What is sustainable development and what are the implications for the Shell Center for Sustainability?

Peter Hartley
George & Cynthia Mitchell chair in Sustainable Development
and
Academic Director
Shell Center for Sustainability, Rice University

The purpose of this note is to define what might be understood by the term "sustainable development" and what that understanding implies for the goals and strategies of the Shell Center for Sustainability. In brief, we shall argue that sustainable development is a process of improvement in living standards that can be sustained or continued for an indefinite time period. In this definition, living standards need to be interpreted broadly to include not only marketed goods and services but also valued items that typically do not have market prices such as environmental amenities, freedom from coercion, the rule of law and the quality of social interactions. Based on this definition, I propose that the central concern of the Shell Center should be to foster research at Rice University that is compatible with, or reinforces existing or potential strengths, and which identifies threats to sustainable development and how those threats might be eliminated.

Sustainability

One can identify both economic and environmental origins for concerns about "sustainability." In the economics literature, there has been a long-standing concern with the sustainability of certain fiscal, monetary and exchange rate policies.

In the fiscal policy arena, budget deficits that lead to a growth in government debt that exceeds the economic growth rate may be feasible in the short term, but they are not sustainable in the long term. Eventually, the government cannot raise sufficient tax revenue to both service the outstanding debt and meet its other spending obligations.

With regard to monetary policy, a widely recognized empirical regularity is that expansionary monetary policy can stimulate real economic activity in the short run, but the stimulus is not sustainable. In the longer run, the expansionary monetary policy accelerates inflation and the stimulatory real effects disappear.

Attempts to fix the value of a foreign exchange rate that is inconsistent with market fundamentals also are unsustainable. If banks or trading houses dealing in foreign exchange believe, for example, that the exchange rate will be devalued they have an incentive to move money out of the country (or delay repatriating it) in order to exploit the anticipated fall in the foreign exchange price of the domestic currency. The resulting net outflow of funds, however, serves only to make the chosen exchange rate even more out of line with an equilibrium value and increases the pressure to change the rate. The result is a "currency crisis" and a large disruption to the domestic economy.

In each of these examples, although unsustainable policy can be recognized after a crisis occurs it is often more difficult to identify before the crisis. The inappropriate policy often results in pressures that build quite slowly. Once the unsustainable nature of the policy becomes evident, however, market responses can occur quite quickly leading to a crisis that imposes substantial costs. Another feature of all three situations is that sustainable policy paths are not unique. Requiring policy to be sustainable is not sufficient to determine an optimal policy. Policy sustainability is more in the nature of a necessary condition or constraint on optimal policies rather than a policy objective.

There is also a notion of "sustainable yield" in natural ecosystems. Suppose there is some species that can be harvested for food or other resources (for example, fish or trees). Assume that the population N_{t+1} of the species in generation t+1 depends on the population N_t alive in generation t according to some function such as

$$N_{t+1} = f\left(N_t\right)$$

If an amount Q_t of the current population is harvested, the population next period will instead be

$$N_{t+1} = f\left(N_t - Q_t\right)$$

A sustainable yield is then a constant harvest quantity Q that results in a constant population N if the equation

$$N = f\left(N - Q\right)$$

has at least one solution for Q as a function of N.[1] This equation need not have a unique solution for Q as a function of N. There usually are many sustainable population levels N and associated yields Q. As with the economic policy examples, the notion of sustainability is not sufficient to determine an optimal level of harvesting for the species.

In fisheries (or forestry) management, a frequent goal is *maximum sustainable yield*. This is the maximum tonnage of fish (or number of trees) that can be taken each year while leaving the surviving fish population (or volume of standing timber) unchanged. If the maximum sustainable yield exists, the yield $Q(N)$ and stable population N then solve

$$f'\left(N - Q\right) = 1 \text{ and } N = f\left(N - Q\right)$$

Although this gives two equations that might in principle be solved for the two unknowns N and Q, the equations are generally both non-linear. Hence, they could have multiple solutions, or no solution at all. Requiring that a sustainable yield be maximal among all possible sustainable yields also might not be sufficient to determine a unique policy.

Leaving aside the theoretical difficulties of existence and uniqueness, and the practical difficulties of calculating a maximum sustainable harvest, the concept illustrates another potential problem with the notion of sustainability. Why should we aim to

---

[1] A similar notion of sustainable yield can be applied to non-living systems such as an aquifer. An amount of water equal to the annual recharge can be extracted without affecting the level of the water table.

maximize the sustainable yield from the system? Setting a goal of determining a maximum sustainable yield might appear attractive insofar as it turns a social goal into a technical or engineering problem, but it begs the question of whether the goal is reasonable. In my view, the objective ought to be obtaining the maximum *value* from the harvest, *all things considered*. Although these two objectives may sound similar, maximizing value is not the same thing as maximizing sustainable yield.

