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The Challenge of Sustainability in a Global System

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The Challenge of Sustainability in a Global System

Documentation of a Transdisciplinary, Multi-country, Dynamic Simulation Model

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ABSTRACT
Sustainability models should consider aspects of the economy-environment-population nexus, be dynamic, and acknowledge the disparity among actors/countries. Lastly, sustainability models should not be programmed either to reject sustainability (e.g., an essential, nonrenewable input) or to affirm it (e.g., costless, endogenous technical change).

We develop a simulation model to assess sustainable development on three levels: economic (by determining production, consumption, investment, direct foreign investment, technology transfer, and international trade), social (by calculating population change, migration flows, and welfare), and environmental (by calculating the difference between environmental pollution and upgrading expenditures). The model follows "representative" countries that differ in their initial endowments (i.e., natural resource endowment, physical and human capital, technology, and population), and thus in their development levels and prospects. In addition, we model free substitution in production, flexible economic structures, the ability to upgrade input factors via investment, and optimizing agents who possess a high degree of mobility and information, and who interact through and in response to market equlibiria.

This working paper contains an overview and the equations of the simulation model. The PASCAL computer code as well as the input files can be obtained in a separate "zip" file.

Model Description

1 Overview

1.1 Motivation and background

The sustainable development paradigm has lead to a substantial amount of interdisciplinary research. Studies routinely integrate aspects of economics, demography, and environment, focus on medium- to long-term direct and indirect impacts, and consider feedbacks within economic, social, and natural systems. Yet, most studies focus on only two of the three important subsystems (economy, population, environment). In addition, studies often consider only one or more developed countries or one or more developing countries, and ignore interactions among levels of development. Lastly, when studies do consider both developed and developing countries, they usually involve cross-sectional analysis, and thus, the studies *assume* transitions or transformations, rather than directly model or observe them. The simulation modeling technique, in theory, can address the above shortcomings by building complete, multi-country dynamic models and running them over long horizons.

Yet, multi-country, dynamic, computable general equilibrium (CGE) models that include environmental aspects are rare; ones that also treat population change, endogenous growth or endogenous technology change, and developing-developed country interactions are virtually non-existent. Dellink (1999) surveyed the literature on CGE studies with environmental issues. He found only two families of models that are both dynamic and, at times extended to, multi-country, but neither has a sophisticated treatment of population or technical change. However, Loschel (2002) surveyed models that contained technological change and environment and found a number of models that have, to varying degrees, endogenous technical change. Yet, the models were nearly exclusively focused on carbon emissions—as was the technology change (rather than more general, growth enhancing technical change). Furthermore, the models he reviewed did not treat population or other sustainability issues like developing-developed country interactions.

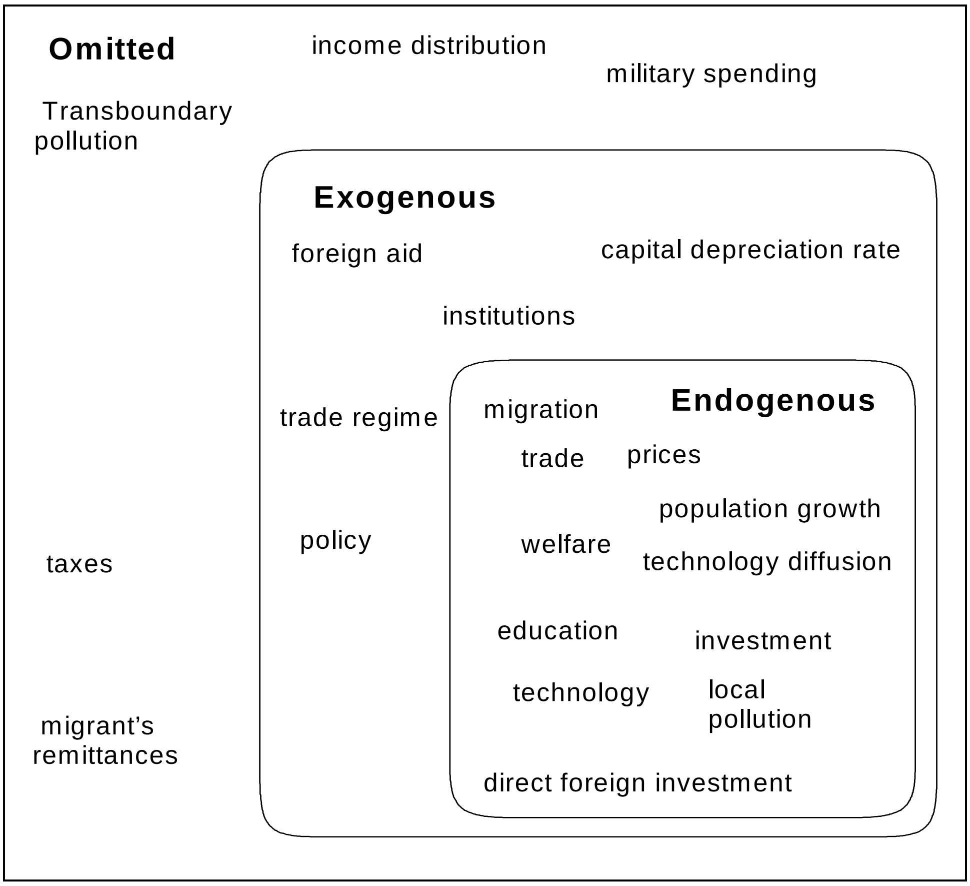
Many dynamic, CGE models use the perfect foresight equilibrium technique. Perfect foresight equilibrium requires model dynamics to be exogenous to some extent since for the model to solve all growth rates must converge to a steady-state rate. But assuming (even eventual) constant growth rates of gross domestic product (GDP) and population is particularly problematic for the type of sustainability analysis intended here. As Pritchett (2000) has noted, GDP growth *instability* is the norm—especially for developing countries—not steady-state growth. Furthermore, as Williamson and Higgins (2001) argued, it is essential for population-development models to confront transitional dynamics, since it is exactly when some groups of the population are growing faster than others that demography will most impact development. Additionally, even in post-demographic transition, developed countries, the "new" demography of continued declining fertility and mortality rates prevails over constant populations. The answer to this criticism is for dynamic, CGE modelers to run their models over extended time horizons and focus only on a period prior to the achievement of steady-state growth. However, the problem of semi-exogenous dynamics remains: there is no robust way of knowing when the output trajectory generated by the model is dominated by past or current decisions and equilibria rather than by the steady-state convergence requirement. Even Solow (1970), over 30 years ago, said that "the steady state is not a bad place for growth theory to start, but may be a dangerous place for it to end."

Considering models other than the CGE variety, Sanderson has done two literature reviews—about a decade apart—on systems models with economic-demographic interactions (1980) and economic-demographic-environmental interactions (1992). All the models he reviewed (including his own) have some combination (of more than one) of no environment, not multi-country, no endogenous growth, and no developed-developing country interactions. Bloom and Canning (2001) argued that models dealing with the "new" demography—emphasizing age-structure effects rather than total population—should necessarily use a systems framework. Yet, their own model, which does not include environment, is currently at only the schematic level. Other population revisionists that use simulation models (e.g., Williamson and Higgins, 2001 and Lee et al., 2001) develop models that are at most partial equilibrium models and are used to project variables like the savings rate rather than to account for feedbacks or the interrelationships at multiple levels of a complex, integrated system.

Sustainability models should consider aspects of the economy-environment-population nexus. Such models must inherently be dynamic—capable of following important indicators over a long time horizon; however, they must also acknowledge the disparity among actors/countries. The sustainability issue is ultimately about both *intra*generational and *inter*generational concerns. Lastly, sustainability models should not be programmed either to reject sustainability (e.g., an essential, nonrenewable input) or to affirm it (e.g., costless, endogenous technical change).

We develop a simulation model, borrowing from and integrating aspects of economics, demography, and environmental and political science, to simultaneously consider environment, economic development, and population/politics by focusing specifically on the impact of important flows (i.e., pollution, capital, technology, production goods, natural resources, and people). The model can assess sustainable development on three levels: economic (by determining production, consumption, investment, foreign direct investment, foreign aid, technology transfer, and international trade), social (by calculating population growth/change, migration flows, and political stress levels), and environmental (by calculating natural resource use and the difference between environmental pollution and upgrading expenditures). The model follows "representative" countries that differ in their initial endowments (i.e., natural resource endowment, physical and human capital, technology, and population), and thus in their development levels and prospects. Figure 1 shows the model boundary: those parameters that are endogenous, exogenous, or not considered.

