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The Future of the Industrial System

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Abstract

Initially, industrialization -- characterized by enormous increases in the use of fossil fuels, technological change, agricultural productivity, urbanization, population, mobility, trade and consumption of material goods -- may have made people wealthier, but the quality of life suffered in other respects. Crowding, unsanitary conditions and pollution made life in many urban areas nastier, more brutish and shorter than in rural areas. Armed with new knowledge and technology, wealth and persistence, the richer countries have shown that these problems can be addressed successfully. And today the state of humanity has never been better. The average person lives longer, is better fed, healthier and wealthier. But unsafe water, unsanitary conditions and indoor air pollution still contribute to millions of premature deaths in the developing countries. Pollution and, more importantly, human demands for food, clothing and shelter (which have diverted large quantities of land and water away from the rest of nature) threaten Earth's ecosystems and biological diversity. These demands, and the demand for materials and energy, will almost certainly grow in the next century with the global population. Nevertheless, the future could see a world in which the population has stabilized, is richer, cleaner, and has room for both humanity and the rest of nature. Alternatively, it could be more populated, poor and polluted, and with the rest of nature pinched for space and water, particularly if climate change exacerbates existing pressures. The odds of the former outcome could be increased by strengthening the co-evolving, mutually-reinforcing forces of economic growth, technology and trade, which requires bolstering the institutions that are their mainstays (which are also the foundations for a robust civil society). However, building and strengthening these institutions may be insufficient if society is hostile to change and if richer societies -- in their quest for zero risk -- reject "second best" solutions. Industrial ecology can play a significant role in moving such solutions closer to perfection, and in hastening the transitions of technological change and economic growth from problems to solutions in the quest for a sustainable industrial society.

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The Future of the Industrial System

Indur M. Goklany[*]

The industrialization of the world underway for the past two centuries has been characterized by enormous increases in the use of inanimate, non-renewable energy in the form of fossil fuels and tremendous technological change. The accompanying increases in agricultural productivity, urbanization, population, mobility, trade and consumption of material goods have changed humanity's relationship to the rest of nature and led to massive social and cultural changes, for instance, redefining the role of women and children, reconstituting the work place, undermining age-old arrangements of caste and class, and developing new forms of organizations. Industrialization also gave us, first, a degraded environment and, as antidotes, environmentalism and a romanticized view of nature.

Initially, industrialization and urbanization may have made people wealthier, but the quality of life suffered in other respects. For many urban dwellers, crowding, unsanitary conditions and polluted air and water may have led, at least initially, to a life that was nastier and more brutish ---- though not necessarily shorter -- than for their rural compatriots (Wrigley and Schofield 1981). Armed with new knowledge and technology, wealth and persistence, the richer countries have shown that these problems can be addressed. But as old problems were addressed, new ones arose.

In the following, I will examine the current state of humanity, the extent of and reasons for its progress since the start of industrialization, and the environmental price of that progress. I will also offer suggestions as to how, based upon historical experience, further advances can be sustained with increases in industrialization (in some countries), post-industrialization (in others), population and consumption, as well as on the role of industrial ecology in bringing about these advances. Brevity, of necessity, forces my treatment to be less than comprehensive.

The Current State of Humanity

Since 1800 A.D., the global population has increased about six-fold from about 900 million to about 6 billion today (McEvedy and Jones 1978, FAO 1999) and industrial potential by over 75-

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fold (Headrick 1995). Between 1810 and 1990, coal production increased 500-fold (Smil 1994). What has all this activity gained humanity?

As Table 1 shows, various aggregate measures generally show remarkable improvements in human welfare from pre- and early-industrial times to the present. First and foremost, life expectancy at birth, which used to be between 20-30 years for much of human history (Preston 1995), has increased to about 66 worldwide (UNDP 1999). Contributing to this was a worldwide decline in infant mortality (Table 1), which typically exceeded 200 before industrialization (Hill 1995), to 57 worldwide in 1998 (WHO 1999a). And not only are we living longer, we are also living healthier (OECD 1998a, Shalala 1998).

Third, daily food supplies per capita (in Kcal/capita/day) have increased 23% from 1961 to 1997 (Table 1, Figure 1) and the real price of food commodities has declined 75% since 1950 (Mitchell and Ingco 1993, World Bank 1998). Thus, despite a 40% increase in population between 1969-71 and 1994-96, chronic undernourishment in developing countries dropped from 920 million to less than 850 million (or from 35% to 19% of their population; FAO 1997, 1999).

Fourth, education levels have increased markedly around the world (Table 1, Figure 2) and adult illiteracy declined worldwide from 45% in 1950 to 23% in 1995 (UNESCO 1998) increasing economic opportunities and social mobility for people in all strata of societies. Arguably, education is also a necessary condition for the proper functioning of a civil society grounded in democratic principles.

Fifth, mankind has never been better off economically. Not only is the average person making more, he is working less. For most of this millennium, gross domestic product (GDP) per capita was below $600 (measured in 1990 International dollars, based upon purchasing power parity, PPP). Today it is more than eight times that (Table 1, Figure 3; Maddison 1998, 1999), and average hours worked per person employed have declined since at least the 1800s (Table 1, Figure 4). For instance, for the average British worker, total life hours worked declined from 124,000 in 1856 to 69,000 in 1981, i.e., from 50% to 20% of disposable life hours (Ausubel and Grübler 1995).

In addition, freedom of expression and the right to choose one's rulers are more widespread today. According to the UNDP (1999), between two-thirds and three-quarters of the population currently live under relatively pluralistic and democratic societies.

TABLE I: Trends in Various Aggregate Indicators of Well-Being (c. 1800 - Present)

LIFE EXPECTANCY AT BIRTH (in years)

Year(s) / *Area*	*Middle Ages*	*Pre- or Early-Industrial Phase* [A,B]	*1950-55*	*1997*
France		~ 30 (1800)	66.5	78.1
UK	20-30	35.9 (1799-1803)[C]	69.2	77.2
Developed Countries	20-30		66.5	74.5[D]
India		24-25 (1901-11)	38.7	62.6
China		25-35 (1929-31)	40.8	69.8
Africa			37.8	53.8[D]
Developing Countries			40.9	63.6[D]
World	20-30		46.5	65.6[D]

INFANT MORTALITY (< 1 year of age, per 1,000 live births)

Year(s) / *Area*	*Middle Ages*	*Pre- or Early- Industrial Phase* [A,B]	*1950-55*	*1998*
Sweden		240 (1800)	22	5
France		182 (1830)	45	6
Developed Countries	> 200		58	9[D]
India			190	72
Developing Countries			179	62[D]
Africa			185	91
World	> 200		156	57

FOOD SUPPLIES (Kcal/capita/day)

Year(s) / *Area*	*Pre- or Early- Industrial Phase* [A,B]	*1961*	*1997*
France	1,753 (1790)	3,193	3,518
Developed Countries		2,947	3,235
India	1,635 (1950-51)	2,070	2,496
China	2,115 (1947-48)[E]	1,642	2,897
Developing Countries		1,932	2,650
Sub-Saharan Africa		2,077	2,183
World		2,257	2,780

TABLE I (continued) : Trends in Various Aggregate Indicators of Well-being (c. 1800 - Present)

EDUCATION (average number of years per person aged 15-64)

Year(s) / *Area*	*1820*	*1870*	*1913*	*1950*	*1973*	*1992*
France			6.99	9.58	11.69	15.96
USA	1.75	3.92	7.86	11.27	14.58	18.04
Japan	1.50	1.50	5.36	9.11	12.09	14.87
India				1.35	2.60	5.55
China				1.60	4.09	8.93

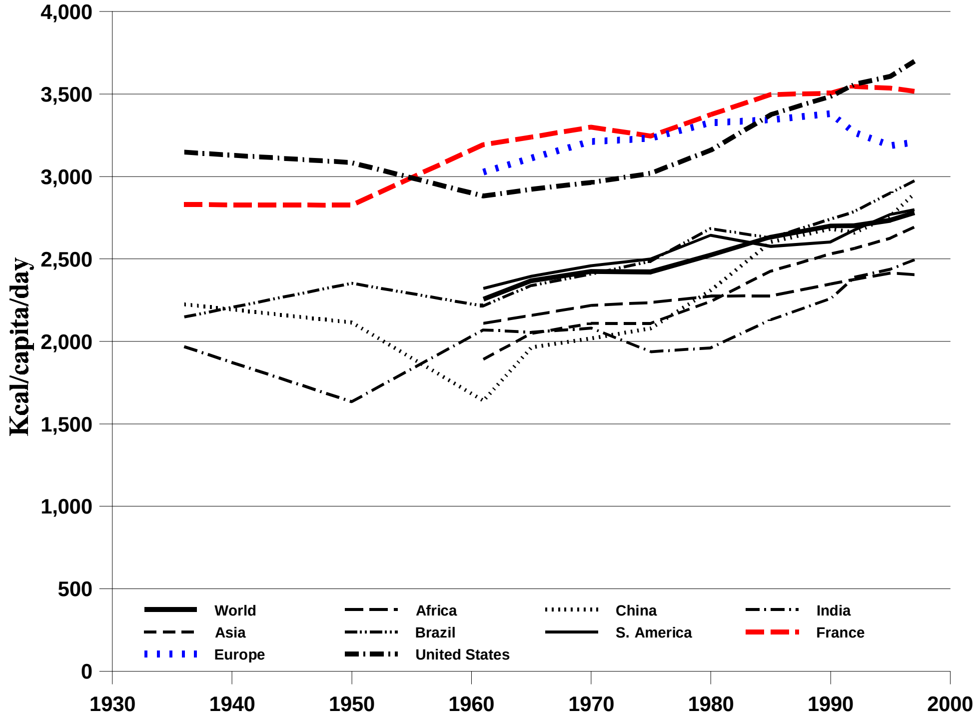
GROSS DOMESTIC PRODUCT PER CAPITA (1990 International $, PPP-adjusted)

Year(s) / *Area*	*0*	*1000*	*1500*	*1700*	*1820*	*1952*	*1995*
Europe	~425[F]	400	~640[F]	870	1,129	4,374	13,951
USA	400[G]	400[G]	400[G]	600	1,260	10,645	23,377
India				531	531	609	1,568
China	450	450	600	600	600	537	3,196
Africa	400	400	400		400		1,221
World	425	420	545	604	673	2,268	5,194

Sources: Life expectancy - Wrigley and Schofield (1981), Preston (1995), WRI (1998), Lee and Feng (1999), UNDP (1999). Infant mortality - Mitchell (1992), Hill (1995), WRI (1998), WHO (1999a). Food supplies - Burnette and Mokyr (1995), Goklany (1999), FAO (1999). Education - Maddison (1995, 1998). GDP/capita - Maddison (1998, 1999).

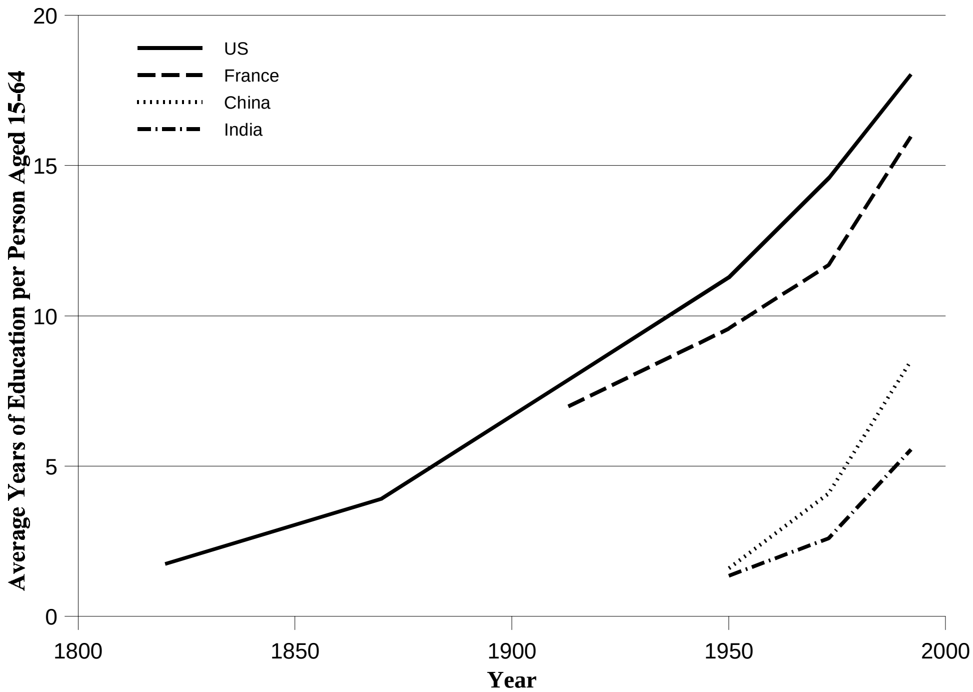
[A] Data are for the year(s) shown in brackets. [B] Many developing countries, e.g., India and China, had barely embarked upon industrialization until after World War II. [C] 1799-1803 data are for England and Wales, only. [D] 1995-2000, from WRI (1998). [E] Based upon data for 22 provinces. [F] Based upon Maddison (1999) using arithmetical average for “Western Europe” and the “Rest of Europe.” [G] Using Maddison’s (1999) estimate for “North America.”