There are a number of reasons why maximizing value could deviate from maximizing a physical quantity like the harvest yield. To begin with, there might be other costs or benefits associated with different levels of N, for example, because of interactions with other species that we care about. For example, the maximum sustainable yield of timber might not maximize the value one could obtain from a forest since people also value things such as recreational opportunities that could be provided by the forest. In addition, changes in N may affect not only direct consumption benefits that have a market value but also other services people may value. For example, people may value having a viable functioning ecosystem that helps clean air or water supplies of undesirable substances, or which sustains a variety of species they enjoy observing.[2]

Last but not least, while the harvest is extracted today it affects population levels in the future. In general, people do not value a good or service today the same way they value the otherwise identical good or service at some future date. Investments of all sorts have to yield a positive rate of return to reflect this preference for present over future benefits. Similarly, since people are risk averse, they value an uncertain benefit at less than its expected value. When valuing new proposed investments, future costs or benefits need to be discounted to reflect these preferences for lower risk and for the present over the future. Discounting for time and risk reflects the notion of *opportunity cost* or the cost of the next best opportunity forgone. When applied to investments, the opportunity cost of any one investment is the future benefit that could instead be obtained from the next best alternative investment of equivalent risk. If the future benefits per unit of current cost of that alternative investment are greater, the alternative investment is preferable.

In summary, a more appropriate objective than maximum sustainable yield is the maximization of the discounted value of *all* benefits, not just the marketed or marketable benefits. Furthermore, the appropriate discount rate should reflect not only a preference

---

[2] A notion closely related to maximum sustainable yield might be applied to an ecosystem as a whole. In this case, however, a more sophisticated definition is required. Since ecosystems are continually evolving, it does not make sense to speak of maintaining a particular assembly of interacting organisms in some stationary state. A more reasonable goal might be the maintenance of a stationary probability distribution over states of the system, or perhaps a limitation on the rate of change of the distribution over states. For example, ecosystems may be said to have a natural waste assimilation capacity analogous to a "maximum sustainable harvest." This could be interpreted as a maximum level of pollution or waste disposal beyond which the possible states of the ecosystem would be drastically and permanently altered. No amount of time without pollution would allow the system to recover many of the states it could previously have attained. Such a permanently damaged system will have a dramatically reduced ability to provide environmental services in the future.

for the present over the future but also the risk associated with the uncertain future benefits or costs.

Sustainable development

The above notion of sustainability relates to isolated or “micro” level decisions or policies. We can extend the notion to an aggregate context by considering the sustainability of an overall social system. This is one way to interpret the notion of “sustainable development.”

The most widely cited definition of sustainable development is the one given in the document commonly known as the Brundtland Report:[3]

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

There are a number of problems with this definition as a reasonable social objective. First, the notion of a “need” is not well defined. The usual objective discussed by economists is “standard of living” as evaluated by people themselves and revealed through their economic, political and social behavior. The general idea behind distinguishing a “need” would seem to be that we care only about some minimal standard of living and that marginal increases in living standards above that minimum are of zero value. Under this interpretation, however, a second problem arises. It then is not clear that sustainable development so defined represents development at all. Meeting a minimal standard of living for a generation is a constraint that is static from one generation to the next, while development usually implies that generations are getting better off from one generation to the next.

A third problem with the definition is that focusing on “ability … to meet … needs” confuses means and ends. Standards of living achieved by different generations are what people care about and they represent outcomes of the social decision-making process. The constraints that each generation faces are among the inputs that help determine the welfare levels that people in that generation attain, but many variations in the constraint set will have no impact on their achieved level of welfare. In particular, many otherwise possible choices that are eliminated by changes in the constraints could be irrelevant to what makes people better off. If so, why should we designate such changes as undesirable?

Perhaps a concern about irreversible changes (such as allowing a species that might later prove to be extremely valuable[4] to become extinct) motivates the focus on potential rather than actual choices. However, using resources in an irreversible way today that nevertheless is almost certain to raise the welfare of present *and* future

---

[3] The official title of the publication is *Our Common Future*, produced by the World Commission on Environment and Development and published by Oxford University Press, 1987

[4] Not all extinctions are undesirable. For example, few would object to eliminating HIV.

generations should surely be regarded as desirable. For example, using sand to make optical fibers permanently alters the set of feasible choices for future generations by reducing the sand they would otherwise have had access to, but surely no-one would argue that forgoing the benefits of optical fibers is a sensible policy.