Figure 1: Model Boundary Diagram

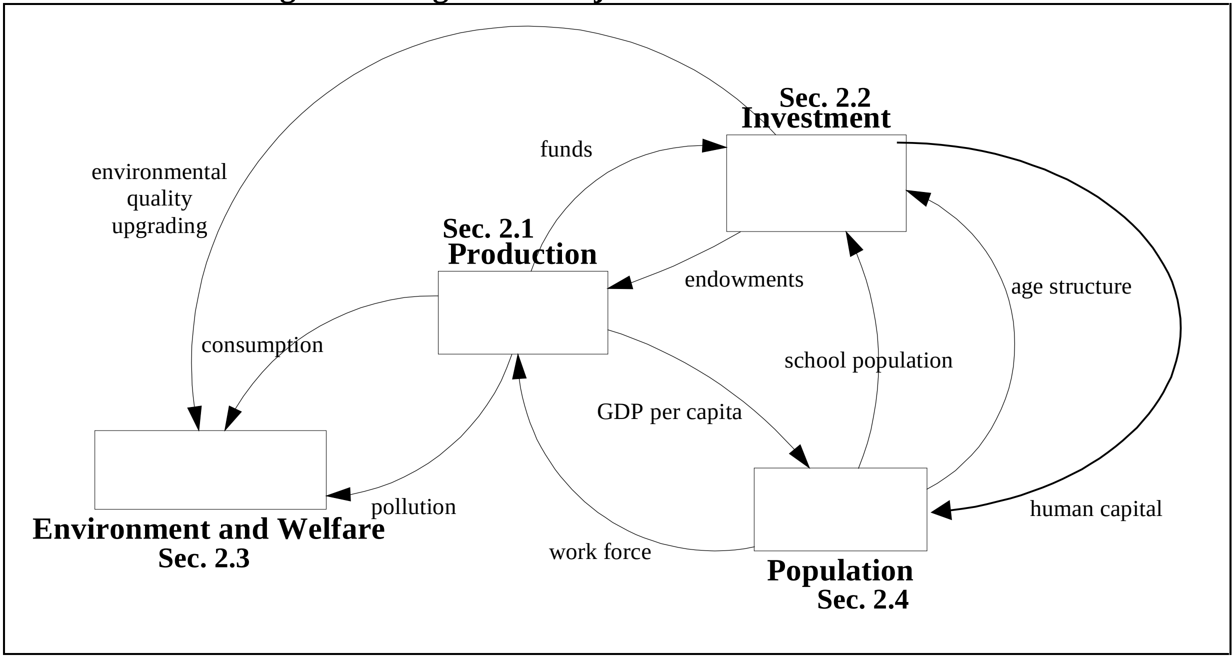


We model economic growth endogenously by explicitly modeling the choice to invest in technology enhancing (over other investments). Thus, technology improvements are not essentially free as they are in learning-by-doing models. Our treatment of environment includes *costs*, but not *limits*. Although our natural resource intermediate good is effectively nonexhaustible, the extraction function allows the good's price to increase with use. Pollution, which cannot be avoided completely via trade, has a welfare impact that increases with income, and environmental quality upgrading has rapidly diminishing returns; however, we do not set a threshold level of pollution. Lastly, our model takes full account of transitionary dynamics (in demography as well as the environment-income relationship). Furthermore, we do not enforce terminal conditions on growth rates; rather, the dynamics unfold period by period in response to specific adaptations by actors (who apply “realistic” foresight). In a world with movement of goods, people, and capital, free substitution in production, flexible economic structures, and the ability to upgrade input factors via investment, we find the initial disparities in circumstances among countries are still vital to their development prospects—i.e., history matters.

1.2 Model flows and dynamics

The model contains the following major segments: (1) a global economic system, covering seven significantly different “countries”; (2) an environmental natural resource system, relating environmental quality and natural resource capacity to welfare and economic production and consumption; and (3) induced changes in population growth and age distribution in each country (including international migration). The economic system comprises sets of relationships in different stages for each country: (1) production of three kinds of commodities (two final goods and one intermediate); (2) patterns of international trade and foreign direct investment; (3) determination of consumption and investment; (4) allocation of investment resources over five investment categories (physical capital—both domestic and foreign, human capital, natural resource capacity, environmental quality upgrading, and development of new technology). Figure 2 is a diagram of the major modules and flows. The figure also indicates the following sub-section in which those modules are discussed.

Figure 2: Diagram of Major Model Modules and Flows



There are four types of decision-makers in the model: (1) all consumers; (2) owners of productive resources, i.e., workers and owners of physical capital and land (or the firms); (3) in each of seven countries, three separate production sectors (thus making 21 individual "firms" overall); and (4) an aggregate national "investor" for each country. The aggregate national investor allocates a country's total investment pool among different types of investment, actually engages all those investment activities, determines the size of the total investment pool via a Keynesian investment function, and determines the market goods-environmental quality tradeoff (by choosing to spend on environmental quality upgrading).

Each type of decision-maker renders decisions via optimization. Consumers choose their consumption mix (between two final goods) to maximize their utility, derived from demand functions. The national optimal consumption mix is based on national utility maximization reflected in consumer goods demand. Since we have no interest in specific consumption preferences, we assume these demand functions all have unitary price and income elasticities; thus, budgetary allocations to these goods are constant and, for simplicity, are equal for the two goods in all countries. Laborers of a certain age group can maximize their wages by migrating internationally. Each "industry firm" maximizes its profits. Since there is no leisure or operation-related depreciation, factor owners maximize period returns to their assets by supplying what is demanded. The national investor maximizes present discounted value of all investments performed in each period, based on the marginal productivity of different investment types and on national preference tradeoffs between market goods and environmental quality.

Each type of investment generates, via sectoral production functions and profit-maximizing levels of output, a lifetime marginal value productivity that is transformed into a present discounted value via a single social rate of discount specified for each country as a function of its per capita GDP. Relative rates of return form the basis of allocation. The size of the investment pool is given by a Keynesian consumption-investment function, modified by social provision for rates of population dependency.

The model sequentially, deterministically, and in discrete-time "periods" runs through (i) equilibria (individual country labor markets and internationally traded goods), (ii) optimizations (profit maximization, wage maximization through international migration, final goods consumption mix, and investment mix—including welfare-maximizing goods consumption versus environmental quality choice), and (iii) updates (productive endowments, discount rates, and population—number, age structure, and mortality and fertility rates). Thus, at the end (and as a result) of this sequence of events, each country has a new set of input endowments and prices. In addition, there is a new set of international trade prices. In this manner the whole global system will generate 90-100-period (or year) national trajectories. The model is *recursively* dynamic: equilibrium in the individual country labor markets and in the international trade markets set the prices (for any specific period) that agents use (along with simple forecasts of the future) to make their decisions (during that period). Again, having the model achieve simultaneous equilibrium in all markets over all time (i.e., perfect foresight dynamics) necessitates constant, terminal growth rates for all stocks—a restriction we did not want to impose. Rather than assume the global system is in equilibrium, apply a shock, and then use the model's dynamics to examine the transition to a new equilibrium, we are interested in the dynamics of the global system because we believe it be always in a transition state.

Figure 3 shows a (limited) flow chart/systems diagram for a representative country, while Figure 4 shows the global flows among the different "country groups." (Both figures are at the end of the document.)

1.3 Initial conditions

Assumed differences in our stylized countries have been chosen to show the importance of initial conditions on influential variables in generating different long-run outcome trajectories. The country initial conditions are based on judgmental stereotypes of Rich, Middle, and Poor countries, as enhanced by empirical data on country factor endowments; however, only the age structure and birth and death rates are taken directly from the empirical data of specific countries (from Keyfitz and Flieger, 1990). Since the different levels of development or per capita GDP (in our model and empirically) are essentially *defined* in terms of technology, human capital, and physical capital per capita, *differences* within each level of development refer to population size and resource (land) endowment. Middle countries differ as well in population growth rates.

So, there are two Rich countries, one with larger total population and higher resource endowment per capita; three Middle countries, varying in population, resource base, and population growth; and two Poor countries, differing in population size. The two Poor countries have the greatest resource endowment, followed by Middle3, then Middle2 and Rich2; Middle1 and Rich1 have the smallest resource endowment. The Rich countries' populations have low birth rates and advanced age structures (based on the European Community circa 1980). The three Middle countries use data from Venezuela in 1975, Chile in 1980, and Taiwan in 1985, and thus, vary in the degree to which they have undergone demographic transition (as can be seen in the last three columns of Table 1). The Poor countries have high birth rates and young age structures (initial data from Guatemala in 1985).

Table 1 shows the most important initial country endowments and population structures. The data in Table1—with the exception of TFRs and dependency ratios—as well as the simulation output, are "stylized" and in generic units applicable to the specific variables they describe, e.g., units of physical capital, production, consumption, etc. Although some empirical measures of technology, human and physical capital, and resource endowment exist, there is no way to know what would be the correct "scaling factor" to convert empirically based numbers into ones appropriate for our model and production functions. The country endowments (e.g., technology, human capital, land endowment) were set arbitrarily when the model was first developed, both in absolute magnitude and in relation to their values in the different countries; their values now are an integral part of the model. As the model has been built and calibrated around those initial values, their magnitudes help generate the desired basic behavior, i.e., initially the Rich countries will have the highest per capita GDPs, then the Middle, then the Poor; and some basic variables (GDP, production, prices) will follow fairly smooth trajectories (little oscillation) from the beginning.

Place Table 1 here

2 Model Modules

2.1 Production module

In each country, there are three production sectors: resource intensive industry (producing a final good), resource nonintensive ("service") industry (producing a final good), and natural resource extraction industry (producing an intermediate good). Final goods and processed natural resources are tradables, so their prices are the same for all countries; wage and rent rates are determined locally. Because labor (but not capital) is completely mobile (within each country), countries can shift production each period for competitive advantage. Since the producers are treated as profit-maximizing price takers, and since physical capital is not sectorally mobile, the amount of each good produced by each country is a straight-forward optimization calculation. The local wage rate for each country clears the labor market each period. (We do not assume international migration for the purpose determining the wage rate, rather differences in country's wage rates motivate migration, as will be discussed later.) At the end of each period each country's rent rate on physical capital is updated by recalculating the average marginal value product of capital for the three sectors, weighted by the total amount of capital in each sector.

Lastly, world prices for the two final consumption goods and the intermediate, natural resource good are calculated for use in the following period. These prices are calculated iteratively by equating forecasted world supply and demand. This (arguably simplified) solution method results in actual global supplies and demands that typically equate within +/- 3 percent (after an initialization process taking from three to seven periods). The national aggregate adjustments in equilibrium have many lags, constraints, and uncertainties, making for varied speeds of adjustment. These adjustments are too complex to model simultaneously, so we simplify by adjusting *prices* at the end of each period, and leaving the direction of *behavioral* adjustments to these new prices to the next period. Adjustments, therefore, lead to continued temporal changes—a main focus in the model.

The production functions for the two final consumer goods sectors, with all variables and parameters specific to each period t, are:

Resource nonintensive service sector, S:

$$Q_S = T\,(HL_S)^{\alpha ls} K_S^{\alpha ks} R_S^{\alpha rs} \tag{1}$$

Resource intensive industry sector, I:

$$Q_I = T\,(HL_I)^{\alpha li} K_I^{\alpha ki} R_I^{\alpha ri} \tag{2}$$

Where:

Q_S , Q_I : output for two sectors

T : input-neutral technological improvements (same for all sectors)

L_x, K_x, R_x (x = S,I) : labor, capital, natural resource input for individual sectors

H : human capital factor (same for all sectors)

αkx, αlx, αrx (x = s,i) : productivity exponents for three inputs and two sectors.

The production function for the resource extraction sector, also specific to each period t, is:

$$R = ATK_R^{\alpha kr} \left(HL_R\right)^{\alpha nr} \overline{R^{\gamma}} \tag{3}$$

Where:

R : amount of extraction

A : country specific factor representing land endowment

T : input-neutral technological improvements (again, same for all sectors)

L_R, K_R : labor and capital input

H : human capital factor (again, same for all sectors)

$\alpha kr, \alpha lr$: productivity exponents for capital and labor

$\overline{R}$: 8 year moving average of past extraction

γ : country specific drag parameter based on the extent of recent extraction (less than -1).

