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Abstract

Environmental constraints have always had and will always have important consequences for human development. It has sometimes contributed to or even caused the reversal of such development. The possibility that such constraints will grow significantly throughout this century raises the concern that the very significant advances in human development across most of the world in recent decades will slow or even reverse. We use the International Futures (IFs) integrated forecasting system to explore three alternative scenarios: a Base Case scenario, an Environmental Challenge scenario, and an Environmental Disaster scenario. Our purpose is to consider the impact of different aspects and levels of environmental constraint on the course of future human development. Using the Human Development Index (HDI) and its separate components as our key measures of development, we find that environmental constraints, directly and through a variety of indirect paths, could indeed greatly slow progress and even, in disastrous conditions, begin to reverse it. Least developed countries are most vulnerable in relative terms, while middle-income countries can suffer the greatest absolute impact of constraints and more developed countries are most resilient. Education advance is the aspect of development tapped by the HDI that is most likely to continue even in the face of tightening environmental constraints.

Keywords: Human development, international futures, environmental constraints, scenarios, forecasting

JEL classification: C6, C8, E00, E1, F5, I00, I3, O1, Q00, Q5

1. Introduction[1]

Historians with long time horizons point to many occasions on which environmental constraints contributed to or caused reversal of human development (Toynbee 1972; Tainter 1988; Diamond 2005). A number of such constraints will almost certainly intensify across this century. That puts at risk the very significant advances in human development across most of the world in recent decades.

We use the International Futures (IFs) integrated forecasting system to explore three scenarios with varying degrees of global environmental constraint. The IFs tool is well suited for this type of analysis because it models large-scale interaction of many relevant systems at global and country levels: demographic, economic, energy, agriculture, human capital (education and health), sociopolitical (domestic and international), physical capital (including infrastructure) environmental and technological. It is extensively data-based, rooted in theory, and widely used for long-term analysis. Section 2 describes the model in more detail.

The three scenarios explored in this paper are the Base Case (which includes some important environmental feedbacks and constraints), an Environmental Challenge scenario (which intensifies such constraints and broadens our attention to them), and an Environmental Disaster scenario (which explores the possible impact of truly vicious cycles and deterioration of systems in ways that may be extreme, but appear within the range of possibility). Section 3 outlines the key assumptions underpinning the scenarios and explains their implementation in IFs.

[1] Many team members in the Frederick S. Pardee Center for International Futures contributed to this paper in addition to those listed as authors. Our thanks especially to Mark Eshbaugh, Eric Firnhaber, Greg Maly, and Patrick McLennan (for a full list of IFs Team members, visit www.ifs.du.edu/community/team.aspx). In addition, we thank Francisco Rodriguez, Jeni Klugman and Martin Heger of the UN Human Development Report Office for suggestions and feedback as we proceeded on the work underlying this document. Errors remain our own.

The fourth section of this paper presents the results of our analysis. It uses the Human Development Index (HDI) and its separate components as our key measures of development. We find that environmental constraints, considered broadly, could indeed greatly slow progress and even, in rather disastrous conditions reverse it. Although such a reversal seems improbable to us, there is a great deal about the dynamics environmental systems that scientists simply do not yet understand (Rochström and others 2009). In the spirit of trying to better understand (1) the boundaries within which we had best maintain our relationship with the planet and (2) the potential for advancing human development, we explore the extent of slowing or reversal in HDI to which the Environmental Challenge scenario and the Environmental Challenge scenario might give rise.

2. The International Futures (IFs) Model

International Futures (IFs) is a tool for analyzing country-specific, regional and global futures through alternative scenarios.[2] Although it is increasingly used in policy analysis, it began as an educational tool. Even in analysis applications the primary strengths of the system are in framing investigation and analysis. Users of computer simulations should always treat forecasts as highly contingent scenarios, not as predictions.

IFs is a uniquely powerful tool for the exploration of the long term future of closely interacting policy-related issues including human development (beyond the Millennium Development Goals), social change (including instability and risk), and environmental sustainability. IFs is a large-scale, long-term, fully integrated global modeling system (no sub-systems are exogenous to the others). It represents demographic, economic, energy, agricultural, socio-political, and environmental subsystems for 183 countries interacting in the global system (see Figure 1). The model is integrated with a large database for its many foundational data series and other variables of interest to users. Series begin in 1960 and even earlier when available. The easy-to-use interface facilitates data analysis, forecast presentation, and scenario analysis.

[2]The Frederick S. Pardee Center for International Futures provides the foundational funding of the IFs project. The Center's flagship project is a series of volumes on *Patterns of Potential Human Progress* (http://www.ifs.du.edu/documents/index.aspx). During 2000-2003, development of International Futures was funded in substantial part by the TERRA project of the European Commission and by the Strategic Assessments Group of the U.S. Central Intelligence Agency. In more recent years funding was provided by the U.S. National Intelligence Council in support of its global trends analyses (for 2020, 2025, and 2030), and by the United Nations Environment Programme for its Global Environment Outlook 4. None of these institutions bears any responsibility for the analysis presented here, but their support has been greatly appreciated. Thanks also to the National Science Foundation, the Cleveland Foundation, the Exxon Education Foundation, the Kettering Family Foundation, the Pacific Cultural Foundation, the United States Institute of Peace, General Motors and the RAND Pardee Center for funding that contributed to earlier generations of IFs. Also of great importance, IFs owes much to the large number of students, instructors, and analysts who have used the system over many years and provided much appreciated advice for enhancement.

IFs is a structure-based, agent-class driven, dynamic modelling system. The demographic module uses a standard cohort-component representation. The 6-sector economic module structure is general equilibrium seeking. The socio-political module represents life conditions, traces basic value/cultural information, and portrays various elements of formal and informal socio-political structures and processes.

The system facilitates scenario development and policy analysis via a scenario-tree that allows users to change framing assumptions, agent-class interventions, initial conditions or any relationship within the model. Scenarios can be saved for development and refinement over time. The easy-to-use interface also facilitates historic data analysis and display of forecasting results.

IFs is used increasingly widely. It was a core component of a project exploring the New Economy sponsored by the European Commission in 2001-2003 (Hughes and Johnston 2005) and served the EC again in 2009 for a project examining the impact of information and computing technology (ICT) on sustainability (Moyer and Hughes forthcoming). Forecasts from IFs supported the National Intelligence Council's *Project 2020: Mapping the Global Future* (NIC 2004) and *Global Trends 2025: A Transformed World* (NIC 2008). IFs provided driver forecasts for the fourth Global Environment Outlook of The United Nations Environment Program (UNEP 2007).

IFs is housed at the Josef Korbel School of International Studies at the University of Denver, and is available to download or use online for free at www.ifs.du.edu/ifs. Please access documentation on the website or other IFs publications for more detail on the model structure and assumptions.

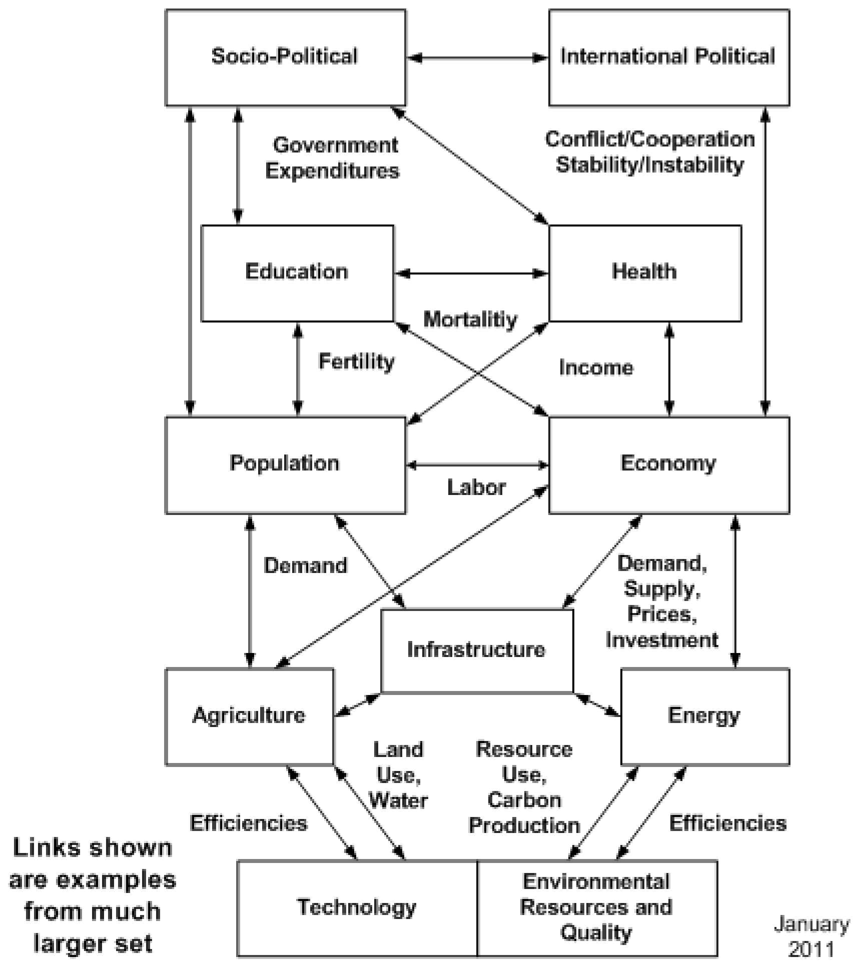

Figure 1. The major modules of International Futures (IFs).