We have emphasized that development involves an improvement in living standards from one generation to the next. While most would agree that this has been a feature of recent history in the developed world, it was by no means the normal course of events for most of the time that human beings have inhabited the world. For most people most of the time, the experience of those in one generation has differed very little from the experience of people in the generations that came before or after them. There are also examples of dramatic declines in living standards over a very few generations. Hence, it is reasonable to question whether development can continue indefinitely.

Many biologists are skeptical that permanent economic development is possible. They reason from the idea that an ecosystem has a limited carrying capacity for any one species. As the population of a given species increases, it places more pressure on the food and other resources that it uses. Declining nutrition levels may reduce decrease birth rates, while competition for scarce resources may lead individuals to fight with each other. At the same time, the increasing population of the species provides more opportunities for other species (including pathogens) that exploit it as a resource. As a result, death rates are likely to increase.

The idea of carrying capacity was developed to assist in managing wildlife in national parks and other restricted geographical areas. Park managers observed, for example, that deer populations in national parks could grow to levels that placed severe pressures on food resources. The weakened deer became more susceptible to disease, which in turn lead to severe population crash. Managed culling could instead maintain the population at a more moderate average level with a reduction in the amplitude of fluctuation from one year to the next.

There does not appear to be a universally agreed precise definition of the concept. The American Heritage Dictionary defines it as "The maximum number of individuals that a given environment can support without detrimental effects," but the term "detrimental" also is not well defined. Another definition is that the carrying capacity is the population level where the birth rate of a species equals its death rate. This is also called a stationary point of the population difference equation above:

$$N = f\left(N\right)$$

assuming such a solution exists and is unique. In practice, the population growth from one period to the next will be affected by many influences, including many that are random. The carrying capacity of the African savannah for zebras, for example, is likely to be much lower in a drought. Hence, it may be misleading to speak of a deterministic carrying capacity and more reasonable instead to think about a stationary distribution of population under normal circumstances.

The notion of carrying capacity also appears to encompass some element of dynamic stability. Although the details can quickly get complicated, the basic idea is that when a population is below the carrying capacity it is likely to increase, and when it is above it is likely to decrease. More generally, stability (in a local sense) is related to the shape of the difference equation[5] around the stationary state. In some cases, the dynamics can be unstable whereby the population of a species can build gradually over an extended period but once a critical level is reached resources become over-exploited and the population crashes dramatically, perhaps even causing extinction. In cases where there is such a locally unstable equilibrium, there may also be another locally stable equilibrium at a lower level of population. Wildlife management programs aim to control the population of the species (for example through culling) in order to maintain the more stable population level, which should also place less pressure on the rest of the ecosystem.

The claim that permanent economic development is impossible is based in part on an analogy with wildlife management programs. Viewing humans as just another mammal species, the global environment is likely to have a limited carrying capacity for humans. Economic development will eventually cause the carrying capacity for human beings to be exceeded. This could in turn lead not only to a dramatic fall in the number of people but also severe damage to the environment and to other species.

This argument echoes the point originally made by Thomas Malthus in 1789.[6] He noted that population growth, if left unchecked, would be exponential whereas "subsistence increases only in an arithmetical ratio." He concludes,

> This implies a strong and constantly operating check on population from the difficulty of subsistence. This difficulty must fall somewhere and must necessarily be severely felt by a large portion of mankind.

As a publication from the UK statistics office reveals,[7] Mathus was writing at a time soon after the UK entered the so-called "demographic transition," which they date as beginning around 1750. The demographic transition is a change in the behavior of population growth that all economies appear to go through as they begin industrialization and associated economic development.

At first, improvements in nutrition and the application of more science-based medical care, together with public health measures (such as improved water supply and sewerage services), produce a decline in the death rate (especially for infants) while the birth rate remains essentially unchanged. The result is a period of rapid population growth. In the UK, this period lasted until around 1850.

---

[5] When there is no distinct breeding season or generation, it may make more sense to represent the process using continuous time and a differential equation.

[6] *An Essay on the Principle of Population*, rendered into HTML format by Ed Stephan, 10 Aug 1997, and available at http://www.ac.wwu.edu/~stephan/malthus/

[7] "The UK Population: Past, Present and Future," by Julie Jefferies available at http://www.statistics.gov.uk under the link to *Focus on People & Migration*

After a lag, birth rates also begin to decline. The initial reason is that the delayed death rates, and increased education, associated with development both delay the age of marriage and first birth, and ultimately the number of children each woman bears. Since early in the twentieth century, better birth control technology has allowed the transition to lower birth rates in other industrializing countries to take less time than it took in the UK.