Figure 1: Food Supplies per Capita, 1936-1997



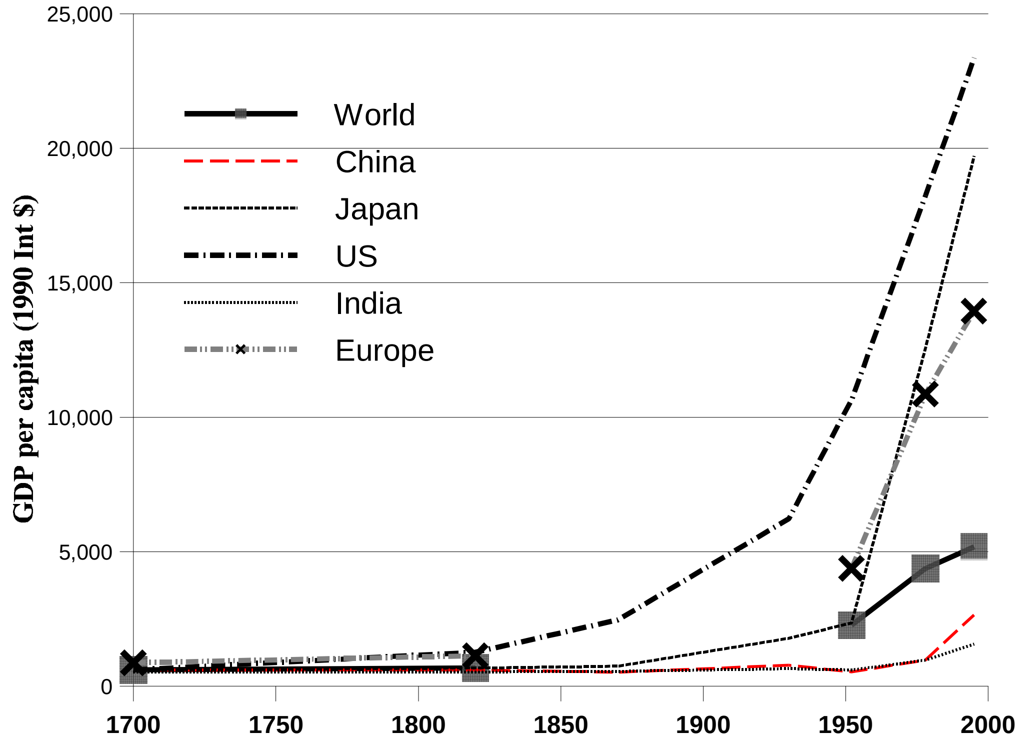
Sources: Goklany 1999a, FAO 1999.

Figure 2: Years of Education per Person, 1820-1992



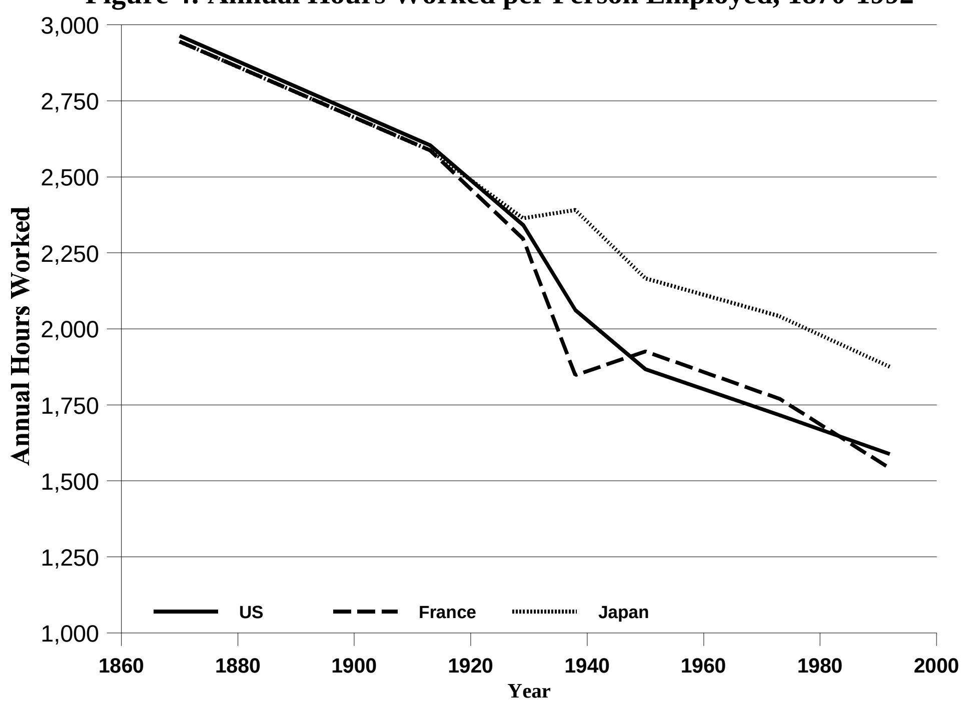
Source: Maddison 1998.

Figure 3: GDP per Capita, 1700-1995



Source: Maddison 1998, 1999.

Figure 4: Annual Hours Worked per Person Employed, 1870-1992



Source: Maddison 1998.

However, progress has not been uniform either within or between countries and there are, in certain regions, signs of regression. Gaps in per capita income between Western Europe and its mainly white ex-colonies and other regions have ballooned since 1700 (Table 1; Maddison 1998, 1999). 1.3 billion people live in absolute poverty (defined as subsisting on less than one US dollars per day; UNDP 1999). UNDP's (1999) statistics also indicate that at least 50 nations have lower per capita incomes today than in 1975 (using real, but non-PPP adjusted dollars). Of these 50 countries, 11 are in East Europe or the former Soviet Union, victims of a failed economic system; another 11 export oil, a commodity whose price has since plummeted; and at least another 11 were involved in civil or other wars.

Gaps in life expectancy and infant mortality between rich and poor countries (at 12 years and 57 deaths per 1,000 live births) are substantial (Table 1). However, these gaps -- a result of poverty which leads to lower access to sanitation, safe drinking water, food supplies and public health services -- have narrowed about 50% since World War II, after widening in the 1800s and early 1900s.

Particularly worrying is that life expectancy has regressed in some countries. Since 1975, it has declined in at least 18 countries -- 10 in Africa mainly due to HIV/AIDS, and 8 in East Europe and the former Soviet Union due, directly or indirectly, to declining economic circumstances (UNDP 1999). Food production in Sub-Saharan Africa also fell behind population growth for much of the last three decades, largely due to wars and failed economic policies, further aggravated by drought in many areas (Goklany 1998a, 1999a). Despite trade and aid, which helped limit increases in food prices, many were priced out of the market, and hunger and undernourishment increased in many Sub-Saharan countries.

Nevertheless, as captured by Table 1, the overall trend in human well-being is upward. Thus, the latest Human Development Report (UNDP 1999), using a composite human development index (HDI) which considers life expectancy, adult illiteracy and PPP-adjusted per capita income, reports that of the 79 countries for which it has data from 1975 through 1997, although per capita incomes (in real, non-PPP adjusted dollars) declined for 17 countries over that period, all but one increased their HDIs.

Factors Responsible for Improvements in Human Welfare

The improvements in human welfare were sustained, if not set into motion, by the mutually-reinforcing, coevolving forces of economic growth, technological change and freer trade (Goklany 1995, 1998a).

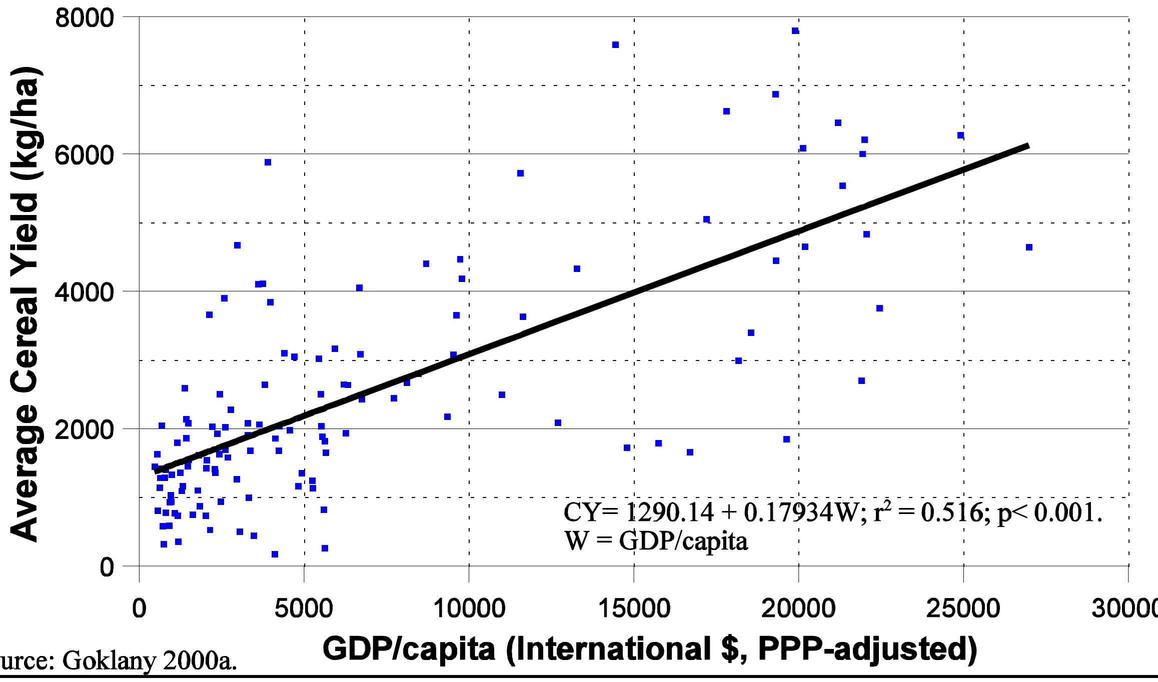
Together these forces increased food production, moved food surpluses to deficit areas and reduced global food prices, which improved nutrition (Goklany 1998a, 1999a). Thus, Figures 5 and 6 show that average cereal yields and available food supplies per capita increase with affluence (per capita GDP) (Goklany 1999c). Improvements in food supply leads initially to a healthier population less likely to succumb to infectious diseases. That -- and fiscal resources targeted on public health measures and technologies providing better sanitation, safer water supplies, immunization and antibiotics against various infectious diseases -- reduced mortality and increased life expectancy (Fogel 1995, WHO 1999a). Hence, Figures 7 and 8 show that life expectancy and infant mortality improve with affluence, i.e., wealthier is healthier (Goklany 1999c).

But the converse is also true: healthier is also wealthier. A healthier population is more productive because it can devote more time and energy to economic pursuits (Fogel 1995, Barro 1998, WHO 1999a), and more likely to fully develop and retain its human capital to enhance technological change.