The population module:

- represents 22 age-sex cohorts to age 100+ in a standard cohort-component structure (but computationally spreads the 5-year cohorts initially to 1-year cohorts and calculates change in 1-year time steps)
- calculates change in cohort-specific fertility of households in response to income, income distribution, infant mortality (from the health model), education levels, and contraception use
- uses mortality calculations from the health model

- separately represents the evolution of HIV infection rates and deaths from AIDS
- computes average life expectancy at birth, literacy rate, and overall measures of human development (HDI)
- represents migration, which ties to flows of remittances.

The economic module:

- represents the economy in six sectors: agriculture, materials, energy, industry, services, and information/communications technology (ICT)
- computes and uses input-output matrices that change dynamically with development level
- is an equilibrium-seeking model that does not assume exact equilibrium will exist in any given year; rather it uses inventories as buffer stocks and to provide price signals so that the model chases equilibrium over time
- contains a Cobb-Douglas production function that (following insights of Solow and Romer) endogenously represents contributions to growth in multifactor productivity from human capital (education and health), social capital and governance, physical and natural capital (infrastructure and energy prices), and knowledge development and diffusion (research and development [R&D] and economic integration with the outside world)
- uses a Linear Expenditure System to represent changing consumption patterns
- utilizes a "pooled" rather than bilateral trade approach for international trade, aid and foreign direct investment
- has been imbedded in a social accounting matrix (SAM) that ties economic production and consumption to representation of intra-actor financial flows.

The education module:

- represents formal education across primary, secondary (lower and upper separately), and tertiary levels
- forecasts intake or transition from lower levels, rates of survival and/or completion, as well as net and/or gross enrollment
- differentiates males and females
- is fully linked to the population module
- computes education or human capital stocks by adult age cohort

The health module:

- builds on the distal-driver foundation of the WHO Global Burden of Disease (GBD) formulations for major causes of death and disability
- extends the GBD representation of major causes of death from 10 plus AIDS to 15 total across communicable, noncommunicable and injury/accident groups
- looks to the Comparative Risk Assessment (CRA) approach on relative risk to represent such proximate drivers of health as malnutrition, obesity, smoking, vehicle accidents, indoor and outdoor air pollution, water/sanitation quality and climate change, so as to explore the impact of interventions.
- forecasts years of life lost, years of living with disability, and disability adjusted life years (DALYs).

The socio-political module:

- represents fiscal policy through taxing and spending decisions
- shows seven categories of government spending: military, health, education, R&D, infrastructure, foreign aid, and a residual category

- represents changes in social conditions of individuals (like fertility rates, literacy levels or poverty), attitudes of individuals (such as the level of materialism/postmaterialism of a society from the World Values Survey), and the social organization of people (such as the status of women)
- represents the general evolution of other governance variables related to competence, including corruption.
- represents the possible change of regime type
- represents the prospects for state instability or failure

The international political module:

- traces changes in power balances across states and regions
- allows exploration of changes in the level of interstate threat

The agricultural module:

- represents production, consumption and trade of crops and meat; it also carries ocean fish catch and aquaculture in less detail
- maintains land use in crop, grazing, forest, urban, and "other" categories
- represents demand for food, for livestock feed, and for industrial use of agricultural products
- is a partial equilibrium model in which food stocks buffer imbalances between production and consumption and determine price changes
- overrides the agricultural sector in the economic module unless the user chooses otherwise

The energy module:

- portrays production of six energy types: oil, gas, coal, nuclear, hydroelectric, and other renewable energy forms
- represents consumption and trade of energy in the aggregate
- represents known reserves and ultimate resources of fossil fuels
- portrays changing capital costs of each energy type with technological change as well as with draw-downs of resources
- is a partial equilibrium model in which energy stocks buffer imbalances between production and consumption and determine price changes
- overrides the energy sector in the economic module unless the user chooses otherwise.

The infrastructure module:

- forecasts physical extent of and citizen access to road transportation, water and sanitation, electricity, and information and communications technology
- calculates the public and private financial costs of infrastructure and balances public costs with governmental spending
- represents the knowledge society as a form of soft infrastructure

The environmental module:

- tracks annual emissions of carbon from fossil fuel use
- represents carbon sinks in oceans and forest land and models build-up of carbon in the atmosphere
- calculates global warming and links it to country-level changes in temperature and precipitation over time which, with the addition of carbon fertilization, impact agricultural yields

- represents indoor solid fuel use and its contribution to health related variables
- forecasts outdoor urban air pollution and links with respiratory disease
- models fresh water usage as a percentage of total water availability

The technology module:

- is distributed throughout the overall model
- allows changes in assumptions about rates of technological advance in agriculture, energy, and the broader economy
- is tied to the governmental spending model with respect to R&D spending

3. The Scenarios

For this analysis we used IFs to compare three scenarios: the Base Case scenario, an Environmental Challenge scenario and an Environmental Disaster scenario. This section explores the assumptions of these scenarios. The next section will evaluate the implication of the scenarios for human development indicators. All scenarios, as well as the model itself, are available on the Pardee Center for International Futures' website.

3.1 The Base Case scenario

The Base Case of IFs does not involve simple extrapolation of past patterns. It is, instead, the result of the dynamic interaction of all of the subsystems that Section 2 described. Nonetheless, it forecasts a continuation through the century of the substantial human development that has characterized the past 50 years. IFs base results for specific variables or subsystems are generally comparable to reference runs or median variants from other international forecasts (Hughes 2004, 2006). For an overview of the IFs Base Case in detail, see Hughes and Hillebrand (2006).

A range of global transitions drive these Base Case forecasts of ongoing improvements in human development. Incomes continue to rise, driven in part by technological advance and diffusion globally. Education and health levels rise as incomes improve and reinforce economic growth. Advances in infrastructure and improved governance further drive productivity gains. Table 1 outlines some important characteristics of the base-case by issue area and variable.

Although the Base Case generally does demonstrate continuity with historical patterns, its complex dynamics, including a wide range of non-linear relationships, provide a structure that can also generate considerably different possible futures, especially when the user changes assumptions about important uncertainties. Among a great many such elements that generate non-linear behavior are the progression of societies through demographic, epidemiological, and environmental transitions, the forthcoming global shift away from fossil fuels and towards renewable energy, changes in dietary patterns with income growth, economic structure transformations from agriculture to manufactures and then towards services, and complex (inverted-U) relationships between government regime type (the extent of democracy) and state instability. We return to a consideration of the implications of some of these below.

Among such structural representations, the Base Case also includes important environmental constraints. For example, the use of solid fuels for cooking, outdoor air pollution and levels of access to safe water and sanitation all impact health. Also illustratively, temperature, precipitation and carbon fertilization[3] change agricultural productivity and affect food production and undernutrition (which in turn affects mortality in the short run and worker productivity through developmental stunting in the longer run).

[3] IFs calculates country-specific temperature and precipitation change based on results aggregated from grid-level data produced by the MAGICC model (Hughes, Kuhn, Peterson, Rothman, Solórzano, Mathers, and Dickson 2011, Wigley 2008). In combination with estimates of carbon fertilization, these data are used to calculate a change in agricultural yields relative to 1990 levels. Absolute agricultural production declines are mitigated as price signals help more land to be placed under cultivation and more food to be traded.