As an economy continues to develop, a number of economic factors act to reinforce the transition to lower birth rates. First, as wages rise, the opportunity cost of time spent raising children increases. Since women still bear a disproportionate burden of childcare, the entry of women to the market labor force, and increases in the education and wages of women, are particularly important in this regard. At the same time, increasing time spent at school, and a reduced opportunity to use child labor services on farms, further raises the costs of each additional child. In turn, a decrease in the number of children in each family reduces the cost of educating those children, providing them with better health care and nutrition and so forth. However, such expenditures further raise the cost of having an additional child. The interaction between what economists have called the "quantity" and "quality" of children results in a very high elasticity response of fertility to a small exogenous change in the cost of children.

The final result of the demographic transition can be seen in the modern societies of the developed world. Both the birth and the death rates are very low by historical standards and population growth (excluding migration flows) has, in recent years, fallen toward zero and in some well-publicized cases has even become negative.

The reason the historical outcome was different from what Malthus had predicted is that he implicitly assumed that nutrition was the only input needed to produce children. While this might be approximately true elsewhere in the natural world, it is not true for human beings. In the developed world in particular, time (including time of teachers, medical practitioners and so forth purchased from the market) is the most expensive input into the production of children. Hence, even though, as Malthus argued, the relative cost of nutrition (and other material inputs) tends to decline as an economy develops, the cost of the time input rises. The latter effect dominates and hence fertility declines.

This effect can even be seen as dominating at the world level in the last four decades even though most people over that period were living in economies with a relatively low level of economic development. Figure 1 graphs UN data on the population growth rate (denoted $\hat{N}_t$) for the world for the period 1962–2004 (the latest date available at the time of writing). Also included on the graph is a quadratic trend line (estimated standard errors in parentheses, and $t = 1$ for 1962):

$$\hat{N}_t = \underset{(0.0003)}{0.0208} - \underset{(3.3\times10^{-5})}{1.0\times10^{-4}}\, t - \underset{(7.2\times10^{-7})}{2.5\times10^{-6}}\, t^2$$

The trend line implies that the rate of population growth at the world level is trending down over time by around 0.01 percentage points each year and at an accelerating rate. The trend implies that world population would stabilize around 2035 at slightly below 7.75 billion compared with a current population of around 6.5 billion. The UN itself forecasts that population will stabilize at a slightly higher level later this century.

Evidently, they are expecting the falling trend rate of growth to itself level out over the next few decades.