Technological change also reinforces economic growth (Barro 1998, Goklany 1998a). In turn, rich countries have more resources to research and develop new and improved technologies (Goklany 1995a). They can also better afford to educate their population more thoroughly, thereby increasing human capital which further aids the process of technological change. Thus, in 1993, for instance, 10 of the richest (and most well-educated) countries accounted for 84% of global research and development, and controlled over 80% of the patents in the U.S. and in developing countries (UNDP 1999). For its part, freer trade contributes directly to greater economic growth, helps disseminate new technologies and creates competitive pressures to invent and innovate (Goklany 1995a). Thus, we have a cycle: health begets wealth -- and wealth, health. But it is just as easy to visualize the cycle being kicked into reverse (e.g., by wars or poor policies) with both health and wealth going in the wrong direction as seems to be the case currently in parts of Africa, East Europe and the former Soviet Union.

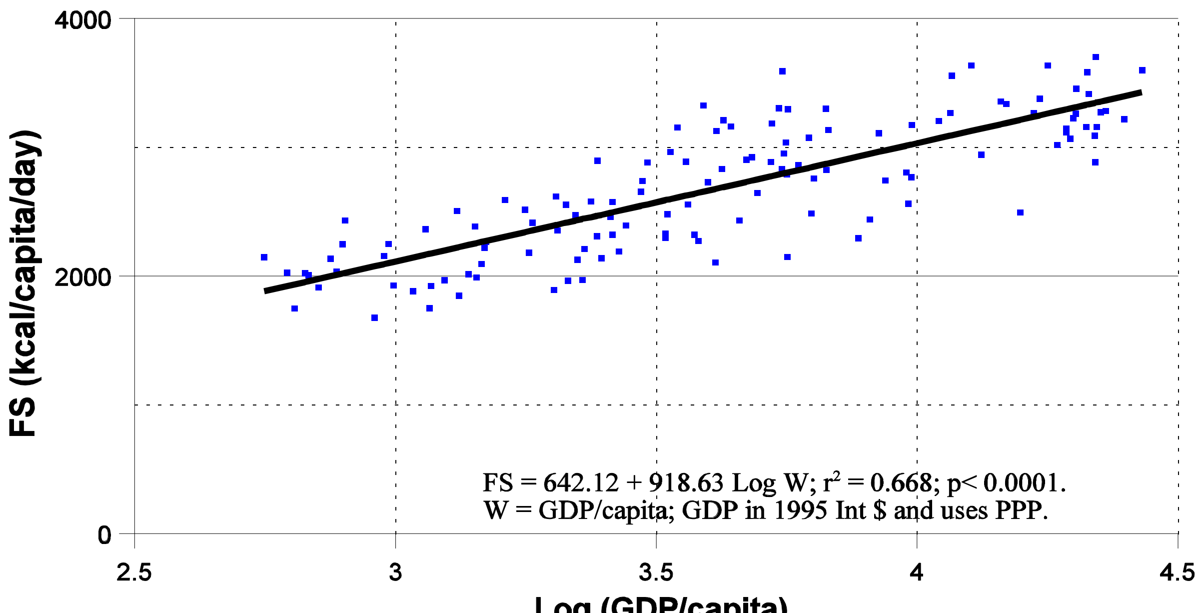
Why do some societies cycle forward faster than others? Why have others barely begun to move economically and socially? Why have yet others slipped back economically and socially? Can their situation be reversed? The answers probably lie in each society’s support for the web of institutions that undergird economic growth and technological change (e.g., free market economies; fair, equitable and transparent rules to govern markets and enforce contracts; enforceable property rights to both tangible and intellectual products; institutions for accumulating and converting knowledge into useful and beneficial products) which, in turn, are

Figure 5: Cereal Yields (CY), 1995



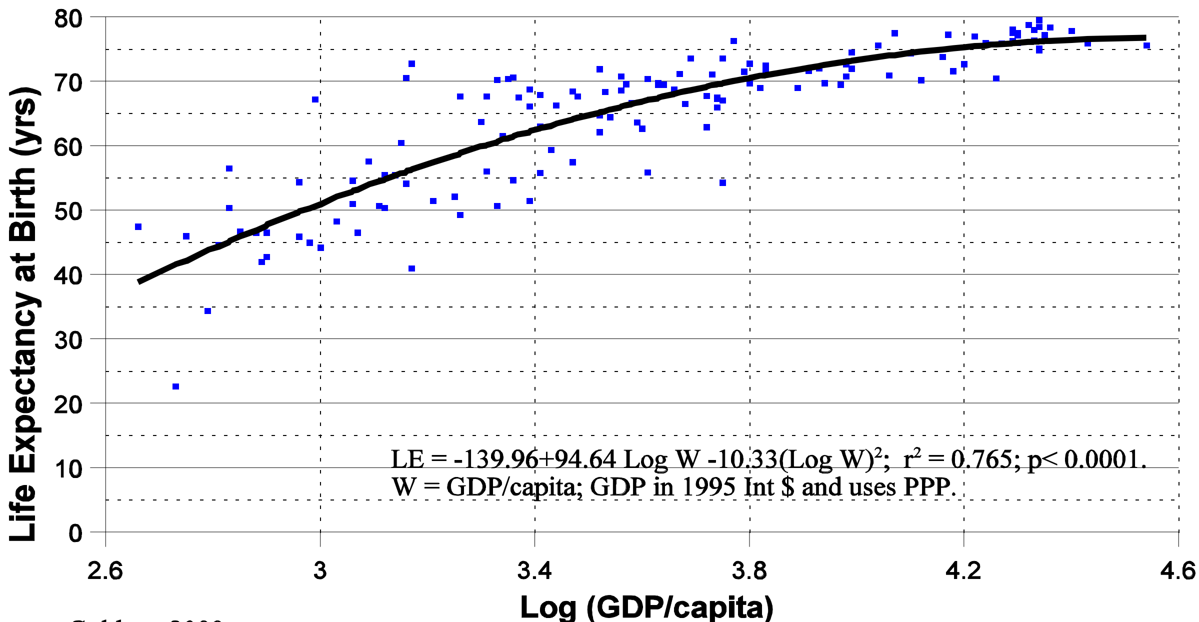
Source: Goklany 2000a.

Figure 6: Daily Food Supplies per Capita (FS), 1995



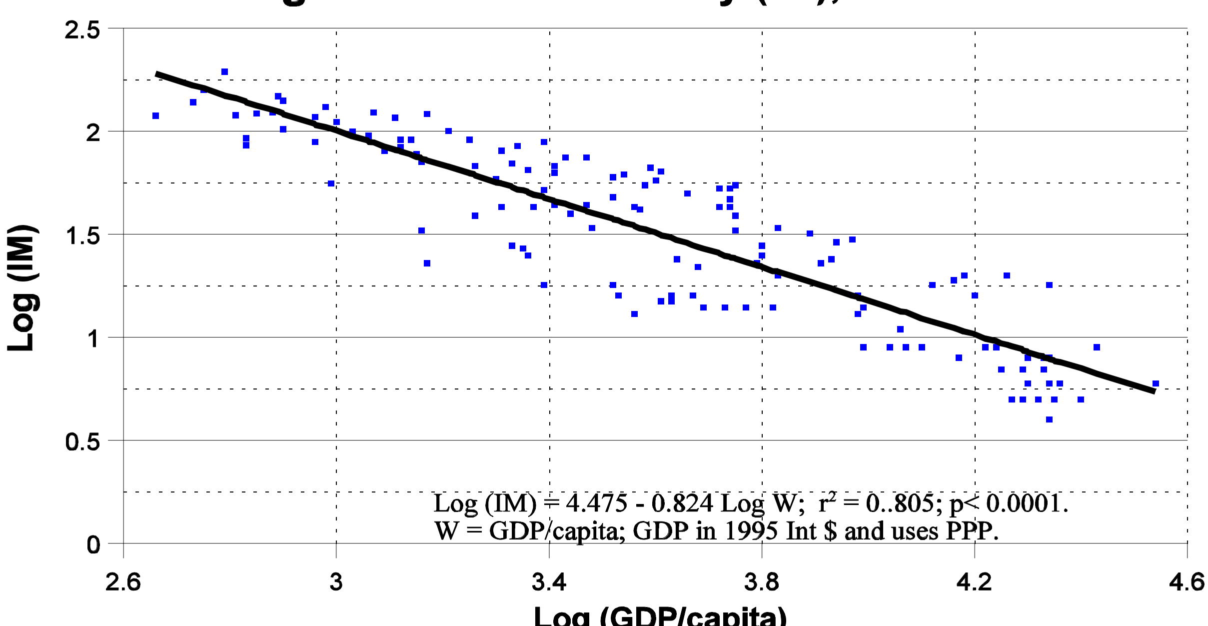
Source: Goklany 2000a.

Figure 7: Life Expectancy (LE), 1990-95



Source: Goklany 2000a.

Figure 8: Infant Mortality (IM), 1990-95



Source: Goklany 2000a.

determined by the society's attitudes towards change, risk and reward, commerce, education, knowledge, science and technology, the role and size of government, and inequality (Braudel 1984, Landes 1998, Rosenberg and Birdzell 1985, Barro 1998). And clearly, wars, internal or cross-border, are inimical to human welfare, as is a large public sector and over-regulation of the economy.

The Environmental Price of Industrialization and Population Growth

The gains in human welfare have come at a steep environmental price. Worldwide, mainly because of poverty in developing countries, over a billion persons lack access to safe drinking water (WHO 1999b). About 2.6 billion lack adequate sanitation (UNDP 1999). According to the UN Commission on Sustainable Development (1997), more than 5 million people die each year just from diseases caused by lack of safe drinking water, water for hygiene and sanitation. In 1998, diarrhoeal diseases alone claimed 2.2 million lives and malaria -- a natural rather than manmade environmental problem – took 1.1 million lives (WHO 1999a). Virtually all these casualties were in developing countries.

Air pollution is estimated to cause 3 million premature deaths world-wide, including 2.8 million attributed to indoor air pollution, mainly owing to burning of fuelwood, coal and dung in developing countries (WHO 1997). Moreover, acidic deposition, in addition to contributing to public health effects, affects visibility, damages materials and affects sensitive soils, vegetation and waters.

Also, diversions of land and water to meet the phenomenal demand of a much larger and richer population for food, clothing, shelter and other needs are at present the major global threats to biodiversity (Vitousek et al. 1997, Wilcove et al. 1998, Goklany 1998a). By some estimates, humanity has transformed between a third and a half of global land area including half the world's original forests, and more than half the accessible surface fresh water (Vitousek et al. 1997, Bryant et al. 1997). Agriculture alone accounts for 37% of global land area (FAO 1999), 70% of water withdrawals and 87% of consumptive use worldwide (UNCSD 1997). Agriculture also affects biodiversity through water pollution or atmospheric transport, for example, by release of excess nutrients, pesticides, and silt into the environment (Wilcove et al. 1998, Goklany 1998a).

Then there is climate change. Although its effects may be small today compared to the more immediate environmental problems noted above, they could be profound in the long term.

Nevertheless, there are numerous signs of environmental progress. Total global fertility rate was halved between 1962 and 1997 dropping from 5.58 to 2.75, annual global population growth rate declined from a peak of 2.07% in 1967 to 1.33% in 1998, and global population increased by 81.0 million from 1996 to 1997 rather than 88.3 million as in 1987-88 (UN 1998, World Bank 1999, FAO 1999). Global access to sanitation and safe water, once alien concepts, has increased to 50% and 80%, respectively (WHO 1999b, UNDP 1999). Malaria mortality rate declined worldwide from 1,940 per million population in 1900 to 180 in 1997 although in Sub-Saharan Africa it rebounded to 1,650 in 1997 after dropping from 2,230 per million in 1900 to 1,070 in 1970 (WHO 1999a). Many forms of indoor, local and regional scale air pollution, particularly particulate matter (PM) and sulphur dioxide (SO_2), have been contained, if not reversed, in the richer nations (Goklany 1998b, 1998c). In the U.S., for instance, emissions per GNP were reduced by a factor of 10 (+) between 1900 and 1997 for SO_2 and volatile organic compounds, a factor of about 30 between 1940 and 1997 for PM-10 (PM less than 10 micrometers in diameter), and a factor in excess of 100 for lead since 1970 (Goklany 1999b). The technologies developed by the richer nations are now generally available, albeit at some cost.