In the earliest versions of the model the natural resource was treated as exhaustible with the ability to increase resource base through investment. In these runs countries quickly extracted all of their original resource base and then treated the extraction sector as a renewable resource through investment. This pattern of extraction meant that rich countries tended to have lower cost curves for extraction because of higher technology and human capital factors. Having countries start with higher resource endowments meant only greater extraction and, thus, greater GNPs in the early periods.

The current extraction equation treats the natural resource as renewable. This assumption may be considered inappropriate for a study on sustainability, but the production function still has many qualities important to our questions; and it avoids the controversial decision of declaring an exact amount of the natural resource remaining. Essentially, we only want to impose problems people can solve, primarily through investment. We do not want to be accused of creating a “model of doom”; thus, we do not allow the resource base to run out, or to have irreparable damage done to it. We make these assumptions, not so much because we think the alternatives are improbable, but because those alternatives lead to predictable model outcomes, perhaps the greatest faults of the *World Dynamics* (Forrester, 1971) and *Limits to Growth* (Meadows et al., 1972) models.

Besides the difficulty in determining a number for the total amount of natural resource, there are other reasons to support the renewable format we have chosen. We model only one resource; however, in the real world many resources substitute for one another. There is also the empirical paradox that the stock of nonrenewable resources has actually increased over the very period when their extraction accelerated; yet, some potentially renewable resources have been threatened with permanent loss. Our equation allows for countries to differ in extraction ability based on the land endowment coefficient. This land-based difference corresponds to the generalization that resource endowment usually is related to land size; in addition, previous analyses that have considered material inputs, like Riccardo, often have used land to represent material inputs in the production function.

The purpose of the R bar raised to the drag parameter formulation is to allow for heavy recent production to increase rapidly the cost of further extraction, as too much extraction degrades the resource base. (The formulation is not meant to model regeneration per se.) The drag parameter is constrained to be less than -1.0 because we believe past extraction should have an increasingly negative effect on productivity. This increasing cost to extract can lead to *increasing prices* for the natural resource, *despite* its *inexhaustibility*. This drag is reduced by lowering extraction temporarily. The land endowment coefficient can be increased via investment.

2.1.1 Production function exponents

As mentioned above, the production functions are log linear or Cobb-Douglas. This means the elasticity among inputs is one, a reason many researchers believe these functions are appropriate to characterize the aggregate production relationships in many countries. This formulation is particularly appropriate for our model given the degree of aggregation each of the production functions represents. This ease of substitution may seem appropriate for capital and labor, but inappropriate for natural resource inputs. A translog production function would allow different degrees of substitutability between inputs; however, the Cobb-Douglas' rather simple mathematical form makes many of the other relationships in the model much easier to handle (this is another reason why they are generally popular). Furthermore, a more difficult substitution away from natural resources could be approximated by a relatively high exponent in the production function. Cobb-Douglas production functions can exhibit any degree of returns to scale, but we have chosen constant returns (i.e., the exponents sum to one). The log-linear relationship coupled with constant returns to scale lead to the helpful property that the exponents also correspond with the factor (labor, capital, natural resource) income shares for the inputs. We have used this property to estimate the exponents.

2.1.1.1 Data analysis

To estimate factor shares, and thus production factor exponents, we use *The OECD Input-Output Database* (1995a). This data base has input-output tables for 10 OECD countries at roughly five year intervals for, typically, the period 1970-1990 (years reported vary among the countries). The natural resource inputs came from the following sectors: agricultural, forestry, and fishing; mining and quarrying; industrial chemicals; petroleum and coal products; rubber and plastic products; nonmetallic mineral products; iron and steel; and nonferrous metals. Agriculture, forestry, and fishing; and mining and quarrying approximated the extraction and resource replenishment sectors. The resource replenishment function is used to calculate additions to the resource base and will be described in the following section on the investment module. The resource intensive, industry sector production consisted of the following sectors:

rubber and plastic products; nonmetallic mineral products; nonferrous metals; metal products (e.g., hand tools, metal furniture, boilers, steel pipes, steel wire, bolts, and nuts); non-electrical machinery (e.g., engines, turbines, and farm machinery); electrical apparatus (e.g., irons, motors, generators, welding apparatus, and vacuums); motor vehicles; and other manufacturing (jewelry, musical instruments, athletic goods, toys and games, and art supplies). Resource nonintensive, service sector production comprised: office and computing machinery; and radio, TV, and communication equipment. Non-electrical machinery and construction were used for the capital creation sector. The capital creation function is used in the addition of new physical capital and will be described in the following section. Table 2 shows the exponent values used in the simulation model (our results are similar to a number of other studies, e.g., Duchin and Lange, 1992; McKibbin and Wilcoxen, 1995; and Bernard and Jones, 1996).

Table 2

2.2 Investment Module

This section discusses how income is divided into investment and consumption; how the investment pool is allocated among the various investments; and how the return of investments are calculated, as well as how the various endowments are updated.

2.2.1 Investment-consumption breakdown

The investment module of the model is very important since it is the major way Poor countries can extricate themselves from the poverty traps, Middle countries can continue to grow, and Rich countries can sustain their prosperity. Thus, the relationship that defines what fraction of GDP is consumed, and hence what fraction is invested, is crucial. In order to calculate the amount invested, we need to determine the consumption fraction, c, then use the following equation:

$$I = (1-c)\ Y, \qquad (4)$$

where Y is GDP.

The share of a country's total GDP allocated for investment depends positively on the country's per capita GDP relative to the initial per capita GDP of the richest country (a measure of a minimum consumption necessity), and negatively on the country's young (ages 0-14) and aged (65+) dependency (i.e., the ratio of those cohorts to the total population). This relationship is one of the most important in the model[1]:

$$c = 0.34 + -0.071 \ln(GDP/\ GDP_0^R) + 0.7 \text{ x } pop(0\text{-}14) + 2.1 \text{ x } pop(65+) \qquad (5)$$

where c is the fraction of GDP for consumption, *GDP* is per capita GDP, GDP_0^R is the initial per capita GDP of the Rich country, *pop(0-14)* is the fraction of population aged 0-14, and *pop(65+)* is the fraction of population over 65. The GDP ratio term as well as c are constrained (by other equations) to be less than or equal to one. (Because our model does not have a financial sector, countries must invest all income that is not spent on goods consumption in projects commencing in the current period; thus, Equation 5 does not have a term for the return on investment.)

2.2.1.1 Regression analysis

The coefficients in Equation 5 were derived econometrically from panel data (observations in 1985 and 1990) from World Bank (1994b)[2]. All of the coefficients are statistically significant at least at the 95 percent level (the adjusted R-squared for the regression was 0.42). We normalize the per capita GDP term—by dividing by initial Rich country per capita

1 The one exception to the model's lack of *behavioral* sensitivity occurs when all the coefficients in Equation 5 are adjusted (by one standard deviation from their econometrically derived values) in the way that constrains investment the most. Under this scenario the rich countries' per capita GDP displays "growth and then collapse," as their share of income for investment eventually reaches zero (driven by their population aging).

2 More details on the regression analysis can be found in the appendix of Liddle, 2000.

GDP—(1) to render its impact indifferent to the magnitude of GDP and, thus, appropriate for the stylized values used in the simulation model, and (2) to lessen some of the regression problems common when the dependent variables are a combination of rates and levels. These results are similar to other econometric models, like Kelley and Schmidt (1994) and Mason (1987 & 1988); however, we attribute a greater drag on investment to aged dependency (perhaps because those analyses were only concerned with developing countries). Yet, a more recent study by Loayza et. al. (2000), finds, as we do, that old aged dependency has a significantly greater negative effect than youth dependency on savings (twice as great in their results). Our formulation gives middle countries (with per capita GDPs about one-fourth of rich countries') an opportunity to invest, but gives poor countries (with per capita GDPs 1/20 or less of rich countries') very little chance to catch up in the absence of transfer mechanisms like foreign direct investment or policies like fertility reduction.

2.2.2 Investment allocation

Each type of investment has a distinctive production function and cost function. From these functions rates of return are calculated for each investment type. (To project these production and cost functions over the life of an investment, current prices and factor endowments are assumed to be constant.) These different rates determine the percentages of the total investment pool that are allocated to each investment type via a logit share equation (thus, investment funds are allocated in proportion to their relative returns). The amount of the total investment pool, I_T, allocated to each of the seven investments (physical capital in the two final goods sectors and the extraction sector, technology, human capital, resource base enhancement, and environmental quality upgrading) is based on their relative returns to investment, ρ, i.e., the amount allocated to investment x, I_x, is:

$$I_x = I_T \quad \frac{\rho_x}{\sum \rho} \tag{6}$$

Each country's discount rate, at the end of each period, is adjusted linearly for changes in per capita GDP. Initially, the Rich countries' discount rate is five percent, the Middle countries' eight percent, and the Poor countries eleven percent. Sensitivity analysis on the discount rates shows they have little impact, not very surprising since country impatience is accounted for by the GDP term in Equation 5. Using different discount rates does change slightly countries' investment mixes, since the investments have different time lags associated with their returns (higher discount rates typically make physical capital investment relatively more attractive).

2.2.3 Physical capital

Each production sector has its own (well-mixed) physical capital allotment, which is increased through investment (by both domestic investment and foreign direct investment, which will be discussed later) and decreased by depreciation (set at five percent a year). Physical capital created (by investment) at the end of one period is considered operational (included in the production function) in the following period. The rate of return on physical capital for each sector depends on the marginal value product of capital for that sector.