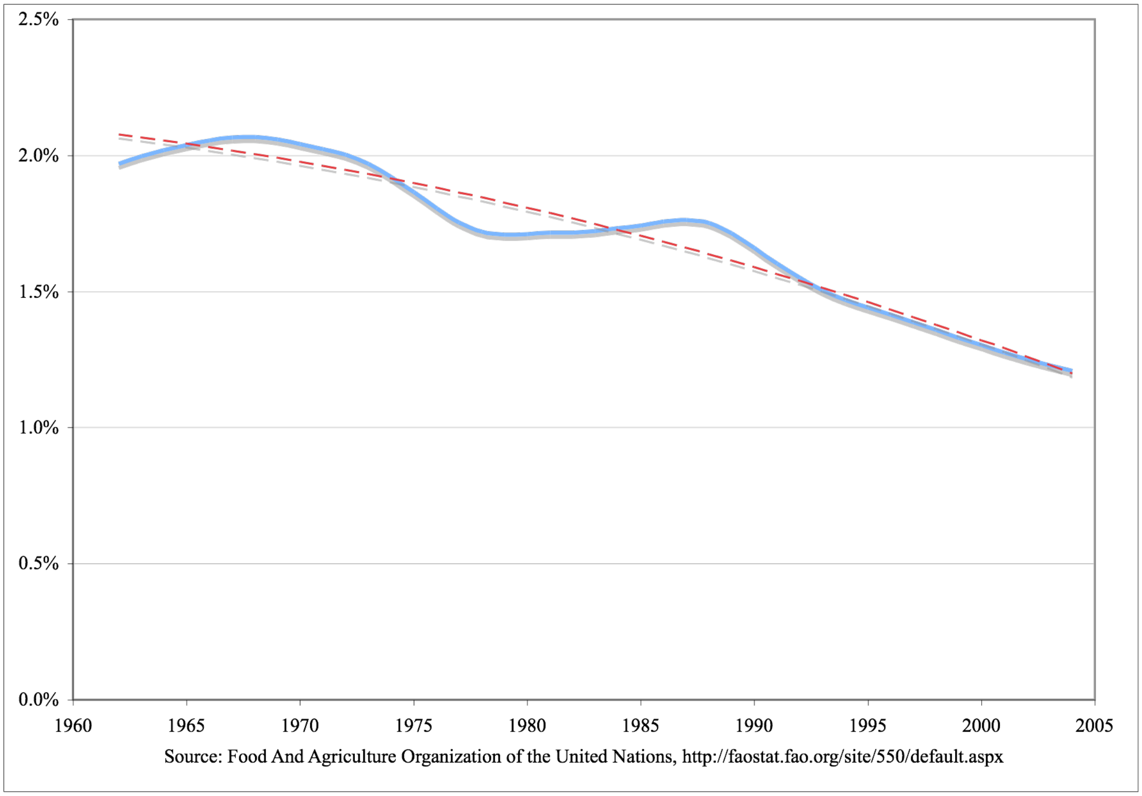


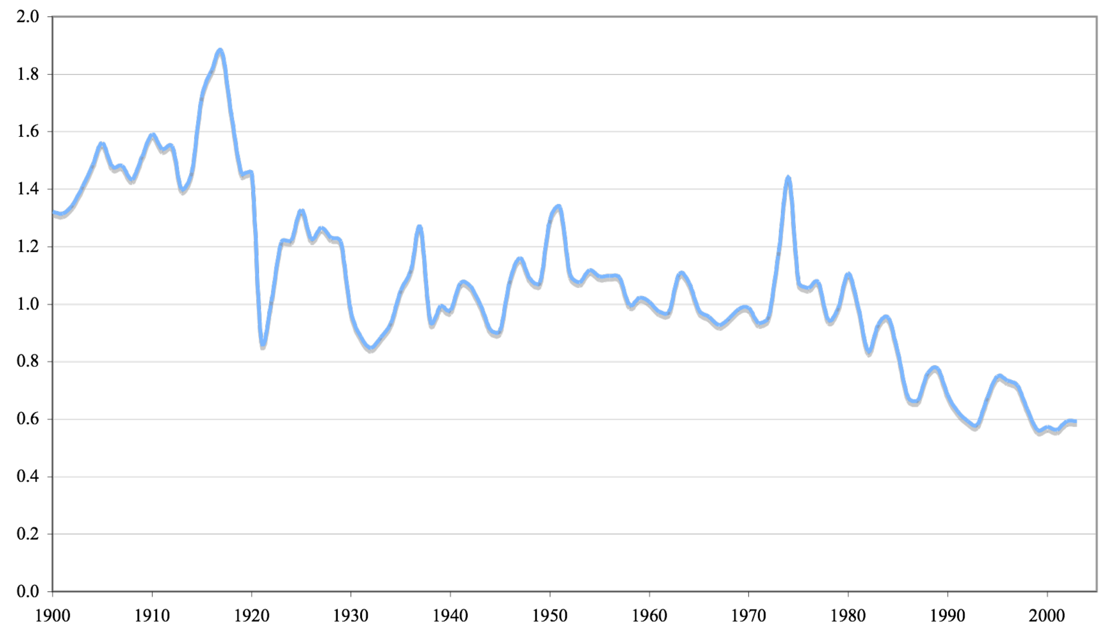
Figure 1: World Population Growth Rates, 1962–2004

Even if permanent economic growth does not lead to permanent population growth, it might be argued that each person will place an ever-increasing demand on resources over his or her lifetime as economies develop. For example, the rapid growth of China and, more recently, India, is a common explanation for increases in the price of resources and natural commodities over the last few years. Some forecasts of growing resource scarcity are based on an extrapolation of current Chinese and Indian economic growth rates.

One problem with this scenario is that it contradicts the standard model of economic development. Just as economic growth leads to a demographic transition, it also leads to a transition in industry structure. An economy at a low level of economic development has a large proportion of its labor force employed in agriculture using low productivity farming techniques. Once the economy begins to develop, people are transferred from the agricultural to the industrial sector, which results in a massive increase in their productivity. At the same time, the use of more modern farming techniques allows the same food and other agricultural commodities to be produced with much less labor. The result is a rapid rate of economic growth once the economy reaches the "take off" level. Large gains in labor productivity can be reaped until most of the labor force is transferred out of agriculture. Beyond that point, however, further gains in productivity are more difficult to achieve and per capita growth declines back toward the

2% per annum rate typical of most of the history of the developed economies since the Second World War.