Table 1: International Futures Base Case Characteristics - Version 6.43

Economy	Population	Education	Health	Government	Technology	Agriculture	Energy	Environment
Global GDP growth ranges from 3-4% annually	Fertility rates decline in all regions	Primary education gross enrollment is over 100% by 2025	AIDs deaths fall to less than 1 million people annually by 2040	Political freedom increases at the global level	Energy efficiency improves at 0.8% annually for first 15 years then more quickly	Cereal yields improve globally at about 0.03 tonnes per hectare per year	Energy from oil, gas and coal dominate global production for the next two decades	Annual carbon emissions grow for the next 2 decades then plateau
Economic production continues to diversify towards services and ICT	Life Expectancy improves in all regions	Secondary gross enrollment levels reach 80% by 2025	Communicable disease deaths decrease by half by 2040	Economic freedom increases at the global level	Energy production costs decrease exogenously differently for each type covered (coal, oil, gas, hydro, nuclear and other-renewable)	Overall crop land increases by about 1 million hectares per year	Renewable energy production surpasses any single fossil fuel by 2040	Carbon build-up in the atmosphere grows throughout the first half of the 21st century going beyond 500 PPM by 2050

International trade as a percentage of GDP ticks up about 0.5 percentage points annually	Migration trends are extrapolated from historic patterns	Tertiary gross enrollment is over 30% by 2025	Non-communicable disease deaths increase 1.5 times over 35 years	Democracy improves	Global convergence of productivity to system leader in technology	Overall grazing land increases by about 2 million hectares per year	Hydrogen and nuclear energy production stagnate	Percent of population with no access to safe water below 10% by 2050
Foreign Direct Investment as a percentage of GDP increases at nearly 0.04 percentage points annually		World literacy levels are over 90% by 2030	Global smoking rates decline to the level in 1980 in 25 years	Corruption is reduced		Overall fish harvest remains constant		Global fresh water use reaches 10% of renewable by 2050, over 100% in North Africa by 2025
Foreign Aid more than doubles in 40 years from 6 trillion USD to over 12 trillion				Efficacy and Rule of Law are improved				Indoor solid fuel use decreases below 20% of global population in 2050

The Base Case does not, however, consider large disruptive changes, be they natural, technological or policy-based. For example, the IFs model is not designed to identify sharp tipping points in natural systems such as dramatic shifts in the thermohaline circulation systems of our oceans or massive releases of greenhouse gas from melting of the permafrost. There is no representation of radical technology advance or its use, such as the widespread uptake of carbon capture and sequestration or dramatic shifts in artificial intelligence. The Base Case does not build in carbon taxes or other significant shifts in global governance policy.

3.2 The character of global environmental challenges and potential disasters

It is extremely difficult to draw a clear boundary between environmentally-based and other challenges to human development. Considered most directly, environmentally-based challenges generally involve either constraints with respect to withdrawals of biophysical resources from global sources or constraints with respect to the use of global systems as sinks for outputs from human ones. Often, as in the case of dirtying our own drinking water, they involve both.

More broadly considered, however, there are many situations in which the consequences (often unacknowledged) of the uses of such sources and sinks, or of our efforts to avoid their use, pose major challenges to human development that have environmental bases that we do not automatically see as such. That is, there are many sometimes longer and more indirect pathways between environmental issues and human development. For example, something as seemingly removed from being an environmental issue as global aging has roots in environmental constraints. Malthus argued that preventative checks on population growth—such as increases in marriage age and the use of contraception—are unintentional adaptive measures of populations to limits posed by land and other resource limits. Humans can also be more intentional. Practices of households (e.g. primogeniture) or countries (e.g. the one-child family policy in China) flow from efforts to constrain population growth or its consequences in the face of limits. Aging populations, for better (e.g. demographic dividends) and worse (e.g. the dependent elderly), naturally follow from such demographic adaptations.

Similarly, in a world recognized as having plentiful capital and labor (and, in fact, having contemporary difficulties putting both to productive use), many of the forces restraining economic growth are, at the core, tied to environmental systems. For instance, one might attribute the so-called "lost decade of development" (the 1980s primarily) in many countries of Latin America, Africa and elsewhere to their having borrowed too much in global financial markets and become over-indebted. Yet cheap capital was a key driver of that borrowing, and it was fed by surpluses generated in oil-exporting countries when energy prices rose. Although the run-up in energy prices had triggers that were significantly political, the peaking of oil production in the United States and that country's push into global energy markets in the 1970s contributed much foundationally, thus connecting growth constraints in the 1980s to environmental resource constraints in the 1970s.

In this section we step back and consider many of the challenges to economic growth and human development without being strictly bound by thoughts of immediate source and sink constraints. Then, in our scenarios, especially the Environmental Disaster scenario, we will draw upon broader sets of challenges in their framing.

One long-term global challenge that has important environmental base—though not always explicitly identified as such—is the maintenance of a high rate of technological advance by leading countries as an engine of global economic growth. Whether one believes in the existence of fairly regular long-waves of such advance—often called Kondratieff cycles—there is no doubt that the pattern of economic growth varies significantly over relatively long periods of time. In the late 1960s global GDP growth sustained a 5-year moving average rate above 5 percent annually. That rate declined sharply in the 1970s, falling well below 4 percent and down to 2 percent in the 1980-82 period. In fact, through the 1980s and 1990s it mostly remained well below 3 percent, recovering to 4 percent only in the middle of the first decade of the new century (before being hit by a major global recession).

The lackluster performance of the 1980s (again, with fairly important roots both in energy and agriculture constraints) led Robert Solow to make his famous quip that, "You can see the computer age everywhere but in the productivity statistics" (Solow 1987). The pattern of economic growth in the U.S., the country generally defined throughout this period as the global technological leader, was not dramatically different, except for a surge of growth in the late 1990s—as would befit a country leading the information and communications technology (ICT) revolution. This surge preceded the rise of global economic growth over the next decade. Those who have worked to separate the impact of waves of technological advance from growth patterns affected by many other variables including energy prices (to be discussed below) generally associate shifts in economic growth from 0.2 percent to as much as 1.0 percent with historic advances such as steam engines (linked to the advantages of steam ships and railways, but also to shortages of wood in England before the coal age), electricity, and information and communications technology (Crafts 2001).

A related issue is whether other countries converge towards the technology, productivity and growth patterns of the technological leaders. The economic literature is colored with large debates about the extent of convergence and the reasons for its occurrence in some countries but not others. For instance, Sachs and Warner (1995) argue that the key driver is adoption by poorer countries of generally efficient economic policies, significantly open trade, and protection of private property. When attention turns to environmental factors, those that receive attention are often geographic (such as being land-locked or resource poor; see Collier 2006; Fukuda-Parr 2006). Other studies, however, also look to environmental factors such as susceptibility to climate change (Busby, Smith, White and Strange 2010).

The IFs model and Base Case build in constant patterns of technological advance for the system leader across the entire forecast horizon, variable by economic sector but contributing about 1 percent annually to productivity advance. The Base Case also represents a pattern of convergence by follower countries exhibiting an inverted-V character, so that middle-income countries are more able than the poorest to adopt and benefit from leading-edge technology. Around that pattern, advances in multifactor or total factor productivity depend on a wide range of physical, human, social, and human factors, many discussed below. Although some environmental factors (notably energy prices) affect that productivity, the model almost certainly under-represents such impact, suggesting the need to layer in additional environmental constraints exogenously into our scenarios.