Calculating the rate of return for the physical capital investments is less complicated than for other investments since an average rate of return can be found without knowing the actual amount invested. The benefits of one additional unit of capital is the marginal value product of capital, $MVPK_x$, where the subscript, x, refers to one of the three production sectors (physical capital is not mobile).

$$MVPK_x = P_x Q_x \alpha_{kx} / K_x \tag{7}$$

where P, Q, and α_{kx} are the world price, production level, and capital exponent from the production function for sector x. The rate of return on capital investment is the per unit benefits divided by the per unit costs, discounted for the life of the investment minus one. The per unit costs are derived from the production function for the creation of capital:

$$Q = T(HL)^{\alpha_l} K^{\alpha_k} R^{\alpha_r} \tag{8}$$

where Q is the physical capital output, T and H are the country specific multipliers, and α_l , α_k , α_r are the exponents for labor, capital, and natural resource (their determination was described in Sec. 2.1.1 and shown in Table 2), which sum to one. If the wage rate is w, the rent rate on capital r, and the natural resource price p, then Equation 8 can be manipulated to a per unit cost of capital, q:

$$q = \frac{1}{TH^{\alpha_l}} \left(\frac{w}{\alpha_l}\right)^{\alpha_l} \left(\frac{r}{\alpha_k}\right)^{\alpha_k} \left(\frac{p}{\alpha_r}\right)^{\alpha_r} \tag{9}$$

2.2.3.1 Return on investment

For all rate of return calculations it is assumed that present conditions (e.g., output, prices, factor endowments) remain constant in future periods. The benefits last for the life of physical capital, Λ, i.e., one over the depreciation rate, d, (Λ is equal to 20 periods for a depreciation rate of five percent). These benefits decline each period, however, since less of the added capital remains. Thus, the discount factor, f, is:

$$f = \sum_{\lambda=1}^{\Lambda} (1+i)^{\lambda} (1-d)^{\lambda-1} \tag{10}$$

where i is the country specific discount rate.

So, the return on physical capital investment is:

$$\rho_x \quad = \quad \frac{MVPK_x}{q} f - 1 \qquad (11)$$

The rate of return for physical capital investment will be higher:

1. the lower the cost of capital formation,
2. the lower the current capital stock,
3. the lower the discount rate, and
4. the higher the value product of production.

Each period physical capital is updated to reflect depreciation and any additions through investment. To find the added physical capital, the investment in physical capital is divided by the per unit cost of capital creation. But the per unit cost must be converted to real terms by multiplying the wage and rent rates and cost of natural resource by the country specific inflator (the ratio of the country's real to nominal GDP). The physical capital in sector *x* at period *t* is:

$$K_t^x = K_{t-1}^x (1-d) + \frac{I_t^{kx}}{q} \qquad (12)$$

2.2.4 Technology

Technology enters the production functions as a constant multiplier (*T* in equations 1-3). This is referred to as neutral technical progress—technical progress affects all inputs equally. The technology multiplier is the same for all production functions within a country (in the absence of direct foreign investment, to be discussed later). There is a 10 period lag on technology investment, i.e., the technology multiplier is *increased* based on technology investment 10 periods ago, but the technology multiplier does not depreciate if investment ceases. The addition to technology at period *t*, ΔT_t, is:

$$\Delta T_t \quad = \quad a \quad \ln\left[\overline{I_{t-10}}\right] H^{0.5}{}_{t-10} \; T^{-0.5}{}_{t-10} \qquad (13)$$

where a is a constant scaling factor, $\overline{I_{t-10}}$ is the five-year, approximate moving average of technology investment 10 periods prior to t, H_{t-10} is the human capital 10 periods ago, and T_{t-10} is the technology multiplier 10 periods ago.

We have used a laboratory or team model for technological innovation rather than a project one. According to Lederman (1987) this is how in fact most developed countries finance research and development (the US being an exception). A five-year moving average is considered the amount of intellectual capital employed in the lab or research group. An approximate moving average[3] is used since we believe an administrator is likely to spread over several years a particularly large investment in one year to finance work that will take many years. The average reflects the fact that innovation is an interactive process that takes time to bear fruit, i.e., labs must "ramp up."

Before the average is calculated, the investment is weighted to reflect uncertainty; the probability distribution of the weight is such that the mean weight is one (the uncertainty aspect was not used during calibration to ensure consistent results). Using a logarithmic relationship both bounds the increase in the technology multiplier and agrees with available data. Data in Lederman (1987) shows a logarithmic relationship both between nondefense R&D spending and technology intensive exports as well as between nondefense R&D and total scientists and engineers for a number of developed countries. Initially, the investment was raised to a power near, but less than one, to reflect diminishing returns. Also, the moving average of technology investment was raised to a power less than one, but a factorial analysis showed that the

[2] For example, a five-year moving average is updated by the following calculation: four times the previous average plus the new value all divided by five.

logarithmic nature of the function provided substantial diminishing returns to scale; so additional adjustments were not needed.

Human capital is a multiplier to reflect the importance of knowledge and skills in the work force in the creation and dissemination of new technology. In addition, this serves to further calibrate the scaling factor, which is the same for all countries. The scaling factor calibrates the creation of new technology function to different initial conditions. The scaling factor is set so the middle countries could increase their technology at five percent a year (the rate Solow, 1964 claimed new capital improves); those countries could do so if they consistently invest an amount equal to 10 percent of the high technology countries's initial GDP (originally it was to be three percent, a number closer to the share for many developed countries, but this made technological improvements too easy). In sensitivity testing the scaling factor was shown to be considerably more important than the size of the exponents. The equation for the scaling factor *a* is below:

$$a_T = T_M(0.05) / (\ln[(0.1)GDP_R](H_R)^{0.5}) \tag{14}$$

where the subscripts *R* and *M* refer to rich and middle countries.

We actually use current technology as a divisor to enforce decreasing returns to scale in technological advances and to help bound the creation of new technology function. This second reason is very important to prevent exponential growth, a large risk because of the input neutral nature of our technology multiplier. The natural log function is used to address the concern of bounding increases in technology[4]. That technology is effectively a divisor rather than a multiplier may seem counterintuitive since information accumulates and innovation tends to

3 Originally, an S-function was used for this purpose; however, it was very difficult to get enough curvature in the function so countries were not investing in the level part of the S. For the rich countries and in the later periods for

beget innovation. According to Rosenberg (1994), “Innovations breed other innovations because one innovation may raise sharply the economic payoff to the introduction of another, bringing those which are known to be technically feasible but so far economically unattractive to the point of adoption.” At any rate, the aspects Rosenberg refers to are captured, in part, in the return on technology investment calculations, as will be discussed below.

2.2.4.1 Return on investment

In order to calculate the rate of return on technology (or resource base enhancement, human capital, or environmental quality upgrading) the amount invested is needed. Of course, the amount invested is based on the relative rates of return. To treat this simultaneity, a simple algorithm is used: an arbitrary initial investment level is used to calculate a rate of return; these rates lead to the amount invested in each of the investments based on their relative values. The two investment amounts (the amount used to generate a return rate and the amount that corresponds to the resulting relative returns allocation) are averaged, and the process is repeated. Trials indicated that six repetitions lead to convergence.

The return on investment for technology is based on the difference in the current period between the technology multiplier with investment and with no investment (investment is assumed to be zero for both in subsequent periods). Based on the two assumptions on investment in technology (one with investment, one without), average past technology investment and delta technology variables are calculated. The increment in the technology multiplier, T, from investment, ΔT_I , is the difference between the two delta technologies. Since T is a multiple of the production function, the benefits of extra T, β_T, are the sum of the value of production in each of the three sectors times ΔT_I:

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the middle countries, a considerable amount of their investment occurred in this asymptotic range; thus, some of the

$$\beta_T = \sum_x (Q_x P_x) \Delta T_I \tag{15}$$

These benefits are assumed to be a perpetuity since *T* does not depreciate, but there is a 10 year lag between investment in new technology and its implementation; thus, the discount factor for β_T, f_B is:

$$f_B = \frac{1}{i} \times \frac{1}{(1+i)^{10}} \tag{16}$$

Since new technology is usually considered embodied in the physical capital stock, there is a cost to upgrade old capital with the new technology. This cost is considered to be a one time cost incurred when the new technology is introduced and is subtracted from β_T. The cost to upgrade capital is equal to the total capital stock, K_T, times the cost of capital formation, q (described in Sec. 2.2.3). The discount factor for this cost to upgrade, f_c, must also take into account that there will be less old capital at the time the new technology is introduced because of depreciation; thus, f_c is:

$$f_c = \frac{(1-d)^{10}}{(1+i)^{10}} \tag{17}$$

And the present discounted value of the benefits to technology investment less the cost to upgrade old capital is:

$$\beta_T f_B - K_T q f_c \tag{18}$$

Because of the nature of the moving average calculation, an investment in the current period will lead to a higher average past technology investment and, thus, higher delta technology

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investment had negative returns at the margin.

in periods beyond 10 periods hence. Therefore, the procedure to calculate the present discounted value of net benefits is repeated for another 10 periods; the rate of return for technology investment is the sum of all those calculations divided by the amount invested minus one. The rate of return for technology investment will be higher:

1. the greater past investment in technology,
2. the greater the level of human capital,
3. the smaller the current level of technology,
4. the lower the discount rate,
5. the lower the cost of capital formation,
6. the smaller the physical capital stock, and
7. the greater the value product of production in the three sectors.

2.2.5 Human capital

A country's human capital multiplier, H (in equations 1-3), is based on the average per student spending on education for the work force. The new H for a country is the weighted average of the H of the graduating class, G, and the current H of the work force, L:

$$\frac{H_G N_G + H_L N_L}{N_G + N_L} \tag{19}$$

where N refers to the size of the populations.

The H of the graduating class is based on the average per student spending for the class over their 12 periods in school. The per student spending for any one period is the sum of the normal level of education spending (a constant fraction of GDP based on development level) and any additional investment of human capital divided by the total student population. The per student spending levels have to be converted to human capital multipliers by a scaling operation. The scaling factors are based on the initial levels of human capital (a model input) and per student spending (a model output). This relationship is assumed to be linear except at the end points. For example, for the interior points, the scaling procedure essentially plots a straight line from two different adjacent, initial levels of human capital and their corresponding initial per student spending from which future conversions of spending to *H* are drawn. At the endpoints (the lowest level of *H* and twice the highest *H*), per student spending has a square root relationship with *H*. Thus, *H* will fall slowly for the poorest country if per student spending drops from its initial level, and at the high end human capital exhibits declining returns to per student spending (i.e., spending $30,000 per student does not produce twice as capable a student as $15,000).

A graduating class's *H* has a greater impact on the country's *H* as a whole when the graduating class is large relative to the work force. Also, a one period increase in per student spending likely will have a marginal effect on the graduating class' *H* since it will be averaged together with the per student spending for the previous 11 periods.