A second problem with the scenario that economic growth will lead to ever-increasing shortages of resources is that, over most of recent history the relative scarcity of resources appears to have declined. Figure 2 graphs the relative price of commodities[8] to manufactured goods over the twentieth century. If the supply of commodities had been unable to keep up with the increasing demand for them, their relative price should have risen, but there is no indication of that occurring. There are episodes, such as in the 1970s (an no doubt over the last few years, but the data is not yet available from this particular source), when the raw materials prices rose substantially. These periods are however, brief interludes in a generally declining series.



Source: "A Short Note on Updating the Grilli and Yang Commodity Price Index", S. Pfaffenzeller, P. Newbold, and A. Rayner, The World Bank Economic Review 2007 21(1):151-163

Figure 2: Relative price of commodities to manufactured goods, 1900-2003

There are three main reasons that economic growth has not increased the relative price of commodities. The first is that an increase in the price of any one commodity produces strong incentives to substitute away from that commodity. For example, increases in the relative price of copper encouraged the use of aluminum in electricity transmission lines, and optical fibers in telecommunications lines, while carbon composites have become a substitute for metals in many applications. Even if the substitute is not perfect, the loss in functionality can be more than compensated by the

[8] Commodities in the index include metals (aluminum, copper, lead, silver, tin, and zinc), agricultural nonfood commodities (cotton, hides, jute, rubber, timber, tobacco, and wool) and food commodities (bananas, beef, cocoa, coffee, lamb, maize, palm oil, rice, sugar, tea, and wheat).

lower cost. In some cases, the substitutes prove to be better than the original after a short period of time. Technological progress often comes in discontinuous jumps followed by long periods of marginal improvements. The optimizations associated with the use of a given technology make it difficult for a competing technology to break into the market. Once a new technology takes hold, however, research effort switches to that technology. This can lead to dramatic advances before a new period of gradual improvements again takes over. Regardless, the ability to use substitutes limits the extent to which the price of any one commodity can rise.

The second reason economic growth has not placed substantial upward pressure on commodity prices is that technological progress has allowed more output to be produced with the same material inputs. For example, new computing technologies have allowed energy and materials to be used more much efficiently in many processes. This is an extension of the first point. Not just other raw materials but also other factors of production can substitute for raw material inputs. For example, capital and skilled labor can be used to develop, program and deploy automated processes. Similarly, biotechnology and other improvements in agricultural practices have allowed more food to be produced for given inputs of land, water, labor and other factors of production. More generally, these improvements are measured as changes in total factor productivity. Not only have such productivity improvements been widespread across many sectors of the economy. They seem, if anything, to have accelerated in recent years.

The third reason economic growth has not placed substantial upward pressure on commodity prices is that continuing economic growth beyond the take-off stage is associated with further changes in the structure of consumption and production. Specifically, as economies mature, services make up an increasing percentage of their GDP, and many services are extremely frugal in their use of resource inputs.

The latter observation reflects a more fundamental criticism of the notion that economic growth necessarily raises per capita demand for raw materials. Measures of economic activity reflect the *value of output to consumers*, which need not be closely related to the physical quantities of resource inputs used to produce the output. Skilled labor is the primary input in producing GDP in modern developed economies. Even consumption items that might be thought of as having a high resource content, such as the food that Malthus was concerned about, have an increasing proportion of their value coming from service inputs as the overall values of the items increase. For example, the overwhelming majority of the value associated with a restaurant meal reflects the skills and knowledge of the chef, not the food or energy used to cook the meal.

It may be useful to relate the final point in particular to the discussion about the carrying capacity of an ecosystem. A limited availability of the physical resources required by a species is the key determinant of the carrying capacity of an ecosystem for a non-human species. Fundamentally, however, economic growth is concerned not with growth in physical inputs to production but rather with growth in the *value of outputs* to consumers. There is no necessary reason why greater value of output requires a higher physical quantity of resource inputs.

The fundamental point is that one can conceive of unlimited growth in the value of economic output despite limited physical resources because there is one critical resource that is in unlimited supply. That resource is scientific understanding of the natural world and ingenuity in applying that understanding to produce higher valued products and services. The accumulation and application of scientific knowledge has been the fundamental force enabling continued growth and progress since the industrial revolution. This view implies that continued investment in science and technology is necessary for sustaining economic development.