Similarly, many rivers in the rich nations (e.g., the Thames in Britain, the Rhine in Germany and the Hudson in the U.S.) are recovering from generations of abuse. DDT and PCB concentrations have dropped to a fraction of their former levels in the Great Lakes and the Netherlands. The peregrine falcon, for instance, is no longer endangered in the U.S.; and Minamata Bay fish are once again safe to eat (Goklany 1994, 1998a).

Moreover, had it not been for technological progress in the food and agricultural sector since 1961, just to feed the world's population at the historically inadequate levels of 1961 (see Table 1 and Figure 1) at least an additional 1,040 million hectares (Mha) would have had to be converted to cropland worldwide beyond the 1,510 Mha of cropland actually used in 1997 (see Figure 9). That progress also helped reverse centuries of deforestation in the richer nations (Goklany and Sprague 1991). Between 1980 and 1995, for instance, forest cover increased by about 20 Mha in the developed countries (FAO 1997).

Technological progress has also contained the growth of carbon emissions. Although they continue to increase, since 1850 the global energy system has been decarbonized at a rate of 0.3% per year. On top of that, in countries for which long-term data are available (e.g., the U.S.), the energy intensity of economies has decreased at 1.0% per year since 1800 (Nakicenovic et al. 1998). Absent the reduction in carbon intensity of the global economy since 1950, global carbon emissions from fossil fuel combustion would have been 57% higher in 1998 (Flavin 1999).

In addition, the global control of CFCs and other stratospheric ozone depleting substances before any adverse health or environmental effects being manifested indicates that humanity is capable of taking anticipatory steps to address pollution that is non-local and whose effects are cross-generational if it perceives the stakes (relative to costs) are high enough.

But perhaps the most encouraging sign for the world's environmental future is that greater economic resources and more human capital, which helped bring about the improvements noted above, are being devoted to solving environmental and natural resource problems. Among the most promising new approaches this has spawned is the emerging discipline of industrial ecology which would launch systematic studies of (and attacks on) the basic processes that give rise to pollution and unsustainability, and harness collective human ingenuity in that enterprise.

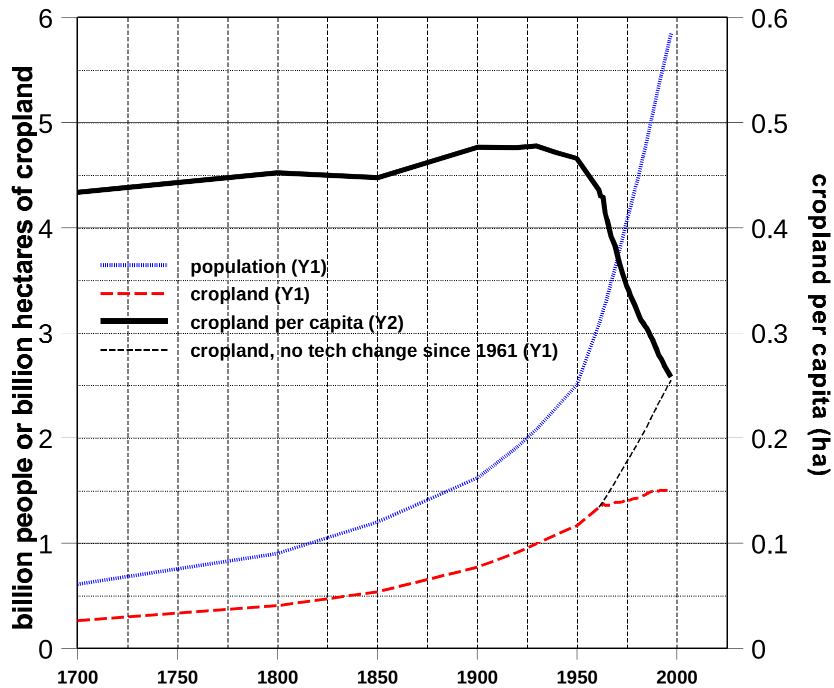
The Environmental Transition Model for Environmental Success

Figure 10 is a stylized depiction of the environmental success stories noted above [e.g., indoor and outdoor air quality for SO_2 and PM, availability of safe water and sanitation, and PCB and DDT residues in humans]. It provides a general model for environmental success. In this Figure, the environmental impact (EI) for a single country as measured by a particular indicator (e.g., national composite ambient air concentration) first goes up, then it goes through an "environmental transition" (ET) after which EI declines, at least to a point (Goklany 1994, 1999b). Till that point, the trajectory for EI is shaped like an inverted-U (IU). For some indicators (e.g., sanitation or safe water), the transitions have historically occurred earlier in a country's developmental history. For others, because the problem has yet to be addressed successfully (e.g., carbon emissions), an ET may not be evident, i.e., the country may still be on the upward slope of the ET.

Notably, cross-country data for some pollutants also result in IU curves (called Environmental Kuznets Curves, EKCs) when EI is plotted against affluence (GDP per capita). Despite the superficial resemblance between the ET and EKC hypotheses the two are not identical. In the former the x-axis represents time (a proxy for both affluence and technological development), and affluence in the latter. Also, a set of single-country IU-shaped ETs does not necessarily result in a IU-shaped cross-country EI vs. affluence curve, instead it could be N- or even U-shaped (Goklany 1999b).

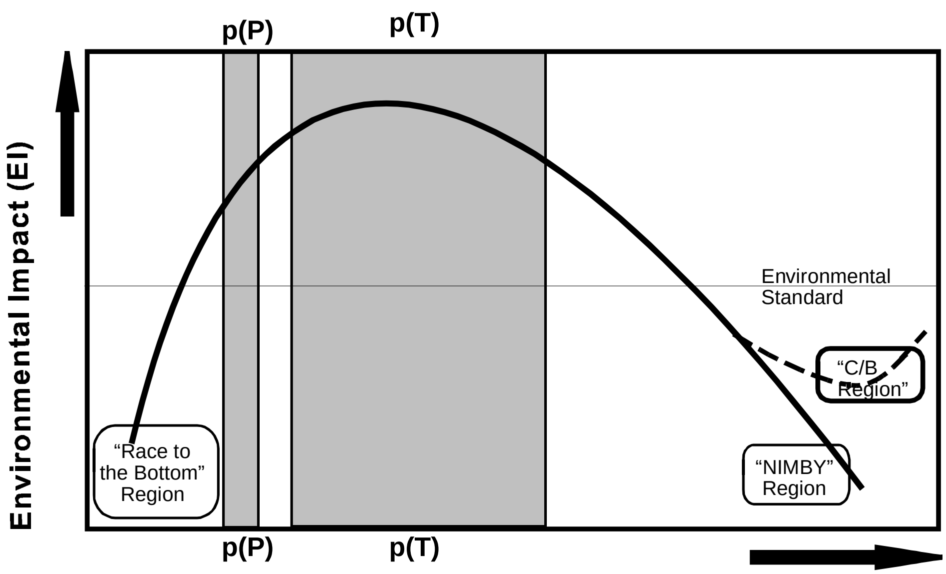
An explanation offered for an environmental transition is that society is on a continual quest to improve its quality of life (QoL) which is determined by numerous social, economic and environmental factors (Goklany 1994, 1995a, 1998a, 1999e). The weight given to each determinant is constantly changing with society's precise circumstances and perceptions. In the

Figure 9. Cropland and Cropland Productivity, 1700-1997.



Sources: Goklany 1995, 1999a; FAO 1999.

Figure 10: The Environmental Transition



NOTE: p(P) = period of perception; p(T) = period of transition; NIMBY region = "not in my back yard" region (ED enters this region if benefits far exceed costs borne by beneficiaries); C/B region = ED enters this region if costs & benefits have to be more carefully balanced.

Source: Goklany 1999b.

early stages of economic and technological development, which go hand-in-hand, society places a higher priority upon increasing affluence than on other determinants, even if that means tolerating some environmental deterioration, because that provides the means for obtaining basic needs and amenities (e.g., food, shelter, water and electricity) and reducing the most significant risks to public health and safety (e.g., malnutrition, infectious and parasitic diseases, and child mortality). Also, in these early stages, society may be unaware of the risk posed by EI. However, as society becomes wealthier, tackles these problems and, possibly, gains more knowledge, reducing EI automatically rises higher on its priority list (even if EI does not worsen). But since economic activity further increases EI, lowering EI becomes even more urgent. Thus, environmental quality becomes a more important determinant of the overall quality of life. This stage is represented in Figure 10 as the *period of perception* or p(P) (Goklany 1998c).

Prior to p(P) one should not expect society to require, or private parties to volunteer, to reduce EI, although reductions may occur due to secular improvements in technology or other reasons (Goklany 1995b, 1996). For example, for SO_2 in the U.S., p(P) dates to the 1950s but indoor SO_2 levels had begun to improve before the 1940s (Goklany 1998c, 1999b). From p(P) onward, a democratic society will often translate its desire for a cleaner environment into laws, either because clean up is not voluntary or rapid enough, or because of sheer symbolism. The wealthier such a society, the more affordable -- and more demanding -- its laws.

At the same time, with increasing affluence and the secular march of technology, society is better able to improve its environmental quality. Affluence also makes R&D targeted on cleaner technologies more affordable, as it does the purchase and use of new or existing-but-unused cleaner technologies, especially if their up-front costs are higher. Thus, EI undergoes a *period of transition*. Ultimately, greater affluence and technological change should result in a decline in EI (Goklany 1994, 1995b, 1999b).

Other factors have reinforced ETs in the richer countries for traditional (industry-related) pollutants. Historically, economic development involved technology-mediated transformations from, first, an agrarian to an industrial society and, then, an industrial to a post-industrial knowledge- and information-based society. Emissions of industrial pollutants per capita or per GNP (both leading, rather than true, indicators of environmental impacts) increased with the first transformation but declined with the second, and temporal trends for these leading indicators also look like stylized IUs. Second, as the industrial sector waxed and waned so did its political power. In 1900 the U.S. mining and manufacturing sectors, traditionally associated with pollution, employed 40.2% of non-farm labor (USBOC 1975). After declining during the

Depression, the employment in these sectors rebounded into the 40(+)% range during World War II before dropping to 28.2% in 1970 and 17.0% in 1997 (USBOC 1975, 1998). A decline in a sector's economic and demographic power only makes stiffer environmental laws more likely for that sector, particularly in a democracy. Currently we see this principle in operation for the U.S. ranching, mining, lumbering and agricultural sectors (Goklany 1998c).

Once past the ET and EI drops below the environmental standard, it could then move in one of several different directions. If the (perceived) benefits of control substantially exceed (perceived) social and economic costs, or if the costs are shifted to others while benefits are retained, EI will be driven down farther (as indicated by the solid post-transition curve in Figure 10). In effect, the EI trajectory enters a "not-in-my-backyard" (NIMBY) phase. However, if EI enters a region where costs approximate benefits, which may occur if technological progress has been unable to substantially reduce costs or costs cannot be shifted to someone else, then the precise trajectory will depend upon a more careful balancing of the perceived costs and benefits (Goklany 1994, 1995b, 1998c). Such a region is denoted in Figure 10 as the "cost-benefit" or CB region. In a democracy such balancing is often done by legislators or agencies authorized by them. Almost inevitably, such balancing is qualitative and imprecise (Goklany 1999b).

The dashed line in Figure 10 depicts a case where further control is no longer perceived to enhance QoL, i.e., the additional costs of further control once again exceed additional benefits, and EI swings upward. That may occur, for example, if the costs of additional cleanup increase exponentially while benefits diminish, as is not unusual; society decides that for the particular EI, the environment is clean enough and scarce resources should now be spent on other unmet needs; and limits of clean technologies have been reached and no cleaner substitutes are available (Goklany 1994, 1995b, 1999b).

Finally, it is worth noting that an environmental transition resembles a demographic transition in many respects (Goklany 1995a).

Does Greater Wealth Lead to Cleaner Environments?