Turning to energy issues, which clearly also contributed to the economic downturns of the 1970s and 1980s, M. King Hubbert produced one of the most famous and prescient forecasts when he predicted in the 1950s that U.S. oil production from the lower 48 states would peak between 1965 and 1970 (for foundational analysis see Hubbert 1949). Even with Alaskan production it peaked in 1970, contributing to rapidly rising global energy prices in the 1970s. The key uncertainty around global oil production is, of course, not whether it will peak but when (U.S. General Accounting Office 2007) . Estimates generally range from now through 2040, depending not just or rate of growth of production but also on assumptions about more unconventional sources such as tar sands and shale, as well as deep ocean drilling. Production in 54 of the largest 65 global producers globally appears to have passed peaks, leaving large producers like Saudi Arabia in swing positions, and estimates of their future capacity are hotly debated.[4]

The Base Case of IFs represents energy production not just of fossil fuels, but also of hydropower, nuclear power, and new renewable forms (in the aggregate) such as wind and direct solar energy. In the base case of IFs, global oil and gas production do not peak before 2030. That pattern is rooted heavily in the use by IFs of estimates on ultimately recoverable resources from the U.S. Geological Survey. The very rapid expansion in recent years, particularly in the United States, of natural gas production from shale formations through the use of hydraulic fracturing technologies greatly complicates

[4] Colin Campbell and others at the Association for the study of Peak Oil & Gas are among those who argue we have reached the peak of global oil production.

understanding of resource bases, which the technology has undoubtedly expanded even as environmental debates rage around its use. The Environmental Challenge and Environmental Disaster scenarios consider more conservative assumptions than those of the Base Case.

In addition, the IFs Base Case makes assumptions about likely improvements in energy efficiency and reductions in costs of new renewable energy forms. These technological changes specific to energy (affected also by energy prices) are also difficult to forecast and could be overly optimistic.[5] If various constraints on energy in an Environmental Challenge scenario lead to higher energy prices, there will be an effect on economic productivity and growth; one generalized rule is that a rise in prices by $10 per barrel lowers growth in an economy like that of the U.S. by 0.2 percent.[6]

Energy resources are, however, only one of the major global challenges posed by the interaction of humans with the environment via extraction from sources of needed inputs (e.g. energy, water, and forests) and dumping outputs (e.g. carbon, nitrogen, and phosphorus) into sinks. Rochström and others (2009) identified nine "planetary boundaries" associated with such use of global biological and geological sources and sinks. They argued that we have already transgressed three of the boundaries, around

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[5] In particular, IFs does constrain the advance of renewable energy, which in the base case grows quite rapidly, by the growing needs for electric-grid infrastructure or power storage that will need to accompany an alternative energy system if it is heavily dependent on new renewable forms.

[6] As cited by David Wessel, economic editor of *The Wall Street Journal* (see http://www.npr.org/2011/03/31/135002308/economy-update). This is an uncertain relationship subject to controversy and an alternative generalized rule is that the effect is 0.5 percent. Dean Baker of the Center for Economic and Policy Research explores this second generalized rule and suggests that the effect might be only half as great, closer to the assessment of Wessel. See http://www.businessinsider.com/the-impact-of-oil-prices-on-economic-growth-2011-2. Hamilton (2011) reviews the complications of such analysis, emphasizing that oil shocks have highly variable impact depending on the structure of the energy system, the economy, and other factors occurring simultaneously.

climate change (associated with atmospheric levels of carbon and other greenhouse gases), rate of biodiversity loss, and the global nitrogen cycle (in their look at both the nitrogen and phosphorus cycles). The other boundaries they considered relate to ocean acidification, stratospheric ozone, freshwater use, land system change, chemical pollution, and atmospheric aerosol loading.

That study also made clear the extent of uncertainty surrounding analyses of these boundaries and the impact of exceeding them.[7] Even with respect to one of the issues that has received most attention, namely atmospheric carbon levels, they pointed out the complications around their identified value of 350 parts per million (which is below current levels of about 390 ppm). For instance, they noted that contemporary climate models assess only "fast feedbacks" linking atmospheric carbon and global temperature, looking at those such as water vapor, clouds and sea ice. Fast feedbacks give rise to association of doubling pre-industrial CO_2 levels with temperature rise of about 3º C. Some analysis around inclusion of "slow feedbacks" such as decreased ice sheet volume, changed vegetation patterns, and flooding of continental shelves suggests an impact of 6º C. And, of course, this uncertainty about temperature change patterns precedes in impact analysis considerations of how atmospheric carbon might affect agricultural production. Because many variables affect yields, including the ability of scientists and farmers to adapt crops to new conditions, the uncertainty is considerable.

Even the extensive analysis of Rochström and others (2009) left potential challenges under-explored. For instance, with respect to water use, they focused on "green water" (soil moisture) and "blue water" (run-off). Among the major water issues facing many

[7] They did not determine boundaries for chemical pollution and atmospheric aerosol loading.

countries and regions, however, is draw-down of ground water faster than recharge (as in many parts of India and China) including heavy exploitation of extremely slow recharge fossil water in aquifers (as in Saudi Arabia and Libya), often with limited knowledge of the actual extent of such supplies.

The Base Case of IFs does forecast the build-up of atmospheric CO_2, the possible global temperature change associated with it, the associated country-specific changes in temperature precipitation relative to 1990, and the impact of those changes on agricultural yields, even considering the positive or "fertilizing" impact that increased atmospheric carbon might have. It does not, however, represent the impacts of increased weather variability or of sea-level rise and coastal flooding. These are potentially very significant omissions. Also important, there is no direct constraint in IFs on future agricultural production from groundwater availability[8] (nor is there any representation of possibly improved efficiency in the use of blue and fossil water).

Moving beyond biophysical challenges to social ones (and, as indicated earlier, these can stem from environmental forces), aging of populations is a major concern and pressure moving forward for many wealthy countries. In this area forecasts are relatively more certain than in energy systems. Yet the implications of these forecast are relatively uncertain, in part because the health conditions of the elderly and possible political choices for care of them will become clearer only over coming decades. In democracies, of course, the elderly tend already to be a powerful political force and are unlikely to become more reticent in pursuit of their interests.

[8] The lack of data on the ultimate availability of groundwater reserves is a constraint to our modeling in this area.

In addition to aging, and for most developing countries a prior and more immediate challenge, the fertility transition to levels near or below replacement (about 2.1 children per average woman) is quite far from complete. In fact, in its 2010 Revision of data and analysis, the United Nations Population Division significantly revised upward its median population forecast (to 10.1 billion in 2100), arguing that the transition is proceeding more slowly than it foresaw earlier in many high-fertility countries, especially in Africa and Asia.[9] The Base Case forecast of IFs, with endogenous representations of changing fertility and mortality that we believe to be quite reasonable, produces numbers closer to the earlier 2008 Revision, including a peaking of global population well before 2100. Again, however, a more challenging scenario is possible.

Many other social factors will challenge humanity over the coming five decades. One of these is considerable and persistent conflict across ethnic and religious groupings—such groups are much less able to live in harmony when pressures of environmental constraints push peoples into competition for water, energy, and land. We may in fact be seeing an increasing trend in conflict between more fundamentalist groupings (with origins in all forms of religion) and more secular humans, as well as across the adherents to competing definitive truths. The Base Case of IFs does not explicitly build levels of domestic and international conflict on assumptions of increasing or decreasing religious, ideological tensions, or environmental constraints (on the link between the environment and conflict, see Homer-Dixon 1999; Raleigh and Urdal 2007; Busby, Smith, White and

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[9] http://esa.un.org/unpd/wpp/Other-Information/Press_Release_WPP2010.pdf

Strange 2010). The drivers often interact and the complexity of sorting them out suggests the importance of having alternative scenario assumptions.

Still other global challenges will almost certainly arise from international conflicts, again many times with deeper environmental foundations. The end of the Cold War ultimately resulted in both a reduction in direct intervention by great powers in the affairs of other countries (with especially notable exceptions such as the wars in Afghanistan, Iraq and Libya) and peace dividends for many governments in the form of lower defence spending as a portion of GDP. The rise of China, as well as of India and other large emerging states, will reshape the global high table in coming decades. Although accommodations to their rise, such as the creation of the G-20 grouping of countries to supplement the G-7, may head off many overt manifestations of conflict, the history of international politics in the face of challenges by rising states to system leaders is not a pretty one. Very often the sources of conflict between declining hegemons and rising powers has been perceptions by the rising state of unfair division of access to a range of potential resources. Moreover, in the particular case of the rise of China, we are seeing an historically unusual gap appear between high-income status-quo states and middle-income emerging ones. That gap has already helped frustrate a number of efforts to provide collective global public goods (such as the Doha round of trade negotiations and multiple high-level discussions on climate change). Even short of overt conflict over competing claims where multiple parties declare important national interests (such as the South China Sea including its energy resources and such as global financial balances), these difficulties could not just frustrate efforts around deepening important systemic connections such as open trade and financial flows, but even lead to some disruption of them (and of globalization more generally).

