Modeling The Environment and Human Well-Being

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Over one hundred years ago President Theodore Roosevelt said something very prescient, *"The nation behaves well if it treats the natural resources as assets which it must turn over to the next generation increased and not impaired in value."* He is quoted on the wall in the entrance hall of the American Museum of Natural History. This insight, which economists took over eighty years to develop themselves, serves as an introduction to the emerging theory of natural capital and ecosystem services and their impact on human wellbeing.

1. Economics, Ecosystems and Natural Capital

We are witnessing the emergence of a new field, perhaps a new paradigm. Society has many forms of capital – physical, human, intellectual, social and **natural**. All are assets that yield a return and in which one can make an investment. In the field of sustainability, the focus is on natural capital. So what is natural capital? An important and more obvious part is made up of mineral resources (first modeled by Hotelling 1931). Less obvious but perhaps more important in the long run are ecosystems, a key ingredient of our natural capital. Lakes and rivers generate hydropower and are clearly assets and a part of natural capital. Watersheds are more complex but are also a critical aspect of natural capital: they clean water and stabilize the stream-flow, and are crucial to human welfare. We will see more examples later.

The key insight here is that ecosystems are assets and are part of natural capital: they provide valuable services – **ecosystem services** – which we can see as a return on this natural capital. So two concepts coming together – **Natural capital** (from economics) and **Ecosystem services** (from ecology).

Ecologists characterize value of ecosystems to society and their impact on human

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wellbeing in terms of services rendered – climate stabilization, pollination, food production, waste decomposition, recreation etc. Economists see these services as the return on natural capital. The economic value of natural capital is the present value of the ecosystem services it provides

This perspective provides insight both into the reasons for the conservation of nature and the returns from this, and into how to think about sustainability

2. The Challenge

The biggest intellectual challenge we face in implementing this approach is linking a change in the biogeochemical state of an ecosystem to the resulting change in the flow of ecosystem services. This requires that we integrate economic and ecological modeling. We need to do this to understand how the services provided by an ecosystem change as it is impacted by human activity, which is a key element in policy evaluations. Examples of such questions are:

> *How does the extent of a mangrove forest affect fishery productivity?*
>
> *How does the extent of a watershed and the nature of its vegetation affect its ability to purify water and stabilize stream-flow?*

We don’t need to answer these questions if we just want to value current services, but we do if we want to value changes in services resulting from policies. Likewise we can value current natural capital if we can value current services, but if we want to value changes in natural capital then we have to know how physical change in an ecosystem translates into changes in flow of services – because the value of a change in natural capital is the present discounted value of the resulting changes in its services. These problems are particularly central if we are to evaluate with any precision the full economic costs of climate change: changing climate will certainly affect many important ecosystems, and understanding how these changes will affect the flow of ecosystem services will be an important part of understanding the consequences of a changing climate for human welfare. Current generations of integrated assessment models make no attempt to model the ecological consequences of changing climate, and so are almost certainly seriously underestimating the costs.

3. Modeling Issues

Figure 1 (from National Academy 2005) shows some of the connections we have to model. Key is the link from human actions to ecosystem structures and functions and on to ecosystem goods and services and their values to humans.