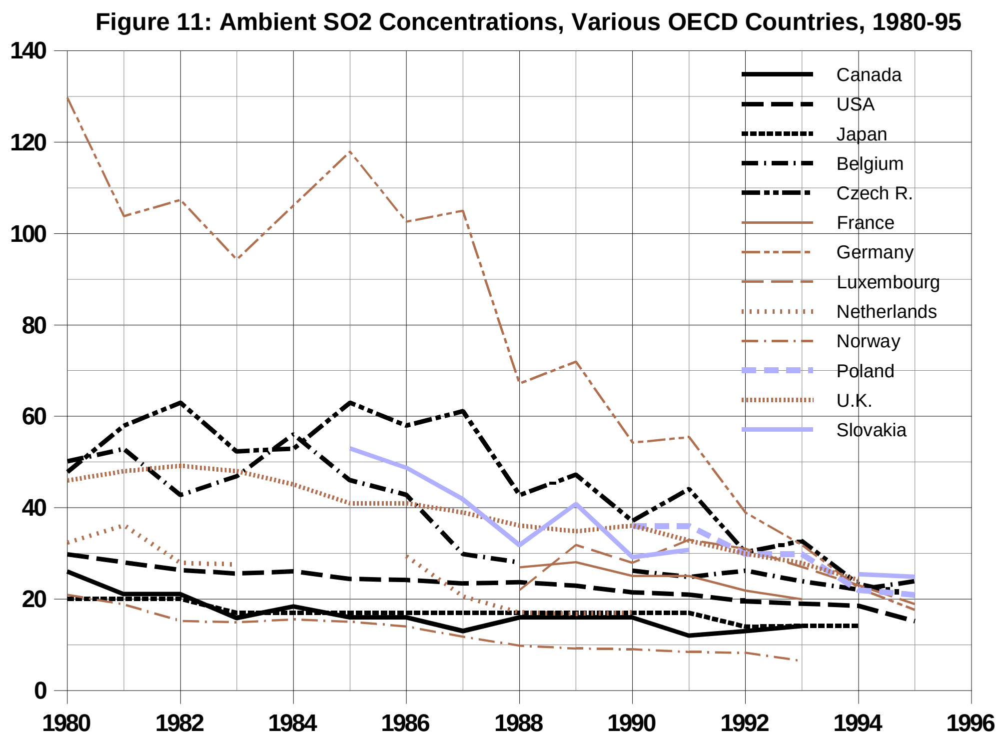
Based upon cross-country EKCs and single-country ETs for various environmental indicators, it has been suggested that as a country gets richer, it will ultimately get cleaner (Goklany 1995b, 1998a). One of the arguments against this proposition is that some cross-country data indicate that at high levels of affluence, a cross-country plot of ambient SO_2 concentrations vs. affluence may swing up, i.e., the curve may be N-shaped (Torras and Boyce 1998, Rothman and DeBruyn 1998). However, a N-shaped cross-country curve can be constructed from a hypothetical set of

IU-shaped single-country ET curves (Goklany 1999b). Thus, an N-shaped cross-country EKC is not by itself a persuasive argument against the notion that a richer country is ultimately a cleaner country.

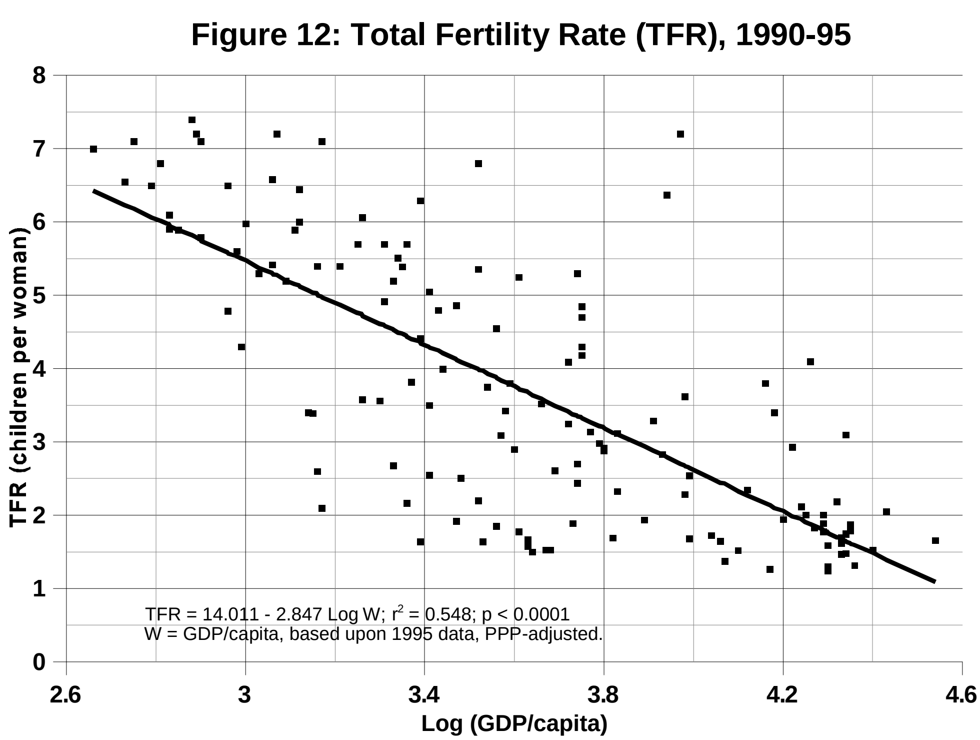
Figure 11 shows trends in "national" composite ambient SO_2 concentrations for the 13 countries for which such data were available from OECD (1997). The PPP-adjusted GDP per capita for ten of these nations (among the world's richest and most industrialized) are above $18,000, and between $3,000 and $10,000 for the remaining three (the Czech Republic, Poland and Slovakia). Each of these countries is currently on the downhill side of an ET and none, so far, has had a sustained upswing. However, a cross-country regression analysis of national SO_2 concentrations against PPP-adjusted GDP per capita for the richer set of countries using a single year (1993) shows no correlation across countries between EI and affluence ($n = 9$, $R^2 < 0.006$, $p >> 0.1$), although there is a much stronger correlation between national SO_2 concentrations and a country's dependence on solid fuels, as measured by the fraction of total fuel consumption due to solid fuel consumption ($R^2 = 0.62$, $p < 0.01$; Goklany 1999b). This example suggests that a richer country is ultimately likely to be a cleaner country, at least until it is "clean enough," but that a richer country is not necessarily cleaner than a poorer one.

Greater wealth also indirectly affects environmental quality through its effect upon total fertility rate (TFR). As Figure 12 shows, TFR drops with affluence, i.e, sooner or later, the richer the nation the lower its population growth rate, which ought to lead to a cleaner environment (Goklany 1995a, 1999c). Ironically, the preferences for current consumption and for highly educated and trained workers are among the reasons why TFR has dropped in the richer nations.

<u>Determinants of Environmental Transitions</u>**.** The height and width of an ET curve for a specific indicator is unlikely to be the same for all countries. In general, all else being equal, latecomers to industrialization should have ETs occur at lower levels of affluence because they can learn and adapt technologies from early industrializers. Other factors can also affect the timing for and level of affluence (A_T) at which an ET occurs for a country. First, it depends on the precise indicator used to characterize EI and how closely it is tied to the QoL. In the U.S., for example, the transitions occurred earlier for indoor air pollution than for outdoor air quality, and for SO_2 and PM -- pollutants most directly related to killer episodes of the 1940s and 1950s – than for less powerful pollutants such as NO_x and O_3. Second, A_T depends upon whether and when p(P) commenced. It also depends on the responsiveness of the government to the perceived needs and desires of the general public; thus, democracies are more likely to see earlier ETs. In addition,



Source: Goklany 1999b.



Source: Goklany 2000a.

the political power of the sectors contributing to EI can affect A_T because that affects stringency of laws directed at them. Fifth, it is affected by the natural resource endowment of the country. A country with large coal reserves is likely to have a more carbon-intensive economy and one with no energy resources, a lower energy-intensive economy (Goklany 1999b). Finally, A_T will depend on the fiscal resources and human capital devoted to bringing about the environmental transition which, in turn, are affected by all the interrelated factors noted previously as being responsible for increasing the levels of economic growth and technological change (e.g., support for property rights, freer markets, research and development, and education).

The Future Sustainability of Industrial Society

According to IIASA's 1996 analysis, the most likely trajectory of global population (based upon central fertility-central mortality assumptions) is that it would increase from the current 6 billion to 9.9 billion in 2050 and then peak at 10.6 billion before declining to 10.4 billion in 2100 (Lutz 1996). However, under an alternative (high fertility-high mortality) scenario, the populations in 2050 and 2100 could be 11.3 and 15.1 billion, respectively. A low fertility-low mortality scenario results in 8.5 billion people in 2050 followed by a decline to 6.5 billion in 2100. A more recent analysis by the UN (1998) estimates that the 2050 population could range from 7.3 to 10.7 billion with a most likely estimate of 8.9 billion in 2050.

Despite uncertainties in population estimates, population will almost certainly grow in the next few decades. But which of the above population scenarios is more likely to occur? Clearly, population growth will peak earlier and at lower levels under the low mortality-low fertility assumptions, both of which are consistent with greater affluence (Figures 8 and 12) and technological change (Goklany 1995a, 1998a).

However, if the future population is richer -- as, indeed, most hope, because that means greater human welfare as measured by life expectancy, lower mortality, less malnourishment, greater education and so forth (Table 1, Figures 6-8) -- the per capita demand for food, energy and material goods is likely to be higher. But will there be sufficient food and natural resources to meet humanity's future demands? Will the scale of activities undertaken to meet those demands be environmentally sustainable?

With respect to the scarcity issue, some argue that the long-term declines in real worldwide prices of food, energy and minerals (due to technological progress) belies the notion of impending shortages (Goklany 1998a,1999a; Hodges 1995; Panayotou and Vincent 1997; Sagoff 1995). More to the point, several recent analyses indicate that there is enough land, energy, and minerals provided technological change continues (e.g., Ausubel and Langford 1997, Ausubel 1998a, Goklany 1998a, Grübler 1998, Nakicenovic et al. 1998). However, there is one natural resource -- water -- for which maintaining adequate supplies could be problematic. But perhaps the most critical issue is whether the global economic enterprise is sustainable given the cumulative effects of various environmental problems (e.g., air and water pollution, habitat loss and climate change). The following briefly addresses what seem to be the most critical resource and environmental problems for the foreseeable future (about 2050 or so).

Air and Water Pollution Including Access to Safe Water and Sanitation

Based upon experience to date (Figure 10), local and regional scale problems of air and water pollution (including access to better sanitation and safe water) will probably be of diminishing importance for countries that will be in their post-industrial phase. In current developing countries, such pollution may or may not be lower depending upon how far along they are in their individual ETs for the various pollutants. The wealthier they become, the more likely that they will reverse their air and water pollution problems, particularly if technological change continues to lower pollution control costs. In general, one should expect that developing countries would follow the pattern established by and learn from the experience of today's rich countries, namely, they would initially focus on public health related pollution problems before addressing other pollution impacts, and that in doing so they would adapt control technologies and management approaches developed by the richer countries.

Their first order of business should be to improve access to safe water and sanitation, and reduce indoor air pollution by reducing use of coal, wood and dung in households. U.S. experience suggests that most households will suspend using solid fuels indoors more or less voluntarily as the population grows more affluent and cleaner substitutes become available (Goklany 1995b). Other options are to use more efficient heaters and cookers, and subsidies for cleaner fuels. Economic growth will hasten these improvements. Other public health problems could be addressed by siting (to the extent practicable) pollution sources in less populated areas (which would help industrialize some rural areas and help reduce population pressures on some of the largest urban areas), using bubble strategies as opposed to stack-by-stack or pipe-by-pipe regulations, possibly taxing pollutants and more fully exploiting sink characteristics of the atmosphere and waters. Because today's developing countries started industrializing later, one should expect that, all else being equal, their environmental transitions for any specific indicator for EI would occur at lower levels of affluence and peak EIs would be smaller.