Not least among the global challenges will be the failure of the global community to raise the poorest, hungriest, and least-enabled human beings from abysmal conditions. In spite of much progress towards the Millennium Development Goals, there remain about 1.2 billion people living on less than $1.25 per day and in hunger. More than 300 million of these are in sub-Saharan Africa and while the IFs Base Case suggests that the still larger number in South Asia is likely to fall, it forecasts that there will still be more than 300 million in sub-Saharan Africa by 2060. Such numbers may prove to be overly optimistic as the IFs Base Case anticipates very substantial improvements in educational advance, extension of life expectancy (especially via reduction in the communicable disease burden), improvement in access to safe water and sanitation and reduction in the indoor use of solid fuels (a major killer).

Finally, but not least, innumerable wild cards or fundamentally unpredictable negative events may dramatically shock human systems over the next half-century. Taleb (2007) referred to these as "black swans": very low probability but high impact events. The fact that a few of them almost certainly will appear in the long-term future of nearly any complex system is one of the reasons for the optimism bias in the field of forecasting. Among those most often cited and perhaps of relatively higher probability is one with a mixture of environmental roots, namely plagues, related in part to density of populations and their close proximity in turn to animal populations (Garrett 2007). Aging and therefore vulnerable populations, growing antibiotic resistance, the proven ability of pathogens to mutate, recombine, and also to jump across species all might seem to make a significant plague a low-to-medium rather than a very low probability event.

There are, of course, wild cards as well as underlying forces that could contribute very positively to global futures and alleviate many challenges. Those would include new and inexpensive energy sources or an African green revolution of major proportions. We will, however, continue to focus on the risks rather than the possibilities for luck and breakthroughs, turning next to the integration of challenges into Environmental Challenge and Environmental Disaster scenarios.

3.3 Environmental Challenge scenario

Rooted in the considerations above concerning the extent to which both missing linkages in the IFs system and uncertainties about the relationships between environmental variables and human development, the Environmental Challenge scenario changes the representation of the Base Case in two ways. First, it increases the driving values for a number of known environmental risks that the Base Case already represents, but that could prove to be worse than we anticipate. To do that we built on the foundation of an Environmental Risk scenario created earlier for work in forecasting global health (Hughes, Kuhn, Peterson, Rothman, and Solórzano 2011, Hughes, Kuhn, Peterson, Rothman, Solórzano, Mathers and Dickson 2011).[10] The scenario represents environmental risks at the household (indoor solid fuel use), local (water and sanitation),

[10] That project built on the modeling work of the World Health Organization's Global Burden of Disease project (Mathers and Loncar, 2006 and undated), thanks in part to the generosity of Colin Mathers in making available the project's formulations for forecasting mortality and morbidity by cause. The IFs project combined the distal driver health formulations of that project with proximate risk analysis building on the Comparative Risk Assessment project (Ezzati, VanderHoorn, Lopez, Danaei, Rodgers, Mathers, and Murray 2006). That gave us the leverage points with which to create the Environmental Risk scenario.

urban and regional (outdoor air pollution), and global levels (especially increasing impacts of global warming on agricultural production). In each case it moves the patterns for countries approximately one standard error in a less optimistic direction from a cross-sectionally estimated function linking GDP per capita at PPP (as a rough proxy for development level) and levels of risk in countries around the world.

To represent additional environmental challenges not necessarily captured by the IFs system or represented in the relatively narrow focus of the Environmental Risk scenario, we further expanded the Environmental Challenge scenario by drawing also on insights from the United Nations Environment Programme Global Environmental Outlook 4 scenario exercise (UNEP 2007). For the GEO 4 project the IFs system built scenario representations of four different scenarios (Policy First, Markets First Sustainability First, and Security First).[11]

Of those four, the Security First scenario represents a number of the broader challenges to global futures emanating from environmental forces, many of which are secondary spill-over effects. The types of impacts captured in Security First include a retreat from openness and globalization. In this scenario states increase protectionism from trade, decrease democracy, lower levels of domestic economic freedom, increase inequality and reduce flows of foreign direct investment. This series of interventions increases the probability of state fragility. These choices lower levels of economic growth relative to the base case and impact human development across a range of systems.

[11] The four scenarios are available for use by others with all releases of the IFs system. See www.ifs.du.edu.

The resultant Environmental Challenge scenario, pulling together most aspects of the foundational Environmental Risks and Security First scenarios, represents a considerably darker world than the IFs Base Case (see Box 1 for the elements of it). We shall see the impacts for human development later in the paper.

Box 1. The Environmental Challenge scenario

All changes are relative to underlying dynamic values. For instance, an increase in fertility would be relative to underlying rates that are decreasing for almost all developing countries. The scenario introduces almost all changes over a period of years, because large, sustained changes seldom happen instantaneously.

Technology/productivity. Reduces the overall rate of systemic technological advance by 0.5 percent and slows the rate of convergence by other countries to the leader. Both China and India, as rapidly emerging countries with high growth rates, lose 2.0 percent annual convergence; South Central Asia and Africa, as especially vulnerable regions, lose 1.0 percent annual convergence; the rest of the world loses 0.5 percent.

Energy. Lowers the rate of progress in cost reduction for production of renewable energy by 50 percent.

Agriculture. Positing impacts on yield from environmental factors not in the model, the scenario slows growth in agricultural yield by 0.5 percent annually to a total of 25 percent. Posits a growth of undernutrition in part related to distribution of 1 percent annually relative to the decline of the base case to 50 percent above the Base Case. Reduces global supplies of fresh water by 25 percent over 50 years (0.5 percent annually). Turns off the effect of carbon dioxide on crop fertilization.

Demographic. Increases fertility rates of non-OECD countries by 10 percent over 60 years. Slows down the global reduction of fertility by 0.15 percentage points over 10 years.

Socio-political. Global and domestic changes occur in interaction. Reduces global migration by 25 percent over 10 years. Increases protectionism on trade by 20 percent over 5 years. Reduces flows of foreign direct investment by 40 percent over 5 years. Reduces economic freedom by 10 percent over 15 years. Reduces political democracy (and the freedom measure) by 10 percent over 15 years. Increases military spending by 20 percent over 10 years. Increases domestic inequality by 15 percent over 20 years.

Millennium Development Goal progress. With respect to health-related MDGs, the scenario slows down progress towards improved and household-connected water and sanitation by 50 percent over 50 years and increases urban air pollution and indoor use of solid fuels by the same amount.

Health. Focusing only on HIV/AIDS directly, increases the death rate globally from AIDS by 20 percent over 20 years, slows down the peaking of HIV prevalence in sub-Saharan Africa by 8 years, and increases the peak incidence in sub-Saharan Africa by 4 percentage points.

Conflict. Increases the probability of intrastate conflict by 20 percent over 20 years.

3.4 Environmental Disaster scenario

Environmental Disaster is the third scenario compared in this set. We have emphasized that there are great uncertainties surrounding current and future environmental challenges (direct or via complex pathways) and the human response to them. Overuse of fossil water and falling water tables, changing run-off patterns from glacial melting, progressive deforestation and land degradation, species loss and dramatic declines in biodiversity, accelerated incidence of extreme weather events, peaking production of oil and gas (which this analysis has largely ignored except for conservative analysis of it in the Base Case),[12] and much more will greatly stress bio-physical and human systems in coming decades. The full potential for associated vicious feedback loops is unknown.

To address these uncertainties in any precise manner is, of course, impossible. They remain uncertainties. Therefore this scenario manipulates fundamentally the same interventions as the Environmental Challenge scenario, but amplifies their magnitude in most cases. For instance, the overall reductions in systemic economic advance, and that in specific countries and regions is roughly doubled relative to Environmental Challenge. Similarly, the increase of fertility rates is roughly doubled, and the reduction in agricultural yield is about twice as fast. With respect to factors around globalization, the protectionism in trade is approximately twice as great; migration declines by about 75 percent instead of 25 percent. In addition to increased military spending, we reduce public education spending significantly in the scenario. The use here of characterizations such as "roughly", "about", and "approximately" is deliberate, because the model is a

[12] An obvious omission from these scenarios is more conservative assumptions on energy resources; the model probably does not adequately represent the forward impact of such change, a modeling issue to which our work will return.

dynamic system and equilibrating mechanisms often partially offset interventions of this kind (although frequently at a cost, such as increased agricultural investment to partially offset decreased yields).