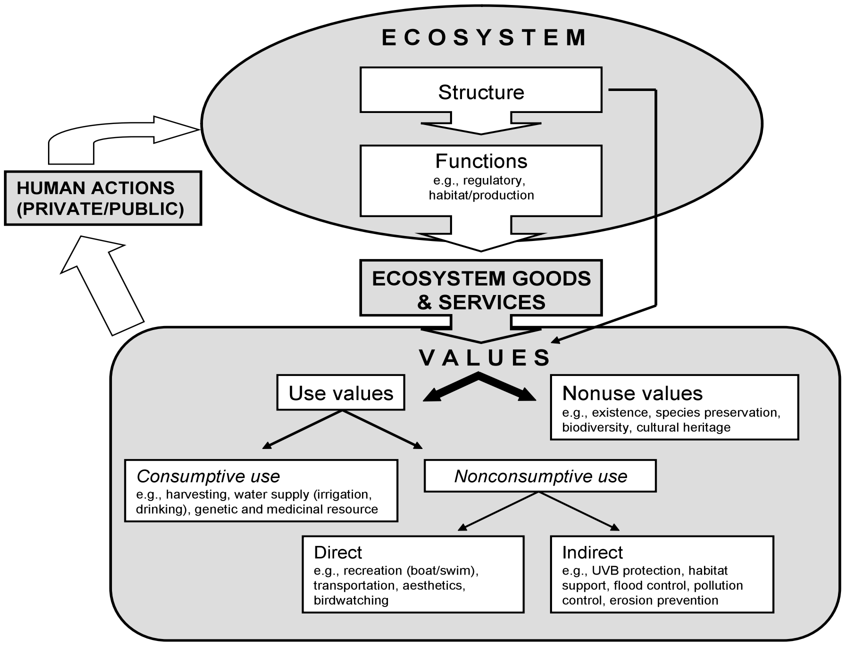


Figure 1

These linked economic-ecological models are complex: typically they are dynamical systems involving non-linearities, thresholds and irreversibilities. A beautifully simple example is given by the eutrophication of Lake Mendota through phosphorus run-off from agricultural land. Lake Mendota is on the campus of the University of Madison at Wisconsin and has been extensively studied by economists and ecologists from Wisconsin.

The driver of change here is that fertilizer runs off farmland around the lake and into the lake, particularly when it rains. Phosphorus in the fertilizer dissolves in water and also is retained by sediment on the lake bottom (Carpenter et all.). At low concentrations of phosphorus the lake is clear and productive, with many sources of economic value: at high concentrations it is biologically almost dead and of little or no economic value. The basic dynamics are that phosphorus leaves the lake through outflow in the stream that exits the lake, at a rate that is proportional to the concentration in the water; it flows in off the neighboring cropland, and may also move from the sediment at the bottom of the lake into solution. We can model this quite simply: let C = concentration of phosphorus, O = outflow, I = inflow. Then

$$\frac{dC}{dt} = I - O = I - kC \text{ where } k \text{ is a constant}$$

$$I = I_1 \text{ for } C \leq \underline{C}, = \alpha + \beta C \text{ for } \underline{C} \leq C \leq \bar{C}, = I_2 \text{ for } \underline{C} \leq C$$

Here $\alpha, \beta, \underline{\mathrm{C}}, \bar{\mathrm{C}}$ are positive constants

This system is shown graphically in figure 2: there are three equilibria where inflow an outflow are equal, two clearly locally stable and one unstable. The system is “normally” in a stable equilibrium at the low concentration, and is economically and biologically productive. But a sudden heavy rain can wash in enough fertilizer to shift the concentration of phosphorus to within the basin of attraction of the right hand equilibrium, leaving it in a far less productive state. So could a very hot dry spell, by evaporating water from the lake and increasing concentration above a critical level.