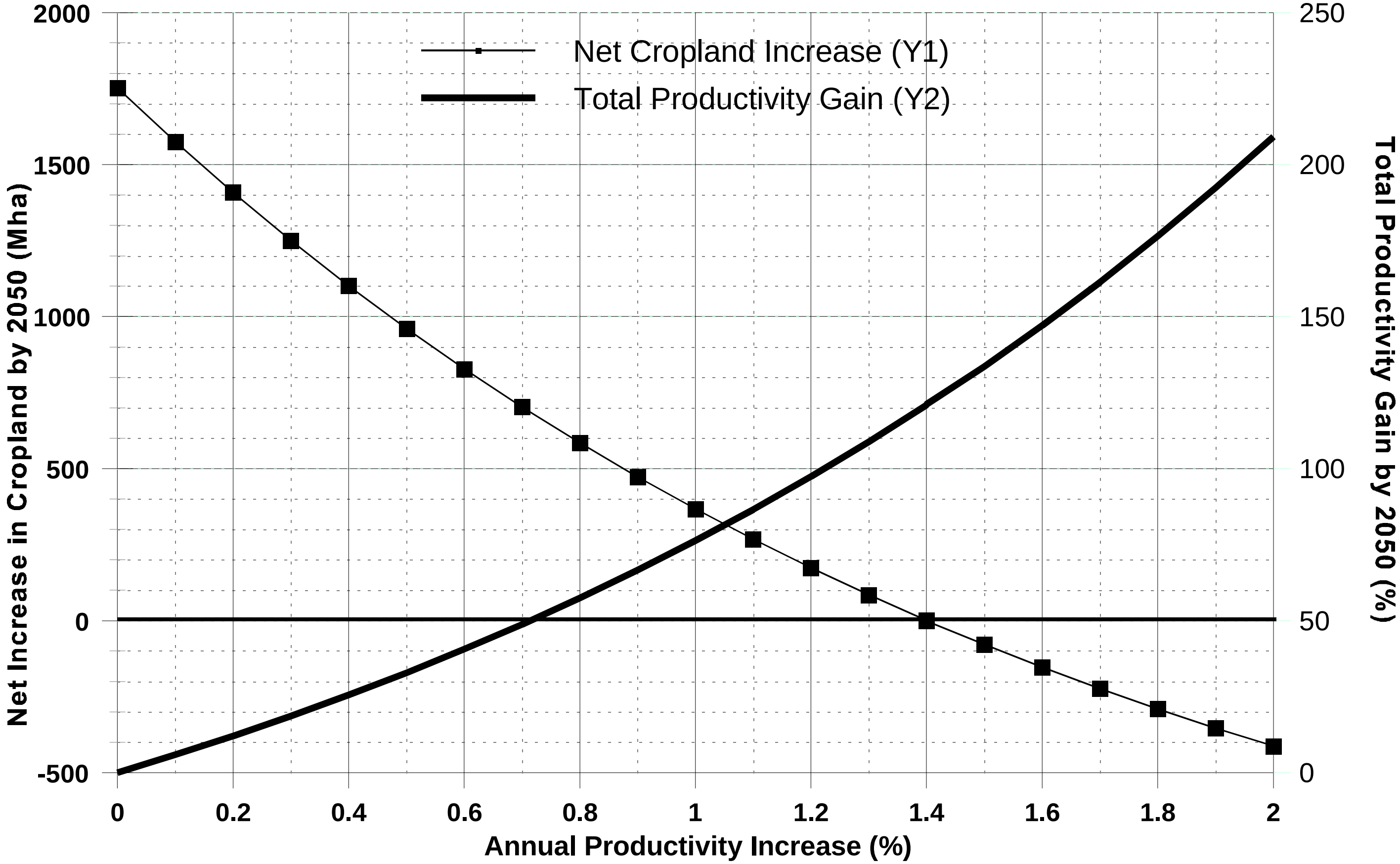
Water Availability

Despite some successes, e.g., drip irrigation in Israel, the worldwide increase in land use efficiency, which forestalled massive conversion of habitat to cropland (Figure 9), has not been matched by similar increases in water use efficiency. This has led to suggestions that water, rather than land, could be the major constraint on future food production (FAO 1996, Postel et al. 1996). The major reason for the disparity between land and water use efficiency is that, unlike land, water is generally not treated as an economic commodity (Goklany 1998a). In fact, because water is crucial to human beings, most societies subsidize its use, particularly in agriculture (Pimentel et al. 1997a). But, perversely, such subsidies reduce the incentive for conservation. Predictably, conservation technologies remain underutilized, and under-researched. Worse, in many urban areas in the developing world, the poor pay much more for water than do the middle and upper classes who are connected to subsidized municipal water systems (Serageldin 1995). Conservation can be induced by modifying institutions and policies to price water, develop property rights to water and allow water trading, as has been demonstrated in parts of the U.S., Chile, Jordan, India and Indonesia (Rosegrant et al. 1995, Serageldin 1995). For example, in Chile water trading increased efficiency of water use by 22-26% between 1976 and 1992. Moreover, water can be recycled and reused, which provides technological opportunities for stretching scarce water supplies (provided there are no disincentives for that). Finally, water can be obtained by desalination of ocean water, albeit at an environmental and economic price. However, new technologies using solar, wave or tidal power may eventually supplant fossil fuels as the preferred energy source in desalination plants (Economist 1995, Discover 1995).

Achieving Food Security While Limiting Loss of Biodiversity

Figure 13 indicates the amount of additional land needed to be converted to cropland between 1993 and 2050 with varying productivity in the food and agricultural sector (*agricultural productivity*, for short). It assumes that global population will be 9.6 billion in 2050, that food supplies per capita would increase at the historical 1969-71 to 1989-91 rate, and that new cropland will, on average, be just as productive as cropland in 1993 (an optimistic assumption). The Figure shows that if current productivity is maintained -- hardly a foregone conclusion -- cropland would have to increase by 1,750 Mha. Much of that would come at the expense of forested areas. On the other hand, a productivity increase of 1.5% per year, equivalent to a 134% increase from 1993-2050, would return 80 Mha of cropland to forests and other uses (Goklany

Figure 13: Trade-off Between Productivity Growth and Habitat Loss
Net Conversion of Land to Cropland from 1993 to 2050



Source: Goklany 1999a.

1998a, 1999a).

Such increases are possible provided appropriate investments of fiscal resources and human capital are made in the food and agricultural sector. Agricultural productivity increased 2.3% per year between 1961-63 and 1995-97 (FAO 1999). More importantly, there are numerous existing-but-unused opportunities to enhance productivity in an environmentally sound manner -- unused largely due to insufficient wealth (one reason why cereal yields are usually lower in poorer nations; Figure 5). Merely increasing the 1992-94 average cereal yields in developing and transition nations to the level attained by the country with the highest average yield (i.e., the *yield ceiling*, Y_C) would have increased global production by 170% (Goklany 1999a). Best farming practices would increase yields even further. For instance, the 1992 U.S. champion corn grower's yield exceeded Y_C by 136% (Waggoner 1994). Also, there are large gaps between the average global cereal yield of 2.77 T/ha (in 1992-94; Goklany 1999a), Y_C of 7.48 T/ha (in 1991-93) and the theoretical maximum yield of 13.4 T/ha (Linnemann et al. 1979).

Agricultural productivity could be increased, for instance, by further limiting pre-harvest crop losses to pests and diseases, which currently reduce global yields by an estimated 42% (Oerke et al. 1994), increasing fertilizer use, liming acidic soils, and adapting high yielding varieties to specific locations around the world. New technologies, including those developed using biotechnology, can be critical to improving yields while limiting adverse environmental impacts, as is the development of location- and crop-specific integrated nutrient, water and pest management systems to help optimize the timing, quantities and mix of various inputs and chemicals used, i.e, "precision" farming (Goklany 1998a, 1999a). Such optimization would, for instance, reduce the estimated 99% (+) of pesticides that do not reach their targets (Pimentel 1997), and excess nutrients in water systems.

Moreover, consistent with the paradigm of industrial ecology, where the focus is on meeting human wants rather than just producing goods (Ausubel 1998b), the objective is to provide not merely large crops at harvest but to increase food supplies at the table. And there are numerous opportunities to increase agricultural productivity at post-production stages until final consumption (Goklany and Sprague 1991) by reducing post-harvest and end-use losses, which are estimated at about 47% worldwide (Bender 1994).

However, to increase productivity, developing countries will need substantial agriculture-related investments (estimated at around $250 billion annually by 2050), most of which will have to come via internal economic growth, probably supplemented by private capital flows from overseas (Goklany 1998a). Moreover, despite productivity increases, developing countries are expected to increase their imports by 2050 because of more rapid growth in demand. Climate change could further increase their food deficits (IPCC 1996). Hence, trade will be even more important for attaining global food security, but to finance food imports, developing countries will need to increase exports from and increase economic growth in non-agricultural sectors (Goklany 1999d).

Similarly, just as increasing agricultural productivity would reduce the amount of land conversion, so would increasing the productivity of forestry. And for forestry too, there are numerous existing and potential opportunities to increase efficiency (Goklany and Sprague 1991; Goklany 1995a, 1998a).

Finally, although water covers 71% of the earth's surface, its contribution to global food security, although significant, is small. About 15 to 20% of all animal protein consumed by mankind comes from aquatic species (FAO 1998). In 1997, 71% of fish production came from marine capture fisheries, 23% from aquaculture and the remainder from inland capture fisheries. However, 44% of the marine fisheries are fully exploited and 22% are either overfished or depleted. In addition, inland capture fisheries are increasingly being affected by habitat clearance and pollution, particularly in the developing world. And while aquaculture increased its share of global fish production from 13 to 23% between 1990 to 1997, it can degrade coastal habitat and water quality (WRI 1998). Thus, if current practices do not change, fisheries' share of the global food supply will diminish. The productivity and sustainability of inland fisheries and aquaculture could be enhanced if habitat clearance and water pollution are reversed (see above). With regard to marine fisheries -- the source of most fish production -- the problem is that we use modern technology for harvesting but not enough technology for producing fish. Thus, if there is an environmental transition curve for marine fisheries, we are currently on its upward slope. To get on the downward slope will require greater investments of fiscal resources and human capital to increase marine productivity and a willingness for society to make the effort. In the long run, increasing marine fish production could reduce pressures on land-based solutions to increase food production. Perhaps, mankind would leave fewer footprints on the land if it spent more time in the water. (Goklany 1999a).

Climate Change

With respect to greenhouse gas emissions, Ausubel (1998a) and Nakicenovic et al. (1998) suggest that given long term trends and the variety of technical options available for providing energy services, economies should continue to decarbonize. These options include increased use of natural gas, nuclear, renewable energy sources, fuel cells and greater conservation. The problems of implementation are as much financial as technical. Fiscal resources for implementation will necessarily have to be generated through economic growth. The higher the economic growth, the higher the rate of decarbonization of an economy (Nakicenovic et al. 1998).

Regardless of how rapidly decarbonization proceeds, some climate change is inevitable, even if it is only due to natural causes. In the long term, the effects of climate change upon food security, diseases, forest cover, biodiversity and coastal areas could be major but, based upon the IPCC's 1995 assessment, over the next few decades (to 2050 or so) other environmental stresses should have a much larger effect on these climate-sensitive sectors. Nevertheless, climate change may be the straw that breaks the camel's back. Moreover, climate change could have a disproportionately large effect on the poorer nations, who are likely to be most vulnerable to the adverse impacts of climate change (Goklany 1992, 1995, 1998d, 1999d).

<u>The Problem of the Last Straw</u>. There are at least two approaches to dealing with the problem of the last straw. The first, more common approach is to focus on reducing or eliminating the last straw. That is equivalent to reducing, if not eliminating, climate change. A second, though not mutually-exclusive, approach would be to lighten the entire burden before the last straw drops, i.e., reduce societal and environmental vulnerability by reducing current urgent environmental and public health problems which might be exacerbated by climate change (before the latter's impacts become significant). This approach addresses the whole rather than part of the problem. Consider malaria: under the first approach – focusing on the last straw – one would try to eliminate the 50-80 million potential climate change related cases in 2100 by totally eliminating climate change (assuming that is possible) while the second approach would attempt to reduce not only the 50-80 million cases due to climate change but also the 500 million baseline (i.e., non-climate change related) cases (IPCC 1996).

In fact, a small reduction in the base rate of malaria could provide greater public health benefits than a large reduction in the additional number of cases due to climate change. Moreover, assuming the potential fraction of malaria cases attributed to climate change in 2100 increased exponentially between 1990 and 2100, an additional reduction of 0.15% per year in the base malaria rate between now and 2100 would more than compensate for any increases due to climate change (Goklany 1999d). The second approach would also provide a steady stream of substantial benefits to humanity decades before any significant benefits are realized from limiting climate change. Moreover, the benefits of reducing the base rate are more certain than those related to limiting climate change. The lessons and technologies developed to reduce the base rate would also limit any additional cases due to climate change whether from anthropogenic or natural causes, or if it comes more rapidly than the IPCC's "best estimates." Thus, reducing the base rate today would also help solve the cumulative malaria problem of tomorrow, whatever its cause. In effect, the second approach would strengthen the ability of human and natural systems to adapt and cope with not just climate change, but any change (Goklany 1992, 1999d).