Although we view this as a very low probability scenario, at least in the time horizon of our forecasts, the individual assumptions are all possible. Moreover, it is by no means a worst case scenario. There exist possibilities, for instance, of either physical or social systems reaching tipping points that fundamentally change equilibrating patterns.

Box 2. The Environmental Disaster scenario
All changes are relative to underlying dynamic values. For instance, an increase in fertility would be relative to underlying rates that are decreasing for almost all developing countries. The scenario introduces almost all changes over a period of years, because large and sustained changes seldom happen instantaneously.

Technology/productivity. Reduces the overall rate of systemic technological advance by 1.0 percent and slows the rate of convergence by other countries to the leader. Both China and India, as rapidly emerging countries with high growth rates, lose 3.5 percent annual convergence; the rest of Asia and all of Africa, as especially vulnerable regions, lose 2.0 percent annual convergence; the rest of the world loses 1.0 percent.

Energy. Lowers the rate of progress in cost reduction for production of renewable energy by 50 percent.

Agriculture. Positing impacts on yield from environmental factors not in the model, the scenario slows growth in agricultural yield by 1.0 percent annually to a total of 50 percent. Posits a growth of undernutrition in part related to distribution of 1 percent annually relative to the decline of the base case to 50 percent above the Base Case. Reduces global supplies of fresh water by 25 percent over 50 years (0.5 percent annually). Turns off the effect of carbon dioxide on crop fertilization.
Demographic. Increases fertility rates of non-OECD countries by 20 percent over 60 years. Slows down the global reduction of fertility by 0.15 percentage points over 10 years.

Socio-political. Global and domestic changes occur in interaction. Reduces global migration by 75 percent over 10 years. Doubles protectionism in trade over 5 years. Reduces flows of foreign direct investment by 40 percent over 5 years. Reduces economic freedom by 50 percent over 15 years. Reduces political democracy (and the freedom measure) by 10 percent over 15 years. Increases military spending by 20 percent over 10 years and decreases global public spending on education by 40 percent over 7 years. Increases domestic inequality by 60 percent over 20 years.

Millennium Development Goal progress. With respect to health-related MDGs, the scenario slows down progress towards improved and household-connected water and sanitation by 50 percent over 50 years and increases urban air pollution and indoor use of solid fuels by the same amount.

Health. Focusing only on HIV/AIDS directly, increases the death rate globally from AIDS by 20 percent over 20 years, slows down the peaking of HIV prevalence in sub-Saharan Africa by 18 years, and increases the peak incidence in sub-Saharan Africa by 6 percentage points.

Conflict. Increases the probability of intrastate conflict by 20 percent over 20 years.

4. Scenario Impacts on Human Development

To see the results of the environmental constraints we will look out 50 years to 2060. This is the time horizon of the Pardee IFs Center's series on Patterns of Potential Human Progress (see Hughes, Irfan, Khan, Kumar, Rothman, and Solórzano 2008 on reducing global poverty; Dickson, Hughes, and Irfan 2009 on advancing global education; and Hughes, Kuhn, Peterson, Rothman, and Solórzano 2011 on improving global health). We begin by comparing the scenarios globally with respect to values of the human development index (reformulated in 2010; UN Human Development Programme 2010). Then we will turn to the various dimensions of the index, health, knowledge or education, and income. In each case we will consider also patterns for countries at different income levels or in different regions. We also devote attention to the equity implications of the alternative scenarios.

4.1 Environmental impacts on human development: The HDI

Figure 2 shows the Human Development Index (HDI) historically since 1960 and in the IFs forecasts for the three scenarios.[13] In the Base Case global HDI reaches 0.803 in 2060. Although the pattern of growth through that year appears nearly linear, but the forecast is not an extrapolation, but rather the dynamic result of the interactions of all model components across 183 countries (aggregated to the global total with population weighting). Even in the Base Case, HDI growth is slower than it has been historically.

[13] The values shown here will differ slightly from those in the latest Human Development Report (UNDP forthcoming 2011) because we have created them with version 6.46 of the IFs system. Among the differences between that version and earlier ones is the movement of the model to a 2010 base year. There are small transients between historical values and those of IFs in the base year because the values IFs computes for all of the inputs of the HDI vary somewhat from those used by the UN Human Development Report Office.

Although that is in part a result of the environmental constraints in the scenario, it is also in part a result of the built-in *saturation effects* of the index's construction. Not only does the logarithmic term on GNI per capita contribute mechanically to such saturation, so more substantively do the inevitable slowing of increments in years of formal education in the middle- and high-income countries, the likely slowing of advance in life expectancy of cutting-edge countries like Japan, and the even more certain decline in speed of convergence by low- and middle-income countries as the health and education gaps with high-income countries narrow. In contrast to the 2060 global value of 0.803 in the Base Case, the HDI reaches only 0.741 in the Environmental Challenge scenario and only 0.657 in the Environmental Disaster scenario (almost unchanged from the value of 0.632 in 2010).

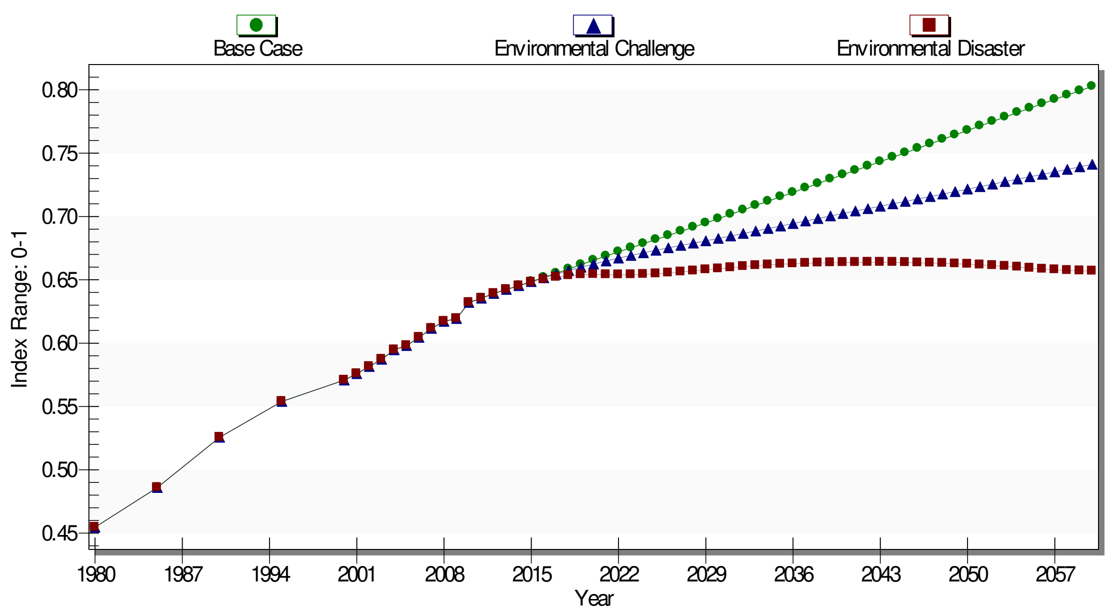

Figure 2. Global differences of HDI across environmental scenarios

The impact of environmental constraints on different sets of countries varies, of course. Figure 3 shows the global difference between the two more extreme scenarios (Base Case and Environmental Disaster) for three global income United Nations groupings (more developed, less developed and least developed).