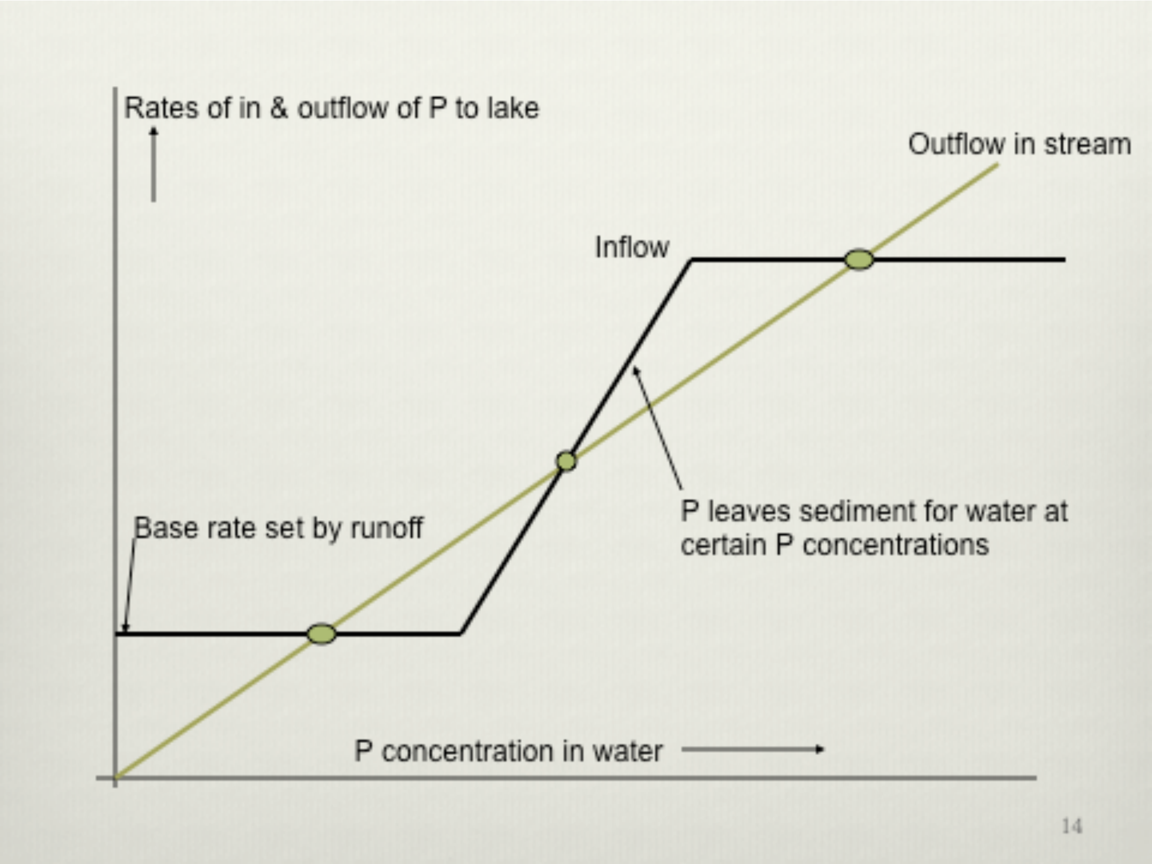


Figure 2

This is a very simple illustration of the kind of system that can emerge from trying to understand the behavior of ecosystems under stress from human economic activity: multiple equilibria with basins of attraction of varying sizes are common, and knowing how the system may move between these is critical.

Another very simple example of non-linearities comes from the response of stream chemistry to the deposition of oxides of nitrogen. Oxides of nitrogen are formed whenever we burn fossil fuels in air at high temperatures, and dissolve in water to form the weak acid nitrous acid, potentially changing stream and lake chemistry radically. In fact some streams have a limited capacity to buffer or neutralize NOX, so that up to a certain level the deposition of NOX has no effect on water chemistry such as pH: above this there is an impact. Again we have a very non-linear response of an ecosystem to human stresses (Bernhardt et all. 2005).

4. Sustainability

There are several possible definitions of sustainability and all revolve around natural capital. We can think of sustainable income as the return on *all* of our capital stocks. Hicks famously defined income many decades ago as the most you can consume this month consistent with consuming the same in all subsequent months, so defining sustainable income as the return on all forms of capital is saying that this is Hicksian income with an appropriately general concept of capital. Alternative definitions of sustainability are that sustainability is keeping the total value of all capital constant or increasing (sometimes known as weak sustainability) or keeping the total value of natural capital intact (known as strong sustainability) (Neumayer 200X).

An important mathematical result is that the former definition (of weak sustainability) implies that preset value of future welfare (which is just the value of the state valuation function) is non-decreasing. A demonstration is given below.