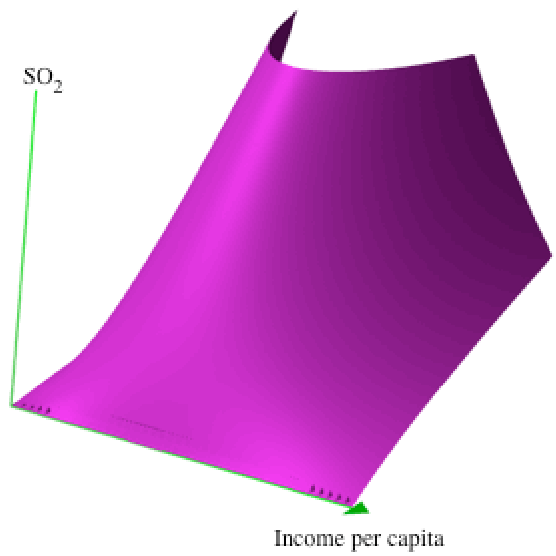
To this point in the discussion, we have implicitly taken the measured value of output, or GDP, as a measure of the overall value of economic activity. In general, however, the overall value of economic activity will differ from its market value. In particular, pollution and other non-marketed consequences of productive activity can affect the overall value, but are generally not included in market prices. The fundamental problem is that resources such as clean air or clean water are inputs into many production processes but there is no charge for using them.

If the amount of pollution is low enough, as in hunter-gatherer societies, the environment can usually assimilate it without difficulty. A good or service, like the purifying services of natural ecosystems in hunter-gatherer societies, that is in excess supply at a zero price is said to be free.

Once pollution grows beyond levels that can be assimilated by the environment, clean air and water are no longer free goods. Nevertheless, unless property rights to the resources are defined and allocated, people will not have to pay to use them. The resources become common property, leading to a tragedy of the commons as the resources become over-exploited.

The costs of pollution associated with increased production could easily overwhelm the value of that extra production. If so, the overall value of economic activity would decline even though the measured value increases. Economic development, conceived as an increase in the *overall* value of economic activity, would not be sustained.

Environmental economists have studied the relationship between various measures of environmental quality and economic development as conventionally measured. They have presented evidence that a wide range of pollutants tend to increase with economic development at low levels of development, but eventually pollution levels decline. For example, studies of fuel use in South Asia have found that households tend to burn more fuel of the same (very polluting) type as incomes start to rise. At higher levels of income, however, households switch to more expensive, but less polluting fuels. Clean air in the home is treated as a “luxury good” that is demanded more at higher levels of income. In addition, people everywhere are observed to lobby politically for government action to reduce pollution and protect natural ecosystems from destruction as incomes rise.



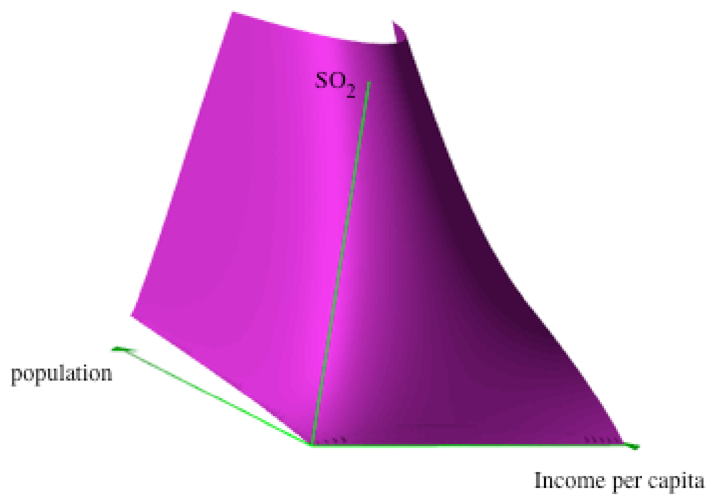


Figure 3: Estimated effect of economic development and population on SO_2 emissions

$$\ln SO_2 = \underset{(6.6007)}{-11.4895} - \underset{(0.000028)}{0.00011}\, y - \underset{(1.4501)}{3.9093} \ln y + \underset{(0.0961)}{0.3224} \left(\ln y\right)^2 + \underset{(0.4157)}{2.2552} \ln N - \underset{(0.0135)}{0.0357} \left(\ln N\right)^2$$

Estimated with country random effects, within R^2 = 0.1386, between R^2 = 0.8741

Figure 3 presents one example of the latter type of relationship. This particular surface was estimated using data on sulfur dioxide emissions in 176 countries over three years (1990, 1995, 2000) obtained from the World Resources Institute[9] together with data on real income per capita and population obtained from the World Bank World Development Indicators database.

An easy way to understand the implications of the estimated surface in Figure 3 is to consider what happens as income per capita increases holding population constant. This is equivalent to taking slices of the surface parallel to the income axis. SO_2 pollution at first rises with income per capita but then declines again at higher income levels.

Similarly, the effect of increasing population alone, holding per capita income fixed, can be seen by taking slices of the surface parallel to the population axis. At low and very high levels of per capita income, increased population has a small effect on SO_2 emissions. At intermediate income levels, however, where countries are partially developed, an increase in population leads to a dramatic rise in SO_2 pollution.