2.2.5.1 Return on investment

The rate of return on human capital investment is based on the difference in the country's human capital with and without investment. Like technology, human capital is essentially a multiple on the production function; however, it will have a different strength for the different sectors since the labor exponent is different. The net benefits to investment are equal to the difference between the sum of value products of production for each sector with investment and without investment. As before, all other aspects of the model are assumed to be constant; thus, given human capital investment *I*, the net benefits are:

$$\sum_x \left[Q_x P_x \frac{H_I^{\alpha lx}}{H^{\alpha lx}} - Q_x P_x \frac{H_0^{\alpha lx}}{H^{\alpha lx}} \right] \qquad (20)$$

where H_I, is the new human capital after the investment, H_0, is the human capital with no investment, and H is the previous level of human capital.

These benefits are assumed constant and last for the lifetime of the average worker (calculated from the country's age specific death rates). In addition, a new flow of benefits is added for the following 11 periods as each of the other current classes graduates into the work force. Thus, the discount factor f, is:

$$f = \frac{(1+i)^{L_e} - 1}{i(1+i)^{L_e}} \left[1 + \frac{(1+i)^{11} - 1}{i(1+i)^{11}} \right] \tag{21}$$

where L_e, is the worker life expectancy.

The return on human capital is the net benefits multiplied by the discount factor divided by the amount of investment minus one. The rate of return for human capital investment will be higher:

1. the lower is the discount rate,
2. the higher is the lifetime of the average worker (or the lower are the age specific death rates),
3. the greater the value product of production in the sectors with high labor exponents,
4. the larger the graduating class is relative to the work force, and
5. the larger the graduating class is relative to the other classes.

2.2.6 Resource base replenishment

Investment in the resource base increases land endowment, A (in equation 3). This investment is analogous to exploration, but is limited by original land endowment and the sum of past additions to land endowment (via rapidly diminishing returns); thus, countries with small original land endowments but large amount of investment funds could not end up being the major resource producing country. Finally, there is a five period lag between investment in resource replenishment and increases to land endowment. The equation for additions to land endowment is:

$$\Delta A_t = \left(\frac{I_{t-5}}{\kappa}\right)^{\Psi} \Theta^{\frac{\sum \Delta A}{A_0}} \qquad (22)$$

where:

ΔA_t is the amount of land added in period *t*,
I_{t-5} is the amount of investment in period *t-5*, (there is a five year lag) ,
κ is the cost to add *A*,
Ψ reflects diminishing returns to investment; it is set to less than 1 (currently 0.6),
Θ reflects diminishing returns to additions to endowment; it is also less than 1 (currently 0.1),
$\sum \Delta A$ is the sum of past additions to land endowment,
A_0 is the original land endowment.

The cost to add one unit to *A*, κ; comes from a production function analogous to Equation 3, except there is no term for past extraction, but there is a scaling factor set to 0.25. The cost is derived in the same way the cost to add capital was, as described in Sec. 2.2.3. As with additions to physical capital, the cost to add one unit must be put in real terms by multiplying the wage and rent rates by the country inflator. The moving average of past extraction is then updated to account for last period's production.

2.2.6.1 Return on investment

The amount that land endowment is increased given a certain investment can be calculated once the cost to add one unit is known. The next step is to calculate the approximate constant amount of extraction, five years hence, given today's prices with the new land endowment. The benefits to investment are the difference between the approximate constant extraction with and without augmenting the resource base multiplied by the current resource price. These benefits are discounted in a fashion similar to technology (Equation 16), except the perpetuity begins in five periods. The rate of return is the benefits dividend by the investment amount minus one. In order to approximate future extraction, the past use variable is updated by assuming the current rate is maintained for the next four periods. The rate of return for resource base replenishment investment will be higher:

1. the lower is the discount rate,
2. the lower is the cost to add to A,
3. the higher is the natural resource price,
4. the higher is initial land endowment, and
5. the lower is the cumulative past addition to A.

2.2.7 Foreign direct investment

The three middle countries and two rich countries form a multi-national “investment corporation” that invests in and builds, when profitable, physical capital in the two poor countries. The investment corporation allocates its investment pool (the sum of contributions from the five controlling countries) in six investments (physical capital in the three economic sectors of the two poor countries) according to relative returns. The donor countries decide how much to invest in the pool based on relative returns (compared with their average return on “domestic” investments, i.e., their physical capital in the three sectors, technology, resource replenishment, and environmental quality upgrading—to be discussed below). The investment corporation has its own wage rate, rent rate, cost to produce physical capital (determined by the same function used by the individual countries), discount rate, human capital, and technology. These factors are a weighted average of the factors for the contributing countries (based on their share of the corporation’s investment pool). The corporation receives rent payments (based on the rent rate of capital in the host or poor country) on their capital, which it divides among the members according to their share of the total pool. The individual countries repatriate or reinvest their shares depending on the investment-consumption rate of their home investments (determined by Equation 5).

The poor countries pay, out of their own GDP, rent on the foreign capital. They also either nationalize the foreign capital at a specified rate (set at 8 percent, a rate roughly optimal for the poor countries) or tax the investment corporation's remittances (40 percent is roughly optimal). This nationalization or tax rate influences the amount of foreign capital, beyond the obvious, by affecting the profitability of direct foreign investment since the corporation knows this rate and incorporates it into its return on investment calculation.

Hence, the return on foreign direct investment for the donor countries is based on the rent rate in the recipient country, the cost to create capital for the investment corporation, and the donor country's repatriation rate (one minus their savings rate), all of which is discounted at the donor country's discount rate for the life of physical capital. In addition, donor countries make an adjustment to account for either the tax on remittances or nationalization, which effectively reduces the life of capital, and thus the length of the payment stream.

The fact that we only allow FDI flows to go from the wealthier countries to the poorest does run counter to empirical evidence. Most FDI flows occur among countries at similar development levels; indeed, most FDI from developed countries goes into other developed countries. We apply this restriction to FDI in large part to greatly simplify the FDI module; in addition, the sole motivation for adding such a module was to determine how effective it would be in evening growth among the richer, growing countries and the poorer ones.

Lastly, there is a technology transfer from the investment corporation to the poor countries. The rate of this transfer depends on the share of a sector's capital that was foreign produced and the technology's "appropriateness" (based on the difference in technology and ratio of human capital of the poor country to that of the investment corporation).

2.2.7.1 Technology transfer/diffusion

The FDI receiving countries' technology is updated via a diffusion process that assumes (i) the physical capital just added by the FDI corporation incorporates its technology, and (ii) the technology associated with capital indigenously created is increased, over time, based on the technology gap between the receiving country and the investment corporation and on the ratio of their human capital. Thus, the receiving countries' new technology (now sector *x* specific), $T_{x,t+1}$ is:

$$T_{x,t+1} = T_{x,t} \times \left(1 - \frac{K_{FDI,x,t}}{K_{x,t}}\right) + \left[\left(T_{FDI,t} - T_{x,t}\right) \frac{H_t}{H_{FDI,t}} \frac{1}{time_d} + T_{x,t}\right] \times \frac{K_{FDI,x,t}}{K_{x,t}} \qquad (23)$$

where the subscript FDI refers to the investment corporation, $K_{x,t}$ is the total amount of capital in sector *x* at time *t*, $K_{FDI,x,t}$ is the amount of foreign capital just added to sector *x* during period *t*, and $time_d$ is the time for technology to diffuse (set to 3).

2.3 Environment and Welfare Module

The environmental module essentially considers air pollution and focuses on local and regional impacts of a flow pollutant. The strategy is to relate emissions to economic activity and, to a lesser extent, economic structure and to allow countries to invest in environmental quality upgrading (or remediation). Environmental quality and per capita final goods consumption are the arguments of a log-linear welfare function. Environmental quality is the difference between the environment in a pure state and "effective pollution," or the amount of pollution produced that is not remediated through investments in environmental quality upgrading.

2.3.1 Welfare function and pollution level

The welfare function is log-linear, consisting of per capita final goods consumption and environmental quality. The exponents for environmental quality and goods consumption sum to one.

$$W = EQ^{\theta} C^{\phi} \tag{24}$$

$$1 = \theta + \phi(\theta) \tag{25}$$

Where: *W* is welfare, *EQ* is environmental quality, and *C* is per capita final goods consumption. The exponent for environmental quality changes so that the welfare weight of environmental quality increases with per capita GDP according to the modified exponential function:

$$\theta = g - jb^{GDP} \tag{26}$$

where *GDP* is GDP per capita.

Three initial conditions are needed to solve this equation:

1. the maximum exponent for environmental quality,
2. the minimum exponent for environmental quality, and
3. the initial exponent for a rich country.

If these three conditions are assumed to be: 0.8, 0.1, and 0.275, respectively, for example, Equation 26 becomes:

$$\theta = 0.8 - 0.7b^{GNP} \tag{27}$$

where *b* is:

$$b = 0.75^{\frac{1}{GNP_0^R}}, \tag{28}$$

where GNP_o^R is the initial GNP per capita for the Rich country.

Environmental quality is an index value for a pure environment minus the amount of pollution consumed.

$$EQ = EQ_0 - \Pi(1-\pi) \qquad (29)$$

where:

EQ_0 is environmental quality in a pure state (arbitrarily set at 1100, a value high enough so *EQ* is always positive),
Π is pollution produced, and
π is the percentage remediated.

The percentage remediated is based on the amount of investment in environmental quality upgrading per unit of pollution produced, *e*, and the ease of remediation, Γ (currently set to 0.05), and has the same functional form as the equation for the environmental quality exponent:

$$\pi \quad = \quad 0.99\left(1-\Gamma^{e}\right) \qquad (30)$$

We are assuming that the maximum amount remediated is 99 percent of pollution produced and that environmental quality upgrading investment is made on a yearly basis. The easiest (cheapest) measures are taken first, then the more expensive measures. Removing the last few percentages is quite expensive. This model of rapidly increasing marginal costs of abatement is consistent with empirical data.

The idea that environmental quality upgrading investments must be made anew each period is used to greatly simplify the model. This simplification may seem counterfactual; however, even remediation technologies like scrubbers require yearly maintenance in addition to the capital investment, and many of the least expensive measures like “good housekeeping” require annual efforts. Indeed, a greater role for operating expenditures than capital ones does not contradict some of the evidence. US Bureau of the Census (1996) data shows for all industries the share of operating costs in total abatement expenditures is 71 percent for total pollution (air, water, and solid waste) and 58 percent for air pollution.