5. Theory of Sustainability

Consider the classical Ramsey problem of maximizing the utility from consumption over time subject to a production function and an accounting constraint:

$$\max \int_0^\infty U(c_t)e^{-\delta t}dt$$

$$c_t + \frac{dk}{dt} = f(k)$$

Here U is utility, c consumtion, k a vetor of capital stocks (physical, human, natural etc.), f a production function that is concave increasing and smooth, and δ a non-negative discount rate. Then it is straightforward to show that current welfare level can be maintained for the next time interval if and only if

$$\sum_i p_i \frac{dk_i}{dt}_i \geq 0$$

Here the p_i are the shadow prices or co-state variables from the Ramsey problem, the social values of the various types of capital – built, human, intellectual, natural etc. The proof is as follows.

$$V(k) \equiv \max \int_0^\infty U(C_t) e^{-\delta t} dt \text{ subject to } C_t + \sum_i \frac{dk_i}{dt} = f(k)$$

$$\frac{dV}{dt} = \sum_i \frac{dk_i}{dt} \frac{dV}{dk_i} = \sum_i \frac{dk_i}{dt} p_i$$ where p_i is the shadow price or co-state variable on the ith state variable k_i

The intuition behind this is clear – *we can sustain current welfare if and only if we are not depleting total value of productive assets*, where the total value is calculated using the marginal social values of these assets, their marginal contributions to social welfare, and the listing of assets is comprehensive.

6. Capital, Portfolios and Growth

Viewed from a very aggregative level, economic growth to date has been a history of increasing some types of capital stock and lowering others – but nevertheless raising the total value. Growth has changed the composition of countries' portfolios of capital stocks, typically raising stocks of intellectual, human and physical capital and destroying natural capital – forests, fisheries, minerals, and species. It is this loss of natural capital that is the source of our current environmental problems and our concerns about sustainability. In spite of this unambiguous loss of natural capital, there is general – though perhaps not universal – agreement that rise in some other types of capital has more than compensated for the drop in natural capital. This observation raises a fundamental question, perhaps *the* fundamental question in the economics of sustainability:

Are there diminishing returns to the replacement of natural capital by intellectual capital and physical capital?

Our ability to continue this process depends on the elasticity of substitution between natural and other forms of capital. There are two places where these substitution possibilities matter: in preferences and in production. "Deep ecologists" believe that substitution possibilities are small, whereas mainstream economists typically believe that it is large. The reality is that we really don't know, but it is certainly possible that no accumulation of other forms of capital can compensate for radical changes in climate or massive loss of species.

We can think of specifying preferences and production possibilities so that they depend on the stock of natural capital k_n as well as other types of capital k_o:

$$U(c,k_n) \text{ and } f(k_o,k_n)$$

Then we are interested in the substitution elasticities in both of these functions. The elasticity of substitution between k_n and other forms of capital k_o may become low or zero as k_n gets small, which would be reflected in high values for p_n shadow price of natural capital. In thinking about the utility function, it is possible that there is a minimum level of environmental services that is needed to attain any positive welfare level: this is shown in figure 3, where the level sets or indifference curves never cross the vertical line corresponding to some minimum level environmental goods and services. Level sets could all asymptote to one minimum, or there could be a distinct minimum for each welfare level or level set, or indeed some combination (Heal 2009). We know nothing about this topic, nor do we know how to specify tractable functions with these properties.