Similar logic applies to the other climate-sensitive sectors (e.g., agricultural production, food security, forest cover, ecosystems and biodiversity) where existing problems would be worsened by climate change. With respect to water resources, the solutions proposed previously, namely, treating them as economic resources, would help any area cope with water shortage no matter what its cause. Regarding food security and the forest sector, continued R&D, for instance, on precision farming, integrated pest management, and reductions in post-harvest and end-use crop and timber losses would enhance future food security and reduce deforestation and habitat loss under the current or a future climate, as would extra emphasis on increasing productivity under conditions of drought, higher salinity, and higher carbon dioxide. Such activities would also help maintain carbon stocks and reservoirs, thereby helping mitigate carbon emissions and, by containing land costs, should reduce costs for carbon sequestration or energy farms, if they are needed (Goklany 1998a).

<u>Reducing Vulnerability</u>. Poorer nations, indeed, are most vulnerable to climate change, not because of climate change per se, but because they lack the economic resources and technology to adapt to or cope with any hardship or misfortune, regardless of its cause. Thus, as illustrated by Figures 6 through 8, it is no surprise that the poorer the society the more likely that its population will be malnourished, that its mortality rate will be higher, and that life expectancy will be lower. Developing or strengthening its institutions to foster economic growth and technological change will increase its resiliency and boost its ability to cope with adversity in general, including any caused by climate or other global change. These institutions include free markets, secure property rights, and honest and predictable bureaucracies and governments (Goklany 1992, 1995, 1999d).

Another general feature of climate change is that its impacts will vary from place to place. However, as the previous discussion on food security indicated, vulnerability to local and national shortages can be reduced by having the wherewithal to trade with other regions (Goklany 1999d).

Discussion and Conclusion

Despite the massive increase in human numbers during this millennium, the state of humanity -- as measured by broad aggregate indicators of the quality of life -- has never been better. The average person is better fed, healthier and lives longer. He is better educated and wealthier. She is freer to choose her rulers and express her views. He is more likely to live under the rule of law, and is less fearful of being arbitrarily deprived of life, limb, freedom, property, wealth, and other basic human rights. Her professional, social and physical mobility, while still limited, is less likely to be circumscribed by caste, class, location or other accidents of birth. Not only is work less physically demanding, he works fewer hours, and has more leisure time and money to devote to optional pursuits. The majority of these improvements have occurred over the last two centuries, coinciding with global industrialization and the tremendous increases in global population and energy usage.

Yet hundreds of millions, if not billions, still live in absolute poverty, and lack access to basic sanitation, safe water and sufficient food (UNDP 1999), mainly in developing countries where malaria, other preventable infectious and communicable diseases, and air pollution still claim millions of lives prematurely. In addition, human demands on land and water are at their highest levels, squeezing out the rest of nature which threatens biological diversity worldwide. And many fear that the effects of greenhouse gas emissions could change the earth’s climate -- and landscape -- for the worse.

Over the next century the population is likely to increase and with it, demands for food and natural resources. Nevertheless, humanity has the ability over the next century to further advance its welfare while ceding back some land and water to the rest of nature. Population could be stabilized; malnourishment, and infectious and parasitic diseases could be virtually banished. Malaria, TB and AIDS could be distant memories. Life expectancies and mortality rates in Africa could be as high as they are today in the U.S. And although there will no doubt be some environmental degradation and the climate somewhat warmer, they need not be catastrophically so. Almost everyone could have access to adequate sanitation and clean water. The air and water could be cleaner even if “code red” days were to still occur occasionally in Mexico City, Beijing and New Delhi.

But none of this may occur and it won’t -- unless there is economic growth and technological change. It has often been claimed that population, economic growth and technology act as multipliers for environmental impacts (e.g., Ehrlich and Holdren 1971, Myers 1997, Tickell 1999). Arguably, population may be a multiplier (Boserupians may disagree), but the role of the other two is more complex. Although economic growth and technology may initially cause environmental problems, eventually they are the sources of the solutions. Thus, they bring about environmental transitions. They are also instrumental in moving countries through their demographic transitions (Figure 8 and 11; Goklany 1995, 1998a), that is, in eventually bringing the population multiplier to heel. Nowadays there is greater appreciation for technology's dual role -- and for its capacity to reduce land, water and energy resources used or appropriated by humanity, while keeping environmental impacts in check (e.g., Ausubel and Langford 1997, Grübler 1998, Goklany 1998a). However, as controversies over genetically modified crops and EMF, to name just two, have shown, suspicion of new technology is widespread.

The Role of Industrial Ecology

The new discipline of industrial ecology can play a significant role in accelerating the transformation of technology from being a multiplier for environmental impacts to becoming a divisor – essentially hastening society along its environmental transition trajectory (see Figure 10).

Industrial ecology provides a systems-oriented approach toward satisfying the goal of (a) meeting the future wants and needs of a larger and more affluent human population while (b) containing environmental damage. With respect to materials and energy, which have been the foci of many of the studies in this new discipline, industrial ecology has emphasized environmentally sound methods of dematerialization, decarbonization and product substitution, with environmental impacts being assessed using life cycle analysis (Ausubel 1998b; Lifset 1998a, 1998b).

However, industrial ecology can also be used to help systematically reduce the environmental impacts due to – as well as learn from -- other spheres of human industry. With respect to food and agriculture, for instance, the first component of the overarching goal articulated above ("meeting…future wants and needs") would require increasing food consumption at the table rather than merely increasing crop yields at the farm. The second component ("containing environmental damage") demands that the technologies used (whether in the field, during transportation and handling, at the processing plant or at the consumers end) be environmentally sound over the life cycle of the food product, i.e., the full chain of events leading from planting and sowing to final consumption and disposal or recycling of wastes (Goklany and Sprague 1991; Goklany 1992, 1995).

Similarly, with respect to forest products, industrial ecology would focus not only on sustainable methods to increase harvested yields but also to utilize harvested amounts more fully by reducing wastage and increasing the life spans of wood products (Goklany 1992, Wernick et al. 1997). Forestry and the forest products industries have a long history of devising such methods (e.g., consider the use of particle board, or chemical treatment of railroad ties). These efforts could be supplemented by efforts to provide "functionality," i.e., meet the consumer's wants through alternate methods rather than through intermediate forestry products. One existing example of satisfying the functional needs of the consumer is to supply books in user-friendly computer-readable CDs rather than by producing pulp and paper for "hard copy" books and wood for bookcases. With respect to water, industrial ecology could emphasize reducing consumptive usage while increasing recycling and reuse, all the while ensuring that the techniques employed do not overload the environment.

Systems-oriented industrial ecology approaches such as those outlined above would reduce the environmental impact of meeting future human demands per unit of demand. However, in addition to the systematic engineering and scientific analyses of environmental impacts based upon alternate product life cycles, industrial ecology also requires the use and, where necessary, development of acceptable risk analysis and cost-benefit tools so that policy makers can make trade-offs among different sources of environmental risks which may be manifested on different time-scales, act through different pathways, and result in different health and environmental consequences. Thus, for industrial ecology to fulfill its potential, it requires the melding of environmental, economic and social analyses. Moreover, the solutions suggested by the discipline of industrial ecology must be practical, affordable and economic.

The Role of Economic Growth

Regarding economic growth, far too many people in the environmental arena still view it as, to coin a phrase, "all problem, no solution" (Ausubel 1998a, Tickell 1999, Landes 1998). But for virtually every indicator of human welfare, poorer countries do worse than the richer countries. Poorer people live shorter and unhealthier lives, their environment is more polluted, they get less education, and they have fewer opportunities to break out of the rigid strictures of caste and class. Figures 5 through 8 suggest that, just as someone suffering from AIDS is less immune to infectious disease no matter what the source of infection, so is a poorer society less immune to adversity no matter what its proximate cause. Diseases such as TB and diarrhoea, which would sicken people in richer countries, kill in poorer ones. In fact, economic growth for a poor society is like AZT for an HIV-infected individual: it boosts the immunity of the entire system, except it is more likely to be successful.

A more affluent society should be better able to cope with adversity in general, whether caused by global change or another agent, because it can mobilize the fiscal resources needed to develop and bring on-line new or unused existing technologies and the infrastructures needed to support them. In fact, as the easier problems of society are solved, the remaining problems are generally harder and costlier to address. Thus, continued progress is aided by economic growth. Economic growth also helps ensure political support and funding for social safety nets for public health, food and nutrition programs.

Moreover, a richer society is more able to support R&D targeted at cleaner and more efficient natural resource and environmental technologies. Thus, it is no surprise that some of the seed funding for industrial ecology, for instance, seems to have come from a relatively rich foundation in a wealthy country (Lifset 1998c, Laudise and Taylor-Smith 1998).

A richer country is also more able to fund R&D in general. This is critical because the course of scientific and technological progress is unpredictable and advances in one field often spread to and inform others (e.g., consider the penetration of microprocessors, personal computers, electric motors or synthetic materials into virtually every economic sector and corner of society). Finally, affluence provides the funds for developing and nurturing the human capital that a technologically advanced society needs to sustain itself, i.e., a more or less universal educational system that ultimately feeds the entire web of universities, laboratories, banks, corporations and even lawyers that participate in the process of invention, innovation and diffusion of technologies (Goklany 1998a, 1999a).

The Role of Free Trade

Freer, and unsubsidized, trade is also necessary for helping satisfy the needs and wants of a larger and more affluent global population while limiting environmental impacts. Such trade enhances economic growth, helps diffuse technology worldwide, and ensures efficient movement of food, natural resources and capital from surplus to deficit areas. In particular, developing nations need trade to import more food, as well as capital for investments in agriculture, other natural resource sectors, and environmentally-benign technologies. For that, they will need exports (and growth) in other economic sectors. In the absence of freer trade, food deficit countries would have higher prices (and therefore higher levels of malnutrition), try to exploit marginal land resources which would result in unnecessary environmental degradation, or both. In 1993, at least 35 Mha of habitat were spared from the plough in developing countries due to trade in cereals alone (Goklany 1998a). A similar argument can be made regarding trade in other natural resources. Finally, trade, particularly in basic commodities, also gives countries incentives to live in harmony rather than obtain them through force. In fact, perhaps the best answer to the question, "who will feed China?" (Brown 1995) is "America and the EU!" That would save China's environment, and reduce the risk of conflict between these giants.

But free trade has its drawbacks and opponents (see Goklany 1995, 1998a). Another danger is that the developed countries may forego producing surpluses because they are unwilling to risk their environmental well-being for products sent abroad. Moreover, North America and the EU might reduce agricultural production not only because they can survive without the additional production but because they would rather use the land for fuel farms or carbon sequestration and move their subsidies from production of food crops to these other activities.

Conclusion

The future could see a world in which the population has stabilized, is richer, cleaner, and with room for both humanity and the rest of nature, or one which is more populated, poor and polluted and where the rest of nature is pinched for space and water. The odds of the former are increased by bolstering the co-evolving, mutually-reinforcing forces of economic growth, technology and trade by strengthening the institutions that are their mainstays. These institutions include free markets; secure property rights to both tangible and intellectual products; fair, equitable and relatively transparent rules to govern those markets and enforce contracts; institutions for accumulating and converting knowledge into useful and beneficial products; and honest and predictable bureaucracies and governments. These institutions are also the foundations for a strong civil society. However, building and strengthening these institutions may not be enough if society is hostile to change and if richer societies -- in their quest for zero risk -- reject imperfect ("second best") solutions. And industrial ecology can play an important role in moving such solutions closer to perfection, and in accelerating society's various environmental transitions so that technological change and economic growth are transformed from being problems to becoming solutions in the quest for a sustainable industrial society.

References

Ausubel, J.H. 1998a. “Resources and Environment in the 21st Century: Seeing Past the Phantoms.” *World Energy Council Journal*, July, pages 8-16.

