and Scotland it appears that there is a need for models which are capable of exploring sustainable scenarios, which explicitly examine both the temporal and spatial development of a system. Many environmental managers and

Table 5
Effects of a switch from manufacturing to financial services

	Sector	Output			
		Current demand (£m)	Change demand (£m)	Change output×£m	% Change
1	Agriculture	292.3	0.00	−0.58	−0.04
2	Forestry	53.4	0.00	−8.32	−7.74
3	Fishing	172.7	0.00	−0.10	−0.03
4	Coal	38.3	0.00	−13.85	−7.33
5	Oil/gas	696.3	0.00	−5.72	−0.54
6	Oil refining	1486.0	0.00	−36.38	−1.62
7	Electric	746.2	0.00	−30.46	−2.19
8	Gas supply	383.2	0.00	−9.84	−1.83
9	Water supply	88.6	0.00	−6.32	−3.58
10	Metal manufacture	742.7	−186.00	−233.51	−18.64
11	Mineral extraction and processing	405.6	0.00	−4.53	−0.51
12	Chemical and fibre manufacture	1454.5	−363.00	−428.19	−22.45
13	Metal goods	415.1	−103.00	−119.47	−16.75
14	Instrument engineering	6693.0	0.00	−28.36	−0.38
15	Transport equipment	1392.6	−348.00	−364.32	−23.38
16	Food, drink and tobacco	5094.3	0.00	−2.19	−0.04
17	Textiles	1498.3	0.00	−2.57	−0.14
18	Paper and publishing	1208.3	0.00	4.09	0.20
19	Other manufacturing	923.0	−230.00	−254.11	−17.10
20	Construction	2767.3	0.00	2.15	0.06
21	Distribution	6630.3	0.00	−41.01	−0.52
22	Railways	160.3	0.00	−3.75	−1.41
23	Road	685.5	0.00	−17.68	−1.32
24	Sea	378.4	0.00	−2.27	−0.53
25	Air	503.2	0.00	−10.63	−1.40
26	Finance and business	3134.7	1230.00	1290.03	20.24
27	Other services	910.5	0.00	3.54	0.25
28	Public and admin. services	9710.4	0.00	0.12	0.00

Pollution Pollutant	Change in pollution	Total pollution	% Change
	000 ton		
CO2 (C weight)	−394.8	11663.7	−3.38
SO2	−11.5	360.1	−3.21
Black smoke	−0.3	18.3	−1.84
NO_x	−5.5	224.8	−2.44
VOC	−9.5	179.3	−5.29
CO	−5.6	368.3	−1.53
Methane	−2.8	419.3	−0.66
Waste	−1596.8	36920.0	−4.33
Lead	−0.0	0.1	−1.32
RA (air)	−0.1	5.1	−2.19
RA (water)	−0.0	0.3	−2.19
RA (solid)	−2.0	233.3	−0.85

strategic policy makers are ill at ease with dynamic models which lack a spatial or a geographical representation of the 'real world'. To actually model spatio-temporal changes in ecological-economic interactions often requires access to supercomputers. It should, of course, be noted that the scenarios generating changes through time or space or both are only guides to possible futures — they are not predictions in a strict scientific sense but are probably the only way we can examine the longer term consequences of our actions which have important implications for both current and future generations (HMSO, 1994). It should also be noted that modelling should not to be confused with, or used as a substitute for, making ethically sound and politically accountable judgements to enhance the life opportunities for future and current generations on Earth.

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