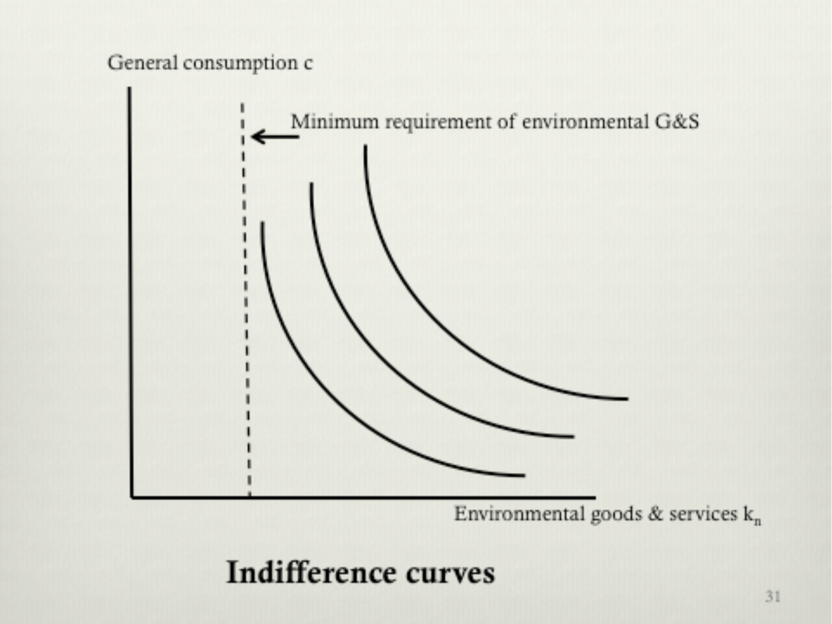


Figure 3

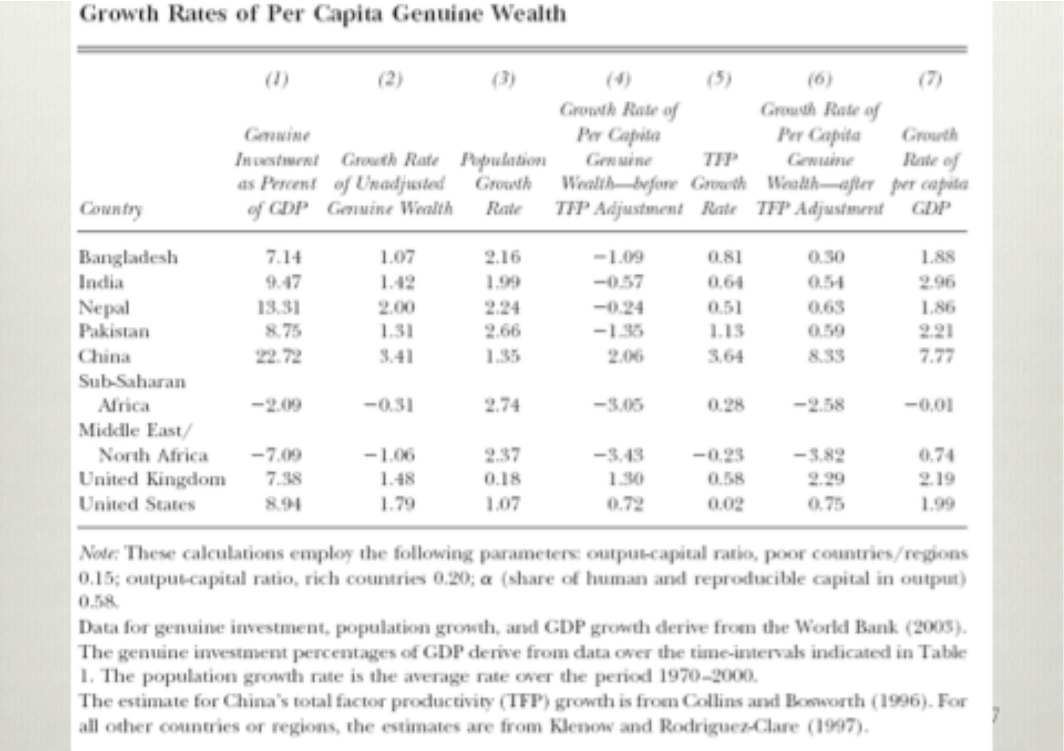
While discussing how human wellbeing depends on the natural environment and in particular how this enters into preferences, it seems appropriate to mention the theory of biophilia, the idea, advanced initially by E.O. Wilson, that humans have an innate psychological dependence on the natural environment, benefit from its presence and suffer from its absence. This posits a mechanism quite distinct from any biogeochemical services provided by the environment.