Despite the environmental module's simplicity, it can account for some of the complexities of scale in environmental quality upgrading. Countries with large amounts of pollution are assumed to have many pollution sources; thus, a relatively large aggregate amount of pollution could be reduced with a small per unit expenditure if at each source only the easiest measures were employed. However, a country with a small amount of total pollution most likely would have fewer sources; thus, a higher per unit expenditure would be needed to achieve a similar aggregate reduction (because a larger percentage reduction is required).

Pollution (which results from energy use) is assumed to be a linear function of resource intensive production and a log-linear function of per capita consumption. The amount of pollution produced follows from Equation 31:

$$\Pi \quad = \quad \eta Q_I + a_{EQ}\left(N \times \mu C^{\nu}\right) \tag{31}$$

where:

Q_I is resource intensive production,

N is total population,

η, μ, and ν are econometrically derived constants, described in Sect. 2.3.1.1 below,

and a_{EQ} is a scaling factor set at 0.10.

Since the energy use from resource intensive production and consumption are index values, the correct way to add them is not clear (dimensional consistency is not meaningful). In order to calculate the scaling factor, a_{EQ}, it is assumed that approximately one-quarter to one-third of the Rich country's initial energy consumption comes from resource intensive production, an amount consistent with empirical data.

The most important aspect of this relationship is that pollution depends on consumption (which means pollution cannot be avoided completely through economic structural change). The log-linear nature of this relationship could be interpreted as consumption becoming *relatively* less polluting as countries become richer; however, in the absence of investment in environmental quality upgrading, the relationship between consumption and pollution is unambiguous, i.e., more per capita consumption leads to greater per capita pollution. This model feature captures the (often overlooked) empirical fact that primarily-consumption-driven pollution is significant in developed countries; for example, in the US, personal transport and energy use in the residential building sector account for the majority of total energy consumption and a large percentage of air pollution emissions. In addition, personal transport and personal living space have generally increased, not decreased, with wealth in developed countries.

2.3.1.1 Regression analyses

To determine the coefficients for energy consumption (μ *and* ν in Equation 31), a log-log relationship between energy as a consumption good per capita and total consumption per capita was assumed. Energy consumption per capita data (in kg of oil equivalent) from World Bank (1994a) was multiplied by the percentage of energy consumption not used in industry (i.e., the amount used in buildings and transport) from IEA (1990 and 1983) to get the amount of energy as a consumption good per capita. This data on energy consumption share was found for the period 1980-1990 for OECD[5] countries and 1973 to 1982 for non-OECD[6] countries. To get the

[5] The OECD countries are: Australia, Austria, Belgium, Canada, Denmark, Finland, France, W. Germany, Italy, Japan, Netherlands, Norway, Spain, Sweden, Switzerland, UK, and US.

[6] The non-OECD countries are: Bangladesh, Brazil, Columbia, Costa Rica, Egypt, Hong Kong, India, Indonesia, S. Korea, Malaysia, Morocco, Pakistan, Panama, Philippines, Singapore, Sri Lanka, Thailand, Tunisia, and Uruguay.

amount of total consumption per capita Summers and Heston (1991) GDP per capita data was multiplied by the percentage of GDP for private consumption (data from World Bank, 1994b).

Because of the substantial difference in the timing of observations between the two data sets (i.e., OECD and non-OECD countries), they were regressed separately. The elasticity for energy consumption was less than one for both groups; the constant term was higher for the OECD countries. All the coefficients were statistically significant (the heteroskedasticity consistent regression statistics are shown in Table 3). Serial correlation was corrected using autoregressive terms. The constant term is the mean of the country effects weighted by the number of observations. Because of the log-log structure of the regression model, the coefficient on the GDP per capita term is the elasticity for energy consumption; i.e., as GDP rises by one percent, energy consumption increases by the elasticity times one percent (or in these cases 0.79 or 0.72 percent).

Table 3

For the simulation model, μ *and* ν in Equation 31 are set to the coefficients of the constant term and the GDP per capita term (respectively) from Column 1 in Table 3 for countries with GDP per capita greater than the initial value of the rich countries; they are set to the coefficients from Column 3 in Table 3 for countries with GDP per capita below the initial value of the middle countries. For countries with GDP per capita in-between these two levels, a simple linear extrapolation is used to determine μ *and* ν.

Since pollution is really an index measure in the simulation model, the structure of the pollution-development relationship is more important than the precision of the parameters; i.e., the important point for our model is that pollution (prior to abatement) rises with income, but at a declining rate, and that per capita pollution from consumption activity (again, prior to abatement) is greater for developed than for developing countries. Indeed, sensitivity analysis showed that changing the parameters in Equation 31 by as much as three standard deviations from the mean values of the coefficients in Table 3 and Table 4 had virtually no effect on GDP or welfare levels.

To calculate the energy used in resource intensive production (or η in Equation 31), the ratio of output to energy input for the steel industry was used. Steel is an important energy intensive production sector, and one in which data on both output and energy input are available. The steel production data (in million tons) come from OECD (1995b). The IEA (1993) publishes data on total energy used (Mtoe), as well as on the breakdown of the type of energy used in steel production for most OECD countries. To account for the greater amount of work that energy forms like electricity, oil, and natural gas can perform compared to coal, a term for the percentage of energy from oil and natural gas and for the percentage of energy from primary electricity used to produce steel was added to the independent variables, as in Kaufman (1992).

The ratio of steel produced to energy used was regressed on a constant term, the natural log of the two energy quality terms, and on country dummy variables (the heteroskedasticity consistent results shown in Table 4)[7]. The resulting coefficient for the constant term (the value of η in Equation 31) is the ratio of output to energy input, after accounting for statistically significant country specific effects and changes caused by fuel mix. The relationship reflected in that ratio assumes a constant technology for energy and one that is the same for all countries. For most countries in the sample the actual ratio does not change much, but for the ones where it does change, energy quality changes in the predicted direction as well. It may seem an oversimplification, however, to have the same technology for developing and developed countries, but the necessary data was not available for developing countries. Furthermore, as with the previous regession, the structure is more important to simulation results than the value of the parameters.

Table 4

2.3.2 Return on investment

Investment in environmental quality upgrading (remediation) is not really an investment, but another form of consumption. Thus, to calculate its return the extra welfare from a cleaner environment must be converted into consumption terms. First, given no environmental upgrading, the welfare level corresponding to the current consumption and environmental quality is calculated. Next, given a certain expenditure on environmental upgrading and the same consumption level, a higher welfare level is calculated. The benefit of environmental upgrading is measured as the additional goods consumption needed to raise the no-environmental upgrading-welfare level to the environmental upgrading-welfare level. Unlike the other investments, environmental quality upgrading has a one-time immediate payoff, so no discounting is required.

The benefit of environmental quality upgrading is the additional consumption needed to raise the no-upgrading-welfare level, W_0, to the upgrading-welfare level. The return on environmental quality upgrading, ρ_E, is simply this delta consumption, ΔC, divided by the expenditure, I_E , minus one.

$$\Delta C \quad = \quad N\left(\frac{W_0}{EQ_I^{\theta}}\right)^{\frac{1}{\phi}} - C \qquad (32)$$

[7] The countries are: Australia, Austria, Belgium, Canada, Finland, France, W. Germany, Italy, Japan, Luxembourg, Netherlands, Sweden, and UK.

$$\rho_E = \frac{\Delta C}{I_E} - 1 \tag{33}$$

where EQ_I, is the environmental quality with upgrading.

Thus, the rate of return for environmental quality upgrading will be higher:

1. the higher the weight of environmental quality in the welfare function (and therefore the current GDP per capita),
2. the higher the pollution level with no upgrading, and
3. the lower the index value of a pure environment.

2.4 Population Module

2.4.1 Model population cohorts

In the model population is adjusted each period for aging, births, and deaths according to the cohort-component method. In the cohort-component method, population is broken down according to gender, typically into five-year age groups (in our model we do not separate male and female, but assume a 1:1 ratio). For each period the number of survivors in each cohort is determined from the appropriate cohort specific death rate; then, a certain number of survivors, usually the reciprocal of the number of ages in the cohort, moves to the next cohort. Births, or size of the new 0-1 cohort, are based on the number of females and the corresponding fertility rates for the cohorts typically in the 10-54 year range.

For the simulation model aging is performed based on one year cohorts, i.e., instead of one-fifth of a cohort moving to the next one, the amount of people at each age is known. The age specific death rates are applied according to the following cohorts: 0-1, 1-4, 5-14, 15-29, 30-39, 40-49, 50-59, 60-64, 65-69, 70-74, 75-79, and 80+. The following cohorts are used to calculate births: 15-19, 20-29, 30-34, 35-39, and 40-49. The school age population consist of 6-17, and the working population consist of 18-64. The birth rates and death rates for infants (0-1), children (1-5), and the aged (approximately 60 and up) are updated every five periods, based on the econometric analysis to be discussed below.

2.4.2 Regression analysis[8]

The relationship between fertility and socioeconomic factors is quite complex, and examining this relationship empirically is very difficult. Rather than using an array of variables like urbanization, extent of work force in agriculture, measures of culture and various interaction terms to get at the nuances of development, we keep our regression models simple. Our goal is not to determine the “true” fertility-development relationship, but to have an empirical basis for adjusting birth and death rates as other model parameters change, and then to test this relationship, along with others, in a series of designed factorial experiments. We use regression models based on percentage changes in variables, specifically, log linear relationships between levels, where the exponents, or regression coefficients, correspond to elasticities.

The fertility regressions are divided in two, i.e., separate equations for developing and developed countries. For the developing countries fertility is regressed against the average schooling years in the female population over age 25, and the previous period’s infant mortality. The education variable does not have a lag, both because a lag is built in by its over age 25 nature, and because the variables, which occur at five year intervals, are all more like averages than point measures. Infant mortality does have a lag because of the way this variable enters the child survival hypothesis. Although this hypothesis is controversial, it is included because the parameter is readily measured in the simulation model, is highly significant and important in all regression runs, and indirectly allows per capita GDP to enter in the relationship (as will be described below). Although statistically significant, per capita GDP was not included in the final regression since the theories behind human capital's involvement are judged stronger. Our human capital measure reflects more than just educational level, but also culture, socioeconomic development, and employment opportunities.

For the developed countries only a time trend is used. The time trend is included since fertility continues to fall for most developed countries, even after it has dropped below replacement level; this drop is probably not caused by increased development or higher education levels for women.