____. 1998b. “Industrial Ecology: A Coming of Age Story.” *Resources*, Winter, Issue 130, pages 14-16.

Ausubel, J.H., and Grübler, A. 1995. ”Working Less and Living Longer.” *Technological Forecasting and Social Change* 50:113-131.

Ausubel, J.H., and Langford, D. (eds.). 1997. *Technological Trajectories and the Environment*. Washington, D.C.: National Academy Press.

Barro, R.J. 1998. *The Determinants of Economic Growth: A Cross-Country Empirical Study*. Cambridge, MA: MIT Press.

Bender, W.H. 1994. “An End Use Analysis of Global Food Requirements.” *Food Policy* 19: 381-395.

Braudel F. 1984. *The Perspective of the World: Volume III. Civilization and Capitalism 15th-18th Century*. English edition, Reynolds, S, translator, New York: Harper & Row.

Brown, L.R. 1995. *Who Will Feed China?* New York: W.W. Norton.

Bryant, D., Nielsen, D., and Tangley, L. 1997. *The Last Frontier Forests: Ecosystems and Economies on the Edge*. Washington, D.C.: World Resources Institute.

Burnette, J., and Mokyr, J. 1995. “The Standard of Living Through the Ages.” In: Simon (1995), pp.135-148.

Discover. 1995. “Pump it Up.” July, pp. 18-20.

Economist. 1995. “Sunshine and Showers.” 21 October, p. 84.

Ehrlich, P.R., and Holdren, J. 1971. “Impact of Population Growth.” *Science* 171: 1212-1217.

Flavin, C. 1999. *World Carbon Emissions Fall*. News Briefing. Worldwatch Institute, Washington, DC. <http://www.worldwatch.org/alerts/990727.html>. 27 July 1999.

Fogel, R.W. 1995. “The Contribution of Improved Nutrition to the Decline of Mortality Rates in Europe and America.” In: Simon (1995), pp. 61-71.

FAO (Food and Agricultural Organization). 1996. *World Food Summit Fact Sheets*. Rome: FAO. <http://www.fao.org/wfs/fs/e/FSHm-e.htm> 7 October 1997.

1997. *The State of the World’s Forests 1997*. FAO: Rome.

_____. 1998. *The State of the World’s Fisheries and Aquaculture* 1998. FAO: Rome.

_____. 1999. *FAOSTAT Database*. <http://apps.fao.org>. 11 July 1999.

Goklany, I.M. 1992. *Adaptation and Climate Change*. Paper presented at the Annual Meeting of the American Association for the Advancement of Science, Chicago, February 6-11, 1992.

_____. 1994. *Air and Inland Surface Water Quality*. Washington, D.C.: Office of Program Analysis, Department of the Interior.

_____. 1995a. “Strategies to Enhance Adaptability: Technological Change, Economic Growth and Free Trade.” *Climatic Change* 30: 427-449.

_____. 1995b. “Richer is Cleaner.” In: Bailey, R. (ed.), *The True State of the Planet*. New York: Free Press, pp.339-377.

_____. 1996. “Factors Affecting Environmental Impacts: The Effects of Technology on Long Term Trends in Cropland, Air Pollution and Water-related Diseases.” *Ambio* 25: 497-503.

_____. 1998a. “Saving Habitat and Conserving Biodiversity on a Crowded Planet.” *BioScience* 48: 941-953

_____. 1998b. “Did Federalization Halt the Race to the Bottom for Air Quality?” *EM (Environmental Manager)* (June): 12-17.

_____. 1998c. “The Environmental Transition to Air Quality.” *Regulation* 24 (4): 36-46.

_____. 1998d. “The Importance of Climate Change Compared to Other Global Changes.” In: *Proceedings of the Second International Specialty Conference: Global Climate Change - Science, Policy, and Mitigation/Adaptation Strategies*, Crystal City, Virginia, October 13-16, 1998. Pittsburgh: Air &Waste Management Association, Pittsburgh, 1999.

_____. 1999a. “Meeting Global Food Needs: The Environmental Trade-offs Between Increasing Land Conversion and Land Productivity.” *Technology* (formerly *Journal of the Franklin Institute, Part A*) 6: 107-130.

_____. 1999b. Clearing the Air: The True Story of the War on Air Pollution. Washington, D.C.: Cato Institute.

_____. 1999c. “Is Climate Change ‘Our Overriding Environmental Concern’?” In preparation.

_____. 1999d. “Richer is More Resilient.” In: Bailey, R. (ed.), *Earth Report 2000: The True State of the Planet Revisited*. New York: McGraw-Hill.

_____. 1999e. “Fueling Technology: Response to Letter.” *BioScience* 49: 499-501

Goklany, I.M., and Sprague, M.W. 1991. *An Alternative Approach to Sustainable Development. Conserving Forests, Habitat and Biological Diversity by Increasing the Efficiency and Productivity of Land Utilization.* Office of Program Analysis, Department of the Interior, December 1991.

Grübler, A. 1998. *Technology and Global Change*. Cambridge: Cambridge University Press.

Headrick, D.R. 1995. Technological Change. In: Turner, II, B.L., et al. (eds.), *The Earth as Transformed by Human Action*. New York: Cambridge University Press, pp. 55-67.

Hill, K. 1995. “The Decline in Childhood Mortality.” In Simon (1995), pp. 37-50.

Hodges, C.A. 1995. “Mineral Resources, Environmental Issues, and Land Use.” *Science* 268: 1305-1312.

IPCC (Intergovernmental Panel on Climate Change). 1996. *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*. New York: Cambridge University Press.

Laudise, R.A., and Taylor-Smith, R.E. 1999. “Lucent Industrial Ecology Faculty Fellowship Program: Accomplishments, Lessons, and Prospects.” *Journal of Industrial Ecology* 2: 15-27.

Lee, J,., and Feng, W. 1999. “Malthusian Models and Chinese Realities: The Chinese Demographic System 1700-2000.” *Population and Development Review* 25: 33-65.

Lifset, R. 1998a. “Setting the Boundaries.” *Journal of Industrial Ecology* 2 (2): 1-2.

_____. 1998b. “On Becoming an Industrial Ecologist.” *Journal of Industrial Ecology* 2 (3): 1-3.

_____. 1998c. “Making Connections.” *Journal of Industrial Ecology* 2 (4): 1-3.

Linnemann, H., et al. 1979. *MOIRA: Model of International Relations in Agriculture*. Amsterdam: North Holland.

Lutz, W. 1996. *The Future Population of the World: What Can We Assume Today? Revised and Updated Edition*. London: Earthscan Publications.

Maddison, A. 1995. *Monitoring the World Economy, 1820-1992*. Paris: OECD.

____ 1998. *Chinese Economic Performance in the Long Run*. Paris: OECD.

____ 1999. “Poor Until 1820.” In: *Wall Street Journal*. The Millennium. 11 January 1999, p. R54.

McEvedy, C., and Jones, R. 1978. *Atlas of World Population History*. New York: Penguin, 342.

Mitchell, B.R. 1992. *International Historical Statistics : Europe, 1750-1988*. New York: Stockton Press, pp. 116-123.

Mitchell, D.O., and Ingco, M.D. 1993. The World Food Outlook. *Hunger Notes* 19 (Winter 1993-1994): 20-25.

Myers, N. 1997. “Consumption: Challenge to Sustainable Development ...” *Science* 1997: 276:53-55.

Nakicenovic, N., Grübler, A., and McDonald, A. (eds.) 1998. *Global Energy Perspectives*. Cambridge: Cambridge University Press.

OECD. 1997. *Environmental Data Compendium 1997* (Paris: OECD, 1997).

_____. 1998a. *Maintaining prosperity in an ageing society*. OECD Policy Brief No. 5-1998. Paris: OECD.

Oerke, E.-C, Weber, A., Dehne H.-W., and Schonbeck, F. 1994. “Conclusion and Perspectives.” Pages 742-770 in Oerke,E.-C, Dehne, H.-W., Schonbeck, F., and Weber, A., eds. *Crop Production and Crop Protection: Estimated Losses in Food and Cash Crops.* Amsterdam: Elsevier.

Panayotou, T,, and Vincent, J.R. 1997. “... Or Distraction.” *Science* 276: 55-57.

Pimentel, D. 1997. “Pest Management in Agriculture.” Pages 1-11 in Pimentel, D., ed. *Techniques for Reducing Pesticide Use: Economic and Environmental Benefits*. Chichester: John Wiley.

Postel, S., Daily, G.C., and Ehrlich, P.R. 1996. “Human Appropriation of Renewable Fresh Water.” *Science* 271: 785-788.

Preston, S.H. 1995. “Human Mortality Throughout History and Prehistory.” In Simon (1995), pp. 30-36.

Rosegrant, M.W., Schleyer, R.G, and Yadav, S.N. 1995. “Water policy for efficient agricultural diversification: market-based approaches.” *Food Policy* 20: 203-223.

Rosenberg, N., and Birdzell, Jr., L.E. 1985. *How the West Grew Rich*. Basic Books.

Rothman, D.S., and De Bruyn, S. M. 1998 “Probing Into the Environmental Kuznets Curve Hypothesis.” *Ecological Economics* 25: 143-145.

Sagoff, M. 1995. “Carrying Capacity and Ecological Economics.” *BioScience* 45: 610-620.

Serageldin, I. 1995. *Toward Sustainable Management of Water Resources*. Washington (DC): World Bank.

Shalala, D.E. 1998. *Eliminating Racial and Ethnic Health Disparities*. SACNAS Journal, Summer 1998 <http://www.sacnas.org/journal/su98/pge11.html>. 12 July 1999.

Simon, J.L. (ed.). 1995. *The State of Humanity*. Cambridge, MA: Blackwell.

Smil, V. 1994. *Energy in World History*. Boulder, CO: Westview Press.

Tickell, C. 1999. "Book Review: An Epidiomology of the Invention Virus." *Nature* 400: 521-522.

Torras, M., and Boyce, J.K. 1998. "Income, Inequality, and Pollution: A Reassessment of the Environmental Kuznets Curve." *Ecological Economics* 25: 147-160.

UN. 1998. *Revision of the World Population Estimates and Projections*.<http://www.un.org/pop1998/>

UNCSD (UN Commission on Sustainable Development). 1997. *Fifth Session*. Document E/CN.17/1997/9. <gopher://gopher.un.org:70/00/esc/cn17/1997/off/97--9.EN> 23 July 1999.

UNDP. 1999. *Human Development Report 1999*. New York: Oxford University Press.

UNESCO. 1998. *UNESCO and the Elimination of Illiteracy: Fifty Years of Fight (1946-1998)*. UNESCO, Paris. < http://www.unesco.org/education/educprog/literacy/lit_eng.html>. 13 July 1999.

USBOC (US Bureau of Commerce). 1975. *Historical Statistics of the United States*. Washington, D.C.: Government Printing Office.

____. 1998. *Statistical Abstract of the United States 1998.* Washington, D.C.: Government Printing Office.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., and Melillo, J.M. 1997. "Human Domination of Earth's Ecosystems." *Science* 277: 494-499.

Waggoner, P.E. 1994. Pages 26-27 in *How much land can ten billion people spare for nature?* Ames (IA): Council for Agricultural Science and Technology.

Wernick, I.K., Waggoner, P.E., and Ausubel, J.H. 1997. "Searching for Leverage to Conserve Forests: The Industrial Ecology of Wood Products in the United States." *Journal of Industrial Ecology* 1(3):125-145, 1997.

Wilcove, D.S., et al. "Quantifying Threats to Imperiled Species in the United States." *BioScience* 48: 607-615.

World Bank. 1998. *World Development Indicators 1998*. Washington, DC: World Bank.

WHO. 1999a. *The World Health Report 1999.* Geneva: WHO.

____. 1999b. *Water, Sanitation and Health*. <http://www.who.int/peh/Watsanhealth/watsanhealth.htm> 22 July 1999.

____. 1997. *Health and Environment in Sustainable Development.* Fact Sheet No.170. Geneva: WHO.

WRI. 1998. *World Resources 1998-99.* Washington, DC: WRI.

Wrigley, E.A., and Schofield, R.S. 1981. *The Population History of England 1541-1871: A Reconstruction*. Cambridge, MA: Harvard University Press, 529.