7. Measuring Sustainability

In thinking about how to measure sustainability, it is natural to start from the inequality

$$\sum_i p_i \frac{dk_i}{dt}_i \geq 0$$

We have seen that this is a necessary condition for welfare to be non-decreasing along a growth path. As we have noted this measures the changes in all types of capital stocks and values these at shadow prices. Several recent studies have tried to implement this measurement scheme. Details of the data used and the calculations are in Arrow et al. (2004): here what matters is the qualitative results. These are summarized in table 1. The key column is column 6, the penultimate one, headed “Growth Rate of Per Capita Genuine Wealth after TFP Adjustment.” This shows the best estimate of the total $\sum_i p_i \frac{dk_i}{dt}$ (known as adjusted net savings or ANS) for various countries and regions. The last column, column 7, contains as a benchmark the rate of growth of per capita gross domestic product, the conventional measure of economic performance. Note that in most cases the rate of growth of total wealth per capita is less than that of GDP, that for most countries it is barely above zero, and that for two regions – the Middle East and North Africa (MENA) and sub Saharan Africa (SSA) - it is clearly negative. These numbers suggest that most countries are barely able to maintain current welfare levels, and that two regions are clearly not. The results for MENA and SSA, sadly, make sense: MENA is a region that lives by depleting natural capital – oil and gas – and does not compensate for this by building up other forms of capital on a sufficient scale. The same is true to a smaller extent of SSA.



Growth Rates of Per Capita Genuine Wealth

Country	*(1)* *Genuine Investment as Percent of GDP*	*(2)* *Growth Rate of Unadjusted Genuine Wealth*	*(3)* *Population Growth Rate*	*(4)* *Growth Rate of Per Capita Genuine Wealth—before TFP Adjustment*	*(5)* *TFP Growth Rate*	*(6)* *Growth Rate of Per Capita Genuine Wealth—after TFP Adjustment*	*(7)* *Growth Rate of per capita GDP*
Bangladesh	7.14	1.07	2.16	−1.09	0.81	0.30	1.88
India	9.47	1.42	1.99	−0.57	0.64	0.54	2.96
Nepal	13.31	2.00	2.24	−0.24	0.51	0.63	1.86
Pakistan	8.75	1.31	2.66	−1.35	1.13	0.59	2.21
China	22.72	3.41	1.35	2.06	3.64	8.33	7.77
Sub-Saharan Africa	−2.09	−0.31	2.74	−3.05	0.28	−2.58	−0.01
Middle East/ North Africa	−7.09	−1.06	2.37	−3.43	−0.23	−3.82	0.74
United Kingdom	7.38	1.48	0.18	1.30	0.58	2.29	2.19
United States	8.94	1.79	1.07	0.72	0.02	0.75	1.99

Note: These calculations employ the following parameters: output-capital ratio, poor countries/regions 0.15; output-capital ratio, rich countries 0.20; α (share of human and reproducible capital in output) 0.58.

Data for genuine investment, population growth, and GDP growth derive from the World Bank (2003). The genuine investment percentages of GDP derive from data over the time-intervals indicated in Table 1. The population growth rate is the average rate over the period 1970–2000.

The estimate for China's total factor productivity (TFP) growth is from Collins and Bosworth (1996). For all other countries or regions, the estimates are from Klenow and Rodriguez-Clare (1997).