The infant mortality regressions are also split in two, along the same lines as for fertility. For the developing countries infant mortality is regressed against the same education measure as for fertility, per capita GDP, and time; for the developed countries infant mortality is regressed against only time. A time trend is included since infant mortality has dropped in developed countries and developing countries, even ones where per capita GDP has fallen or remained constant. In developed countries this result probably reflects continued improvements in health technology, and in developing countries it probably reflects international aid efforts (which are not otherwise accounted for in the simulation model).

The child mortality regressions use the same independent variables as the infant mortality ones. For aged mortality only one model is used (developed and developing countries are not separated), and the independent variables are per capita GDP and a time trend, except for the 75-79 cohort, which only uses the time trend. Tables 5-11 show the various regression coefficients

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[8]The child (1-4) and old age mortality rates are from Keyfitz and Flieger (1990); the total fertility and infant mortality rates are from World Bank (1994b); the per capita GDP data (in 1985 US dollars) are from Summers and Heston (1991), and the education data are from Barro and Lee (1993).

and T-statistics, as well as to which elasticities in Equations 34-38 below the coefficients correspond.

Tables 5-11

2.4.3 Model population adjustments

As mentioned above, the birth and death rates are adjusted every five periods. The birth rate and the infant and child death rate adjustments depend on development level. If the three-period moving average of a country's per capita GDP is less than the Rich country's initial GDP, and if its human capital multiplier is less than 90 percent of the Rich country's, then the country's birth rates are adjusted according to Equation 34; otherwise, Equation 35 applies (*B* refers to the birth rate, *H* to human capital, *D* to the mortality rate, *X* the cohort, *t* the time period, the Δ operator to the percent change from the level 5 periods prior, and the ε's to the elasticities from the regression equations).

$$B_X^t \quad = \quad B_X^{t-1}\left[\varepsilon_1 \Delta H + \varepsilon_2 \Delta D_{0-1} + 1\right] \tag{34}$$

$$B_X^t \quad = \quad B_X^{t-1}\,\exp\left(5\varepsilon_3 5/t\right) \tag{35}$$

The extra term (*5/t*) is included in the exponential in Equation 35 since the rate of decrease in the birth rate must slow down as it approaches zero; for this same reason this function is used in the infant mortality Equation 37. The adjustment for infant and child mortality are the same. As long as a country's (infant or child) mortality rate is greater than the Rich country's initial mortality rate, Equation 36 is used; otherwise, Equation 37 applies.

$$D_X^t \quad = \quad D_X^{t-1}\left[\varepsilon_{4,8}\Delta GDP + \varepsilon_{5,9}\Delta H + 1\right]\exp\left(5\varepsilon_{6,10}\right) \tag{36}$$

$$D_X^t \quad = \quad D_X^{t-1}\ \exp\left(5\varepsilon_{7,11}5/t\right) \tag{37}$$

For all countries the aged mortality is adjusted according to Equation 38 (except for the 75-79 cohort where only the time-trend factor applies).

$$D_X^t \quad = \quad D_X^{t-1}\left[\varepsilon_{12,14,16}\Delta GDP + 1\right]\exp\left(5\varepsilon_{13,15,17,18}\right) \tag{38}$$

Although explicitly modeling population by the cohort method is certainly important, the econometrically derived coefficients that adjust mortality and fertility rates have little impact (of course, the individual countries' initial population parameters and the ways population feeds back into the model are very important). Changing the coefficients in the fertility and mortality rate adjustment equations by one standard deviation (or more in some cases) from their means had a negligible impact on per capita GDP and only a small impact on total population itself. Final populations for the various countries differed by only five percent or less between the two sets of extreme settings (i.e., +/- one standard deviation), and final age structure varied hardly at all. In fact, changing model parameters that lead to more income growth in the poor countries had a much greater impact on the poor countries' populations.

2.4.4 International migration

To examine the effects of migration-induced changes in countries' populations a simple migration module was added. It is assumed that the motivation for a worker's migrating is to maximize his human capital adjusted wage. The human capital adjusted wage is the country's wage rate divided by its human capital multiplier. This operation reflects the fact that lower skilled immigrants expect lower wages than the higher skilled indigenous population. In addition, migrants are assumed to come only from the 20-35-age cohort. Besides the obvious impacts of a larger and younger population, migrants affect their host countries in more subtle ways. Migrants bring with them their country's human capital multiplier and fertility rates, thus affecting the host country's (through a simple weighted average).

The direction of migration is from countries with a lower human capital adjusted wage to countries with higher ones. Migrants do not return to their source countries, nor do they remit any of their wages to relatives in those countries. The destination country of the migrants is determined from a logit model. Besides the relative weighted wage, migrants are attracted to countries where there is a history of past migration from their country and their cultures are similar (as measured by a ratio of the countries' respective human capital). Migrants are discouraged from a particular host country if that country makes an effort to restrict their migration. Countries restrict migration when their population density is high (as measured by the population divided by the initial natural resource endowment) and the prospective migrants' culture is very different from their own. Migration is encouraged when a host country's retired population is large relative to its total population.

There are two "judgmental" parameters in this module that are *particularly* important because they help govern the total flow of people in and out of the countries. One of these parameters is the *maximum percentage of people migrating each period* (set at 0.15), i.e., given a very large difference in adjusted wages, the maximum percentage of the 20-35-age cohort a country (or our model) will "allow" to leave. The other important parameter is the *percentage of migrants remaining in the system* (set at 0.25). Because of the limited number of destination countries in our model (relative to the real world), we believed that all migrants could not be accounted for without rather extreme changes in population occurring. Thus, we allowed the model to be *open* in this one respect: only a certain percentage of migrants actually will find their way to one of the other six countries; others will simply be "lost." For example, if those two parameters were set at 0.05 each, migration would have nearly no impact, and the results would be virtually the same as a no-migration case; however, if they were set at 0.4 and 0.5 (respectively), migration would cause extreme population changes in all the countries, and the rich countries would become the largest countries by a factor of two. On the other hand, if the *maximum percentage of people migrating each period* is set high and the other parameter set low, all countries would have small populations, and the middle countries would effectively experience substantial aging since their out-migrants would not be replenished via in-migrants from the poor countries.

2.4.4.1 Module equations

The probability that someone migrates during any one period is:

$$m\left[1-\left(\frac{\sum \overline{w}}{\overline{w}}\right)^{-0.7}\right] \tag{39}$$

Where *m* is the maximum percentage of the eligible cohorts that are allowed to migrate in any one period (set at 0.15), $\overline{w}$ is the migrant's country's weighted wage, and $\Sigma\overline{w}$ is the sum of the weighted wages of potential destination countries, (i.e., the rich and other middle countries for a middle-source country and the rich and all middle countries for a poor-source country). A country's weighted wage is that country's five-year-moving-average wage times its five-year-moving-average employment rate divided by its current human capital multiplier.

A potential destination country's defensive adaptations against in-migration from a particular source country, $DAI_{s,d}$, is:

$$DAI_{d,s} = \left(\frac{N}{A_0}\right)^{0.2} \left(1-\frac{N_{65+}}{N}\right)^{0.25} \left(\frac{H_d}{H_s}\right)^{0.75} \tag{40}$$

Where the subscripts s and d refer to the source and destination country, A_0 to the destination country's original land endowment, and N to the size of the destination country's population. The probability that a migrant would go to a particular destination country (again calculated from a logit model) is that destination country's "score" divided by the sum of the scores of all potential destination countries, where the score for a migrant from country s to migrate to country d is:

$$\left(\frac{\overline{w_d}}{\overline{w_s}}\right)^{0.5} \left(\frac{H_s}{H_d}\right)^{0.2} \left(DAI_{d,s}\right)^{\zeta} \left(\overline{M_{d,s}}\right)^{0.4} \tag{41}$$

Where $\overline{M}_{d,s}$ is the ten-year-moving-average of past migration from country s to country d, and the exponent ζ represents a policy variable that is used by the rich countries to skew the composition of in-migrants toward the higher-human capital, middle countries, and thus, is either –0.2 or –2.2.

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Table 1: Initial Country Endowments

	Technology multiplier[1]	Human capital multiplier[2]	Land endowment[3]	Total population	TFR	Aged dependency ratio	Youth dependency ratio
Rich1	3.0	3.0	2.5	182	1.81	0.244	0.536
Rich2	3.0	3.0	10.0	300	1.81	0.244	0.536
Middle1	2.0	2.0	5.0	204	3.58	0.073	1.086
Middle2	2.0	2.0	10.0	200	2.47	0.105	0.741
Middle3	2.0	2.0	15.0	300	1.88	0.106	0.635
Poor1	1.2	1.0	20.0	465	5.96	0.071	1.392
Poor2	1.2	1.0	20.0	200	5.96	0.071	1.392

Notes: (1) The *T* in Equations 1-3. (2) The *H* in Equations 1-3. (3) The *A* in Equation 3.

Table 2: Production Function Exponents

	Resource nonintensive, service sector	Resource intensive, industry sector	Extraction sector/ resource replenishment	Capital creation
Labor share	0.6	0.45	0.3	0.5
Capital share	0.3	0.20	0.7	0.2
Material share	0.1	0.35		0.3

Table 3: Energy Consumption Regression Results

	OECD countries		Non-OECD countries	
	(1) Coefficient	(2) T-statistic	(3) Coefficient	(4) T-statistic
Constant	2.568	229.29	1.155	126.64
GDP consumption/capita	0.785	181.82	0.718	117.39
Time	-0.00486	-3.19	0.0150	1.97
AR(1)	0.819	11.94	0.306	2.07
AR(3)	-0.111	-1.57		
Adjusted R^2		0.989		0.993
Breusch-Godfrey LM		0.633		0.000
Probability		0.889		1.000
N		187		181

Table 4 : Steel Output-Energy Input Regression Results

Variable	Coefficient	T-statistic
Constant	3.90	18.25
Ln (Share of oil and gas)	0.26	2.42
Ln (Share of electricity)	0.47	8.89
Canada	-0.25	-4.69
Finland	0.36	3.84
Japan	0.40	3.68
Italy	0.35	4.86
Luxembourg	0.45	7.89
Netherlands	0.29	6.48
Adjusted R^2	0.777	
Durbin-Watson statistic	1.88	
N	78	

Table 5: Fertility Regression Statistics

	Elasticities for Equations 34 & 35	Coefficient	T-Statistic
Developing Countries			
Education	ε_1	-0.0294	-1.99
Infant Mortality	ε_2	0.3996	14.55
Adjusted R^2		0.6913	
Observations		297	
Developed Countries			
Time	ε_3	-0.0124	-3.07
Adjusted R^2		0.16	
Observations		85	