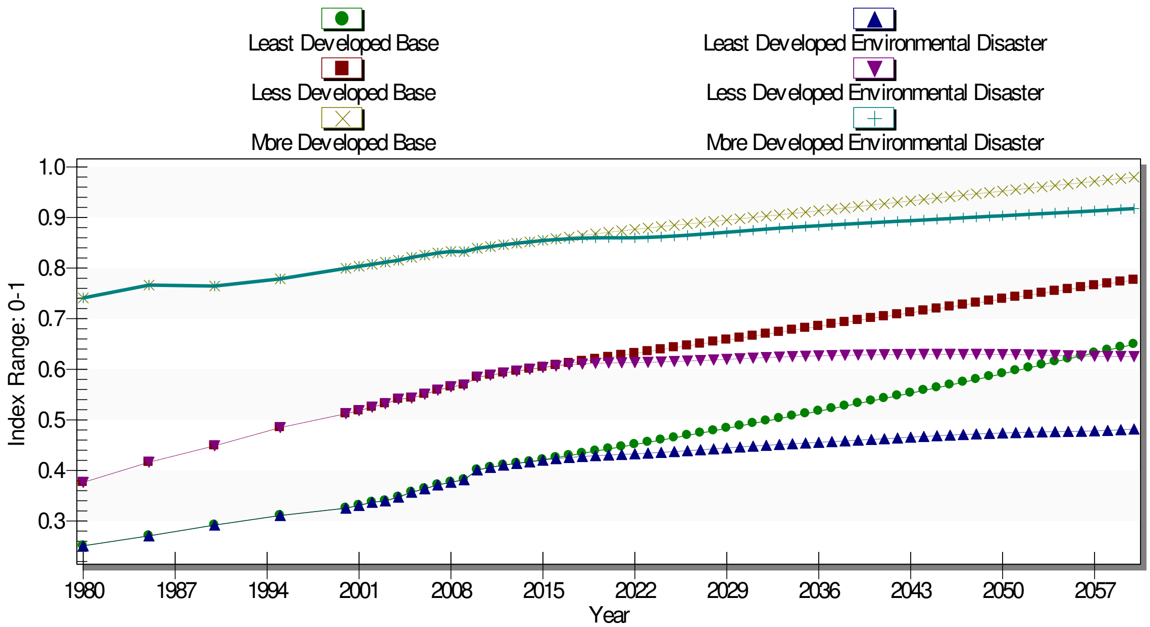

Figure 3. Differences of HDI across environmental scenarios and income levels

The most developed countries are the most capable of coping with environmental challenges—even the disaster scenario does not stop some progress on the HDI. One might argue that the greatest impact of challenges is on the less developed grouping for which the HDI actually turns down slightly in the last 15 years. But both in terms of absolute differences between values for the two scenarios in 2060 and (especially) in terms of proportional difference relative to the Base Case values, the least developed countries are at greatest risk. The value in the Environmental Disaster scenario for them in 2060 is more than 25 percent lower than in the Base Case. The biggest potential losers are Chad (31%), Central African Republic (30%), Cote d'Ivoire (29%), Togo (28%), Pakistan (28%), Djibouti (27%), Zambia (27%), Senegal (26%), Somalia (25%) and

Afghanistan (25%). The least developed countries are more vulnerable to the interactive effects of environmental challenges and the possible vicious cycles they set up across variables, such as that linking income decline and increased domestic conflict.

A significant secondary result of this greater vulnerability of the already poor is growing inequality. Figure 4 shows the global Gini index (using GDP at purchasing power parity) in the three scenarios. In the Base Case the global Gini of income continues to decline across the time horizon, driven especially by the rapid growth rates of countries such as China, India, and Brazil. In Environmental Challenge the decline ceases by about 2040, and in Environmental Disaster the world is slightly more unequal in 2060 than in 2010. Were we to look at the ratio of income of the richest 10 percent of humans to the poorest 10 percent, the result would be equally dramatic. In contrast to a small decline in that ratio in the Base Case by 2060, we would see a near three-fold increase (to more than 300-to-1) in the Environmental Disaster scenario. These results highlight the rather dramatic global distributional consequences that might characterize a more environmentally constrained world.

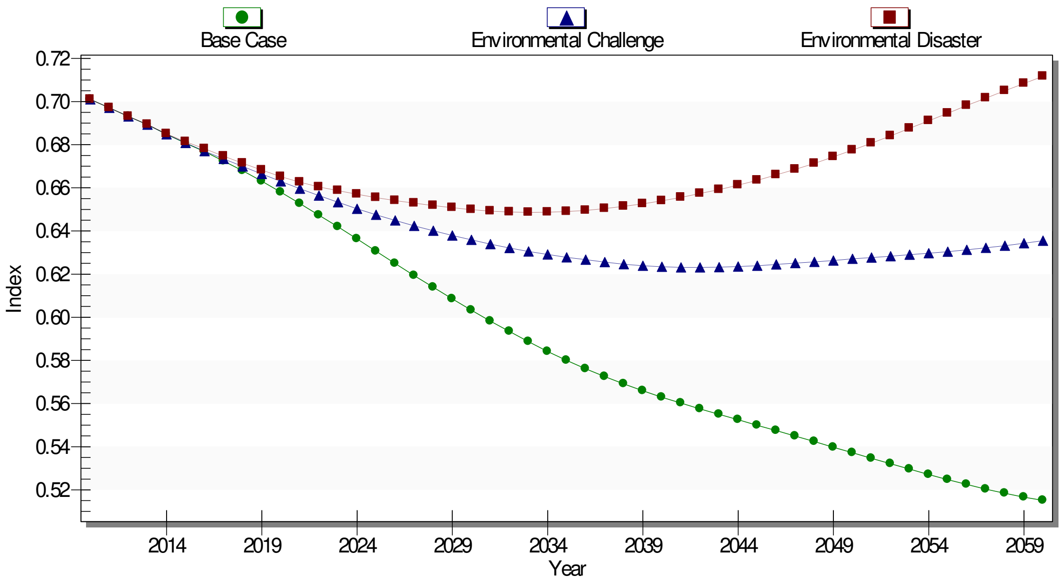

Figure 4. Global Gini of GDP across environmental scenarios

4.2 Drilling down by HDI component

Turning to the sub-dimensions of the HDI—long and healthy life (indicated by life expectancy), knowledge (as measured by mean years of schooling and expected years of schooling), and a decent standard of living (as measured by the log of GDP[14] per capita at PPP)—the environmental impacts on development remain clear. Figure 5 shows life expectancy at birth. The difference in 2060 between the most extreme scenarios is seven years or about 10 percent. Global life expectancy in the Environmental Disaster scenario begins to decline after 2040. Again, the decline is primarily concentrated among less developed countries (not shown); more developed countries continue to slowly gain life expectancy and that of the least developed countries is, on average, mostly flat.

[14] Although the official measure uses Gross National Income (GNI), the IFs system uses the very nearly identical GDP.

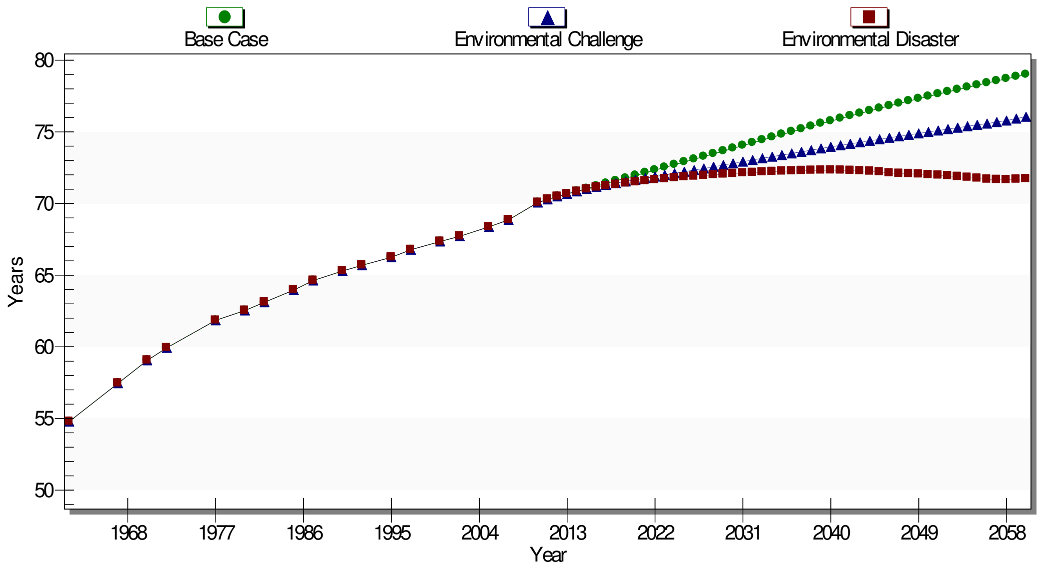

Figure 5. Life expectancy across environmental scenarios

The global pattern across scenarios for average years of formal education (adults aged 25 and older) may surprise some readers (see Figure 6). Figure 6 shows the values for the three scenarios, focusing only on the less developed countries, the set that we have seen to be especially vulnerable to environmental challenges in absolute terms (while the least developed are especially vulnerable in relative terms). In this case the years of education continue to grow even in the Environmental Disaster scenario. Why? Because years of education is a stock across an aging population. The flow of young people who are now, at least in historically relative terms, "pouring" out of primary and secondary schools around the world is replacing elderly cohorts that had very little education. That is, the upward march of average years of education has a great deal of *momentum* even should the flow out of school stabilize or decline somewhat.