Table 1

One of the most striking results here is the number for China – massively positive. This certainly runs counter to one's intuition that China's profligate destruction of the environment and emissions of greenhouse gases render its growth path unsustainable. The calculations behind these numbers leave a lot to be desired, and certainly underestimate the extent of environmental damage and depletion of natural capital in all countries, especially China, because good environmental data is hard to find, and the prices are hard to estimate. Even so, sensitivity analysis suggests that plausible corrections of the data still leave China as the most sustainable nation in the world – in spite of its also being the world's largest greenhouse gas emitter!

A possible resolution of this paradox would be based on the observation that the inequality

$$\sum_i p_i \frac{dk_i}{dt}_i \geq 0$$

tells us that we are currently sustainable, but does not ensure that this remains true any significant distance into the future. Extrapolation of the present path could still imply that this quantity soon becomes significantly negative. A more comprehensive test for sustainability requires forecasting $\sum_i p_i \frac{dk_i}{dt}$ for reasonable projected growth paths some way into the future, something that was tested in the recent Stiglitz Sen Fitoussi (2009) report commissioned by President Sarkozy of France. Figure 4 shows ANS for various countries from this report: note as before that the figure for Saudi Arabia is always negative, and that for China is as before highly positive.

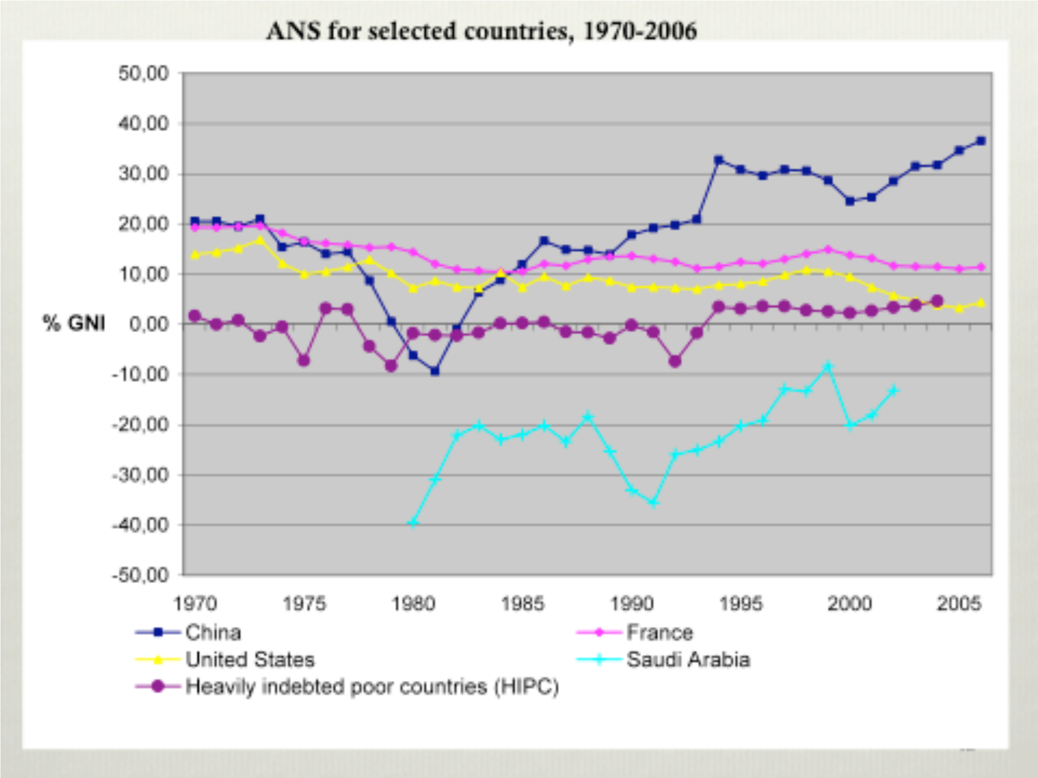


Figure 4

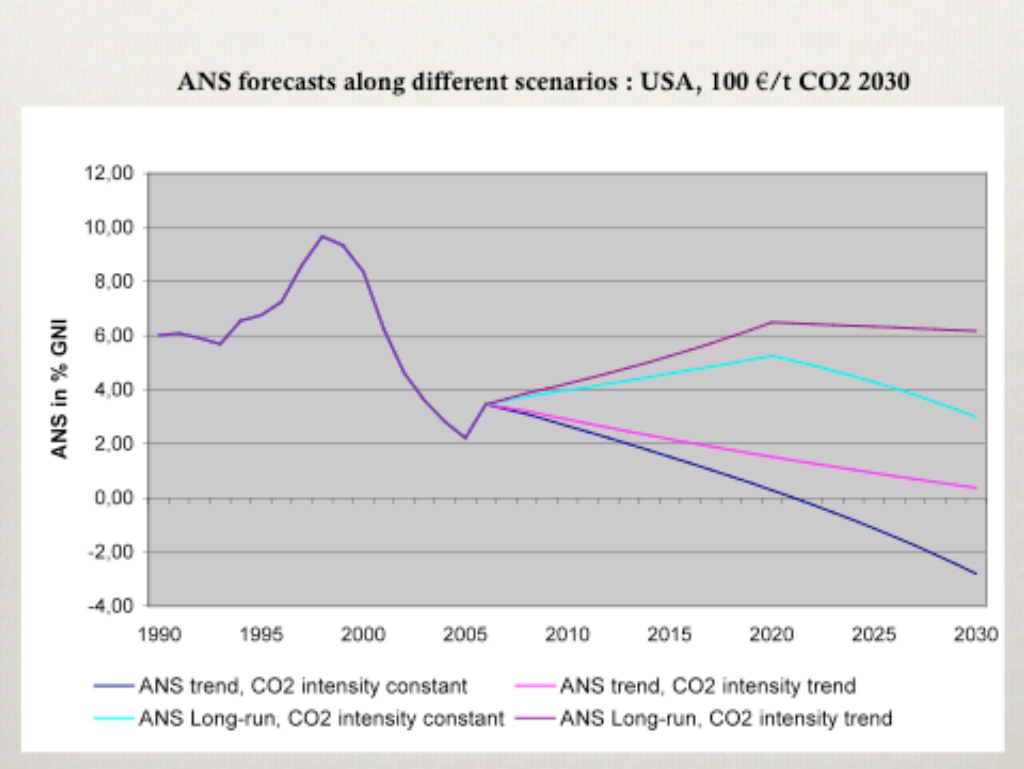


Figure 5