Table 6: Infant Mortality Regressions

	Elasticities for Equations 36 & 37	Coefficient	T-Statistic
	Developing Countries		
Per capita GDP	ε_4	-0.4348	-13.89
Education	ε_5	-0.1598	-7.7
Time	ε_6	-0.0139	-6.87
Adjusted R^2		0.7824	
Observations		406	
	Developed Countries		
Time	ε_7	-0.038	-7.47
Adjusted R^2		0.3089	
Observations		102	

Table 7: Child Mortality Regression Statistics

	Elasticities for Equations 36 & 37	Coefficient	T-Statistic
	Developing Countries		
Per capita GDP	ε_8	-0.9233	-6.54
Education	ε_9	-1.0742	-6.11
Time	ε_{10}	-0.0122	-1.19
Adjusted R^2		0.9009	
Observations		46	
	Developed Countries		
Time	ε_{11}	-0.0434	-8.03
Adjusted R^2		0.4897	
Observations		69	

Table 8: Age 60-64 Regression Statistics

	Elasticities for Equation 38	Coefficient	T-Statistic
Per capita GDP	ε_{12}	-0.1661	-2.87
Time	ε_{13}	-0.0098	-3.33
Adjusted R^2		0.3028	
Observations		173	

Table 9: Age 65-69 Regression Statistics

	Elasticities for Equation 38	Coefficient	T-Statistic
Per capita GDP	ε_{14}	-0.0965	-1.58
Time	ε_{15}	-0.0125	-4.37
Adjusted R^2		0.2503	
Observations		173	

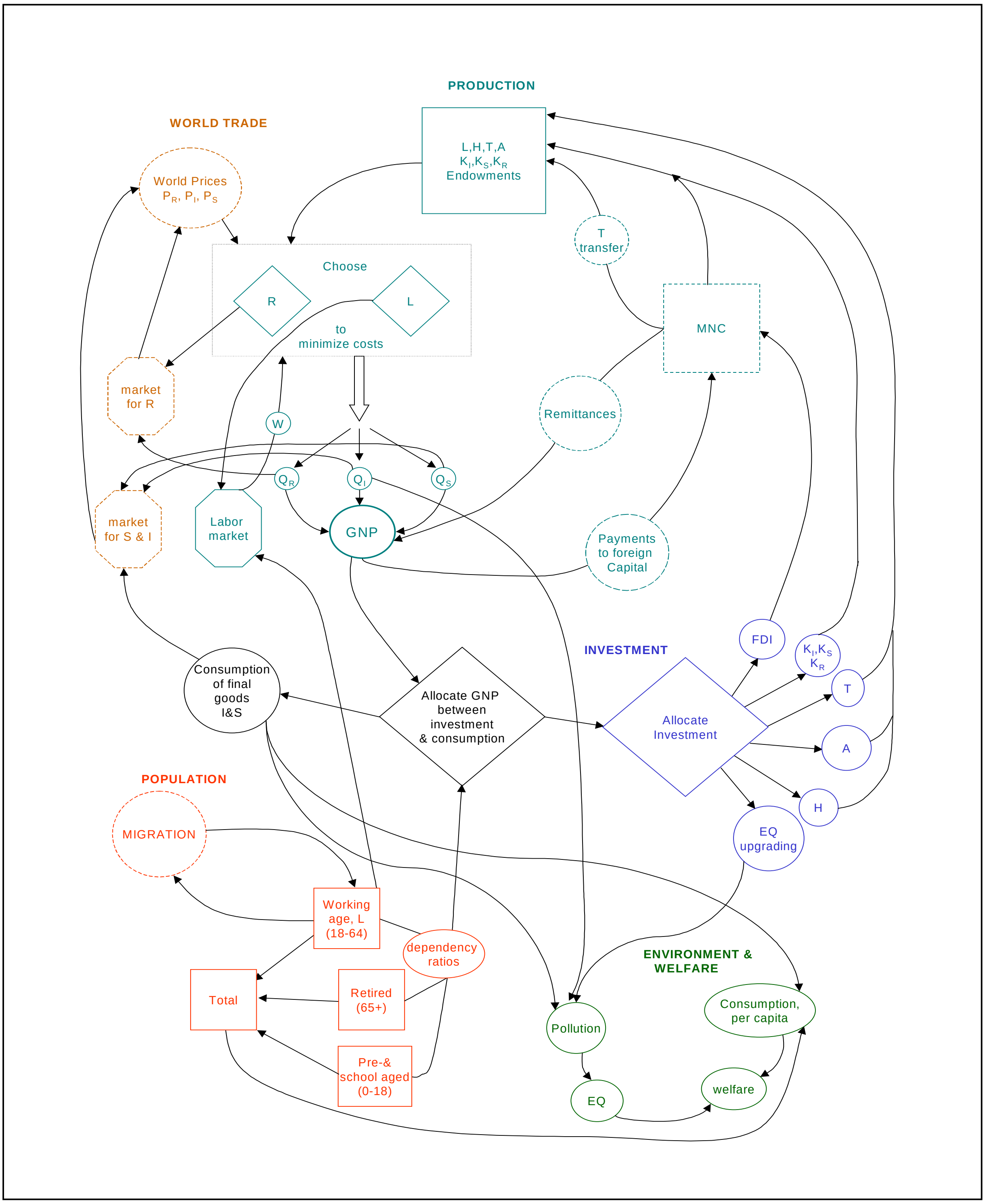
Table 10: Age 70-74 Regression Statistics

	Elasticities for Equation 38	Coefficient	T-Statistic
Per capita GDP	ε_{16}	-0.094	-1.93
Time	ε_{17}	-0.0103	-4.36
Adjusted R^2		0.2858	
Observations		173	

Table 11: Age 75-79 Regression Statistics

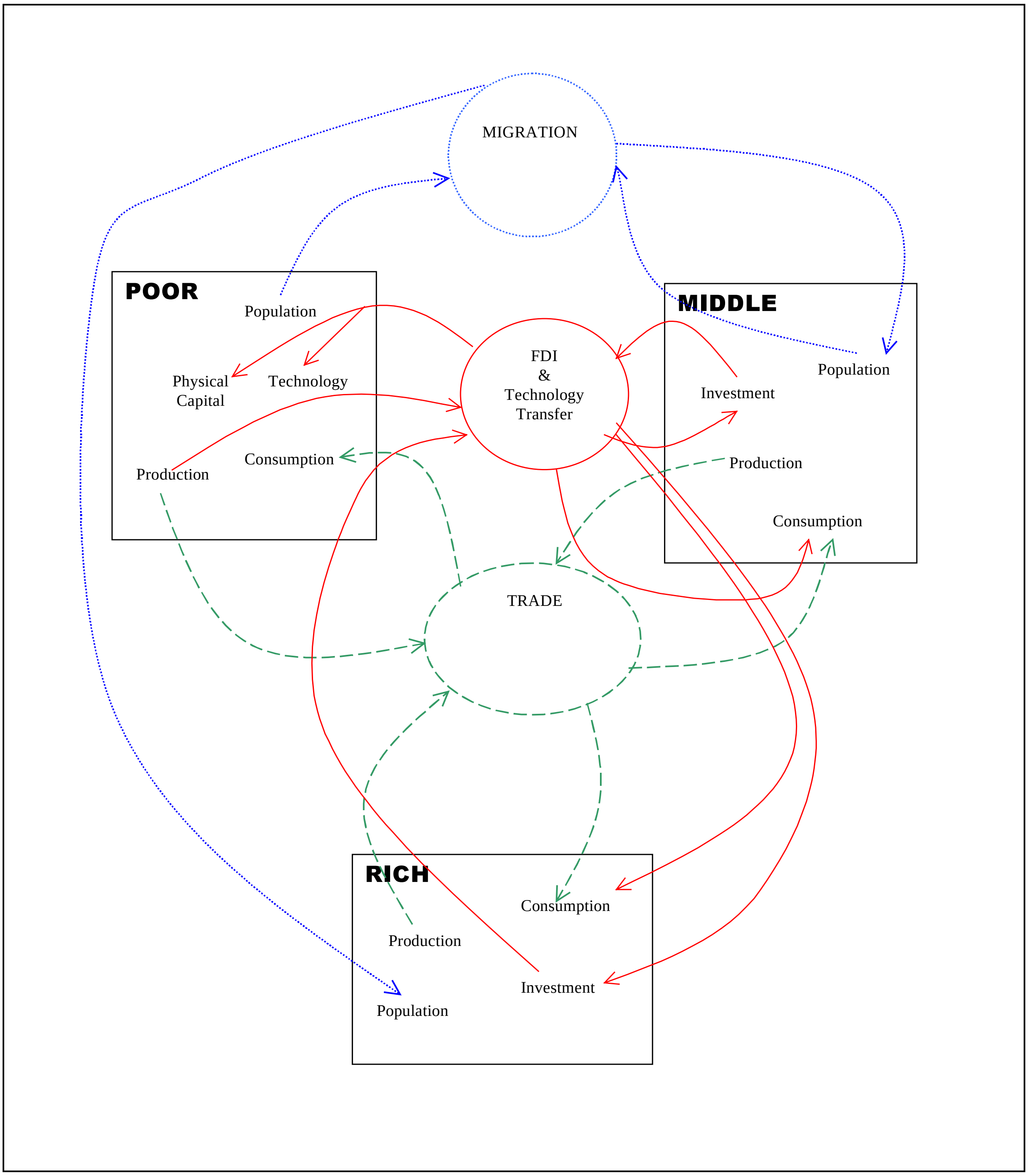
	Elasticities for Equation 38	Coefficient	T-Statistic
Time	ε_{18}	-0.009	-4.64
Adjusted R^2		0.1475	
Observations		173	

Figure 3: Limited Flow Chart/Systems Diagram for a Representative Country



Ovals correspond to rates and flows; rectangles to stocks; hexagons to equilibrating markets; and diamonds correspond to allocation decisions. Dashed shapes refer to international flows, stocks, or markets. “MNC” stands for the multi-national corporation that is made up of the Rich and Middle countries to perform foreign direct investment in the Poor countries.

Figure 4: Direction and Nature of Model Global Flows and the Three Country Groups



There is migration between the two poor countries, and thus, one of the two poor countries receives population via migration.