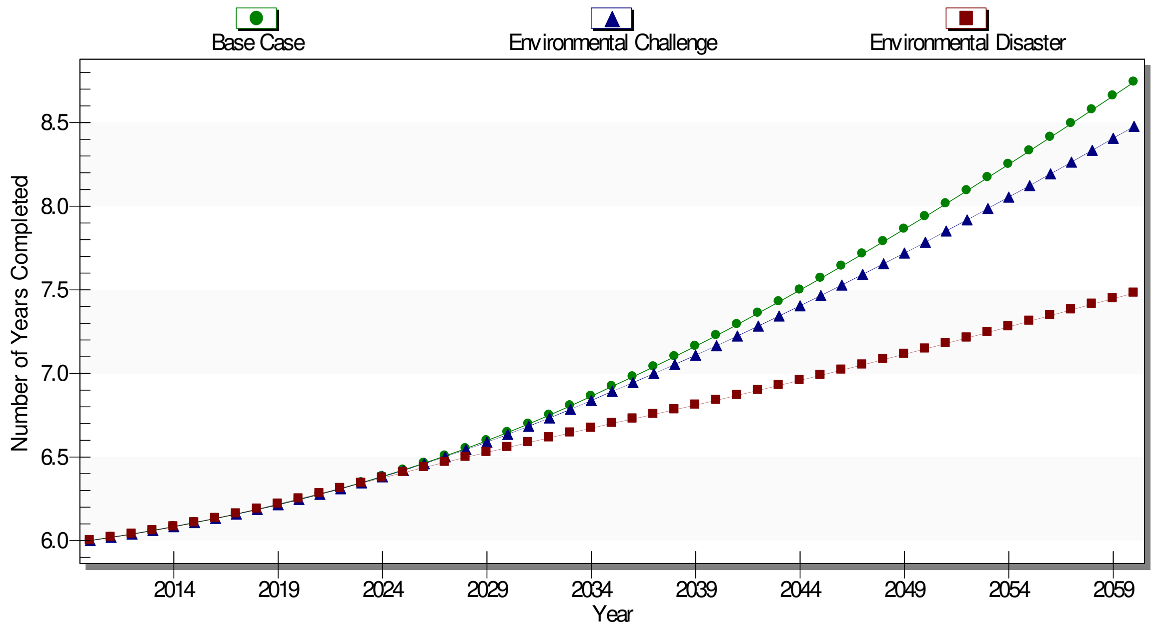

Figure 6. Average years of education of adults in less developed countries across environmental scenarios

Global income across the alternative scenarios (see Figure 7) is a rather sad story. Even in the Base Case the current gap between more and least developed countries is obviously much more dramatic than for either life expectancy or years of education. Specifically, it is nearly $24,000 at purchasing power, a factor of about 22. In the Base Case forecast the absolute gap grows to $64,000 but the ratio declines to a factor of less than 9. The good news of the Base Case, in spite of the large gaps, is that GDP per capita for the least developed countries grows from about $1,100 to more than $8,000 in 2060. But in Environmental Disaster the GDP per capita for the least developed countries rises to only $1,900. The ratio of income in more and least developed countries ends at more than 20, not very different than the current one.

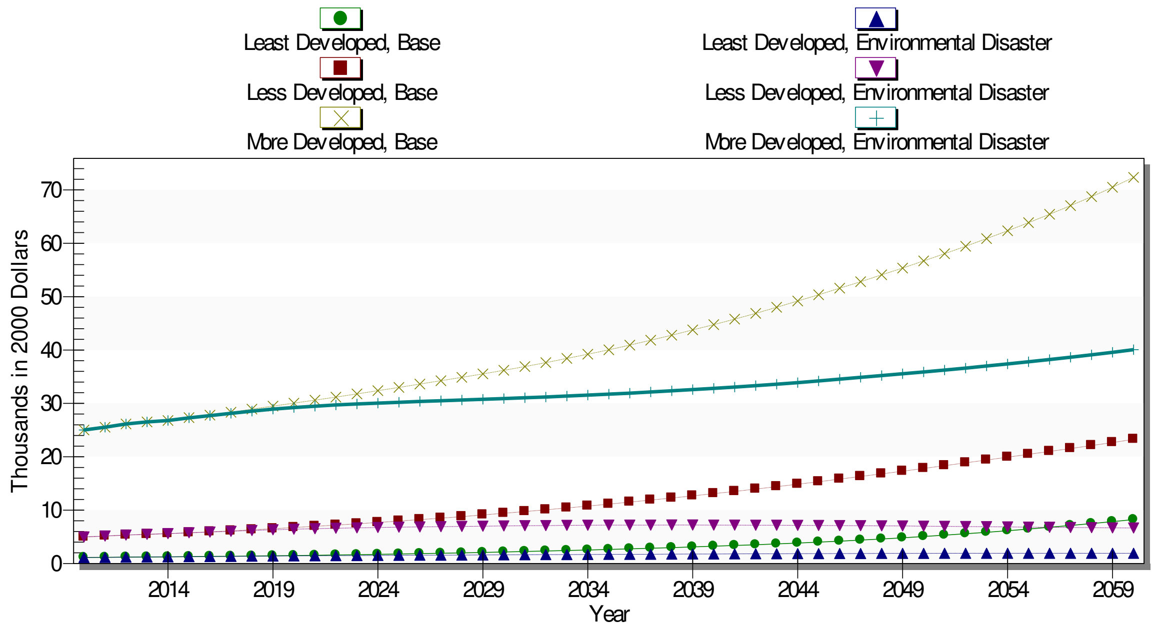

Figure 7. GDP per capita at purchasing power parity across environmental scenarios and income levels

5. Conclusions

As measured by the Human Development Index, the rapid pace of advance in human development of the last several decades will almost certainly slow around the world in coming decades. If for no other reason, the mechanical aspects of the index's construction, including the built-in saturation effects, will assure that. Notwithstanding those effects, and in spite of some important environmental constraints already represented within it, the HDI in the Base Case of IFs climbs quite significantly. By 2060 the world as a whole might add about 0.17 points to the current value, about the same as added in the last 30 years. The least developed countries, because both of lower starting points (and therefore less saturation effect), and because of their more rapid growth on all dimensions of the index, could add nearly 0.25 points. Both human well-being and equity would benefit.

Environmental constraints could, however, threaten such progress in part or almost in total. The Environmental Challenge scenario still allows the HDI to rise globally and across all income categories. That is good news. But it dramatically reduces the size of the gains and very significantly slows the movement towards global equity. The Environmental Disaster scenario nearly stops progress on the index everywhere. The major exception is the knowledge component, notably the indicator of average years of adult education, which has a great deal of built-in momentum because of the demographic replacement over time of poorly educated elderly populations with much more highly educated contemporary youth. The global HDI could be nearly 0.15 points lower in 2060 than in the Base Case; least developed countries, with dramatically lower levels already, could suffer a loss from the Base Case potential of nearly 0.17 points.

Fortunately, Environmental Disaster has a low probability, at least over the time horizon of this analysis. From a pessimistic perspective that is of little consolation because the stock constraints stemming from environmental problems (decreasing fossil fuel availability, falling water tables, rising atmospheric carbon and temperatures, and much more) are likely to keep growing well beyond 2060. From an optimistic point of view the stocks of human resourcefulness (education levels, accumulated knowledge, capital stocks) are also likely to continue growing. It is largely because of those that the Environmental Disaster scenario explored here did not lead to a Malthusian or Limits to Growth-like collapse in IFs forecasts, but rather to a dramatic slowdown in advance of human well-being and something of a stand-off between the two sets of forces. That kind of uneasy stability would not, of course, likely long persist.

Sustainable and equitable human development requires that we protect a better future.

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