Figure 5 calculates ANS for the US up to 2030 for four scenarios or sets of assumptions, showing that in spite of ANS being positive at the time of the calculations, there is a real chance of its changing to negative in the near future. There is a mathematical point at stake here: is there a better measure than ANS or $\sum_i p_i \frac{dk_i}{dt}$? Is there an observable number that will tell us whether current welfare levels can be sustained for longer than the immediate future?

Another interesting question concerns the relationship between sustainability and optimality: we understand the mathematics of optimality far better than that of sustainability, so it would be interesting to have an answer to the question: Is a sustainable path an optimal path for some criteria and constraints? If so, there are automatically shadow prices that support sustainable paths, and there is a body of mathematical-economic literature that can be applied directly.

8. Conclusions

There are several aspects to the ways in which we model the impact of the natural environment on human wellbeing. We can think about how the services of ecosystems affect welfare directly, how they enter into preferences and the determination of welfare. Then we can also think about how these services enter into the production process, perhaps for food or more indirectly for a range of other goods and services. None of these issues has been extensively modeled. Evaluating how human activities affect the supply of ecosystem services requires linking economic and ecological models, resulting in systems that are complex and show many different modes of behavior.

We can also think about how to define and measure sustainability, in which case we are concerned to model how the economy and the environment, the latter represented by stocks of natural capital that give rise to ecosystem services, evolve over time and whether the size and composition of the total capital stock can maintain human welfare levels. This poses challenging problems in dynamics, which remain to be solved.

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