The fact that high levels of income are associated with reduced SO_2 pollution is likely to result from government action. In the United States, for example, the government has issued SO_2 pollution permits. Firms emitting more SO_2 than they have permits to cover are subject to a very large fine. The permits can be traded. Firms that can reduce SO_2 emissions cheaply do so and sell their permits to other firms that have a high cost of controlling emissions. By limiting the overall number of permits, the government can reduce the total SO_2 pollution output. Also, by allowing the permits to be traded, a given aggregate reduction in SO_2 is achieved at lowest overall cost. In effect, the permits turn the clean air that was formerly regarded as a "free resource" into another input into production that has to be paid for. Consumers will be willing to purchase the product produced by the firm only if its value to them exceeds its cost of production *including the cost of the SO_2 pollution output* associated with its production.

The main implication of this analysis for sustainable development is that suitable environmental policies are necessary to ensure that economic development raises welfare appropriately measured to take all costs and benefits into account. If the pollution externality accompanying development is not controlled, development in the sense of improved living standards *all things considered* might not be sustainable. Eventually, living standards would begin to decline even though economic output as conventionally measured continues to rise.

Strictly environmental matters such as air and water pollution, or preservation of biodiversity through limiting the destruction of natural habitats, are not the only sources of externalities associated with economic growth. For example, the traffic congestion accompanying economic growth and urbanization is a serious issue in many developing and developed economies. Once again, a growth in the use of pricing mechanisms, such as toll roads and bridges or the Central London congestion zone, is helping to control the

---

[9] The data is available at http://earthtrends.wri.org/searchable_db/index.php?theme=3 and https://publications.worldbank.org respectively.

problem. Automobile registration fees, parking and fuel taxes, and subsidies for public transport can also all be partly rationalized as price-based mechanisms to limit some of these externalities. Government action in the form of regional and urban coordination and planning of transport routes can also help alleviate some of these problems.

Other problems that accompany economic growth and urbanization include increased crime. Local governments in the Houston region have also recently become aware of the potential threat that floods, severe weather or emergencies associated with terrorist activity pose for the standard of living of residents in this area.

Differential rates of economic growth in different parts of the world, and the demographic transition discussed earlier, have contributed to the large flows of immigrants from developing to developed countries in recent years. The increasing diversity of people with different cultural and religious backgrounds has also raised issues of social cooperation and tolerance as sustainability concerns for cities such as Houston. In addition, there is evidence that just as people become more concerned with issues such as environmental amenities as they become richer, so also they care more about political and religious freedom, equality of opportunity and the number of fellow citizens living in poverty or with inadequate access to basic health and educational services.

In summary, much more than access to marketed goods and services goes into determining a standard of living. Some of these other aspects of life that people value can easily come into conflict with economic growth if the latter is not accompanied by appropriate political and social changes.

Implications for the Shell Center

Given this perspective on sustainable development, what do I believe should be the priorities of the Shell Center at Rice University? In answering this question, I believe that we need to take account not only of the issues involved in ensuring sustainable development but also the interests and capabilities of the Rice faculty. An endless number of issues related to achieving sustainable development could be researched and discussed. We should focus on those where we already have expertise and thus a chance of making significant contributions. Furthermore, in order to build the reputation of the Center, we need to focus on a limited number of issues.

The above analysis has emphasized the critical role of science and engineering in facilitating sustainable development. Of particular relevance are new technologies that facilitate productivity improvements especially in the use of raw materials and energy, and technologies that alleviate the environmental impacts of economic activity. These concerns mesh well with Rice expertise in new energy and materials technologies and environmental engineering.

We also have emphasized, however, that new technologies alone are not sufficient to ensure sustainable development. Energy and environmental policies also play a critical role and have a clear overlap with the energy research program conducted under the auspices of the James A. Baker III Institute for Public Policy and the research conducted in environmental engineering and under the auspices of the Environmental and Energy Systems Institute.

Finally, the Houston area provides a suitable laboratory for examining many sustainability issues in a modern city. Faculty at Rice also have a clear advantage in focusing on these local issues and using them to draw general conclusions that are likely to have wider applicability and appeal. Indeed, the Shell Center has already supported considerable research on local and regional sustainability issues. More could also be done, for example, by looking at the heath effects of air or water pollution in cooperation with the Baker Institute program in health policy or researchers at the Texas Medical Center. Indeed, the Shell Center previously sponsored a very successful mini-series of seminars on the heath effects of air pollution that involved epidemiologists from the Medical Center along with environmental engineers at Rice.