A Celebration of Environmental and Resource Economics

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Several years ago, I took advantage of the award of the Association of Environmental and Resource Economists' (AERE) Prize for a Publication of Enduring Quality, of which I am very proud and which occupies a prominent place in my office, to reminisce about the evolution of our field and its relationship to the rest of economics. When the editors invited me to contribute to the new *Review of Environmental Economics and Policy*, I saw this as an opportunity to develop these points further and to use them as the basis for a rather personal and possibly idiosyncratic review of environmental and resource economics. This is what follows: it meanders from the history of our subject to the evolution of the Hotelling Rule and then on via oil markets to climate change, to natural capital, ecosystem services (ESS), greening national income, and sustainability. The choice is, as I said, idiosyncratic, but I hope interesting.

In my talk at the AERE meeting, there were two main points I wanted to convey. One was that some of the very best minds in economics, people of great prominence and intellectual talent, have contributed to building our field. This is something to be proud of. The other was that the street between environmental and resource economics and the rest of economics is a two-way street, with heavy traffic in both directions. Of course, we borrow from the rest of economics, but we also contribute to it as well, perhaps more than we are aware. Again, this should be a source of pride.

These two observations are related. Why do some of the best minds in economics work on environmental problems? In part, at least, because they think that environmental problems raise issues that matter for the whole of economics, and because they think that understanding environmental problems helps us to understand important issues in economics as a whole. Hence the two-way traffic.

Environmental Contributions of Leading Economic Thinkers

Let me try to document these points. The first is the easy one. During the 1970s, when some of the basic theoretical framework of our field was established, many contributions

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2006 is the seventy-fifth anniversary of the publication of Harold Hotelling's "The Economics of Exhaustible Resources" (1931), which in my opinion marks the foundation of analytical environmental and resource economics. I would like to dedicate my article to a celebration of this anniversary.

Review of Environmental Economics and Policy, volume 1, issue 1, winter 2007, pp. 7–25
doi: 10.1093/reep/rem001

were made by people who went on to receive Nobel prizes. These are people not generally considered to be environmental economists, but who nevertheless felt that environmental problems are sufficiently central to economics to merit the investment of their time. As an example of this point, I have in front of me the 1974 issue of the *Review of Economic Studies*, which was devoted to a Symposium on the Economics of Exhaustible Resources. As the editor, I still have a copy on my shelf. The contributors included Robert Solow on "Intergenerational Equity and Exhaustible Resources," Vernon L. Smith on "General Equilibrium with Replenishable Natural Resources," Tjalling C. Koopmans on "Proof for a Case when Discounting Advances the Doomsday," and Joseph E. Stiglitz on "Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths" and also on "Growth with Exhaustible Natural Resources: The Competitive Economy." All of them, of course, went on to win Nobel prizes. And none are commonly on lists of environmental and resources economists. I doubt that any special issues of journals devoted to labor economics, international economics, or the economics of education had contributions from four people who went on to become Nobel laureates. In fact, there could easily have been more than four such authors in that issue. At that point, Michael Spence was working on environmental issues, with a series of articles on blue whales (Spence 1975), Jim Mirrlees had articles on market versus optimal depletion rates (Kay and Mirrlees 1975), Kenneth Arrow was developing his thoughts on irreversibility and option values (Arrow and Fisher 1974), and James Tobin was working on greening national income (Nordhaus and Tobin 1972).

This profusion of environmental contributions by the leading thinkers in economics was not confined to the 1970s, but goes back further. In many ways, the founder of analytical environmental and resource economics was Harold Hotelling, with his fundamental work on the economics of exhaustible resources, his work on the travel cost method of evaluating national parks, and his very early work applying calculus of variations to the management of fisheries.[1] Hotelling made fundamental contributions all over economics—his model of product differentiation along a line (Hotelling 1929) is still a classic—and he would clearly have been a prime Nobel candidate had there been such prizes when he was alive.

The Two-Way Street

I think I have proved my claim that some very deep thinkers have contributed to building our field. Let me now turn to the other claim that I made above—that there is heavy traffic in both directions in the street that joins environmental and resource economics to the rest of economics. Given the point that I have just made, this more or less has to be true: if really prominent theorists worked in resource and environmental economics, it is because they felt that what they were doing was important for economics as a whole.

I was just speaking of Hotelling, so let me turn first to him. Think for a moment of the famous Hotelling rule[2] in markets for exhaustible resources, which states that the resource rent will rise at the discount rate. This is an arbitrage-free pricing condition: the return on

[1]Hotelling's collected articles are available in A. C. Darnell (1990). The original reference on exhaustible resources is Hotelling (1931).

[2]The Hotelling rule states that $(1/p)(dp/dt) = r$, where r is the discount rate and p is the market price of an exhaustible resource. For this simple version of the Hotelling rule to hold, extraction costs must be zero.

the physical asset—the resource—which comes from the appreciation of its price, must equal the return on other forms of capital. With this result, Hotelling was the first to describe dynamic equilibrium in capital markets in terms of the absence of arbitrage possibilities, back in 1931. It took the field of finance almost half a century to catch up and make the Arbitrage Pricing Theory—the idea that the absence of arbitrage possibilities is a powerful way of characterizing dynamic equilibrium in capital markets—a central perspective.

Another interesting example also relates to finance. I mentioned above the Arrow–Fisher work on real option values (as they are now called). This was published in 1974, as was related work by Claude Henry (1974a,b). This was contemporaneous with the publication of the famous Black–Scholes formula for valuing stock options. Black and Scholes (1973), by focusing on a special case, established a very neat and practical formula, which duly took off in terms of applications in finance. But in some respects, the treatment in the environmental literature was both deeper and more general. For example, Pindyck (1991) and others have traced the connections between the environmental and financial approaches to the valuation of options, and the current literature on real option values owes more to the environmental tradition than to the financial one.

There are many other areas of economic theory whose development was driven in part by pressure from the field of resource and environmental economics. Optimal growth theory is a good example. Environmental economists have worried intensely about the "cake-eating problem" because of its relevance to optimal depletion issues and its connection to the original Hotelling article on resource depletion, and they have moved this area ahead. Recall that the cake-eating problem—so called by the optimal growth theorists of the 1960s, and in particular David Gale (1967)—asks how we should divide a cake of finite size between infinitely many generations, and so is at the core of the pure theory of exhaustible resources. More recently, work on understanding sustainability has shed considerable light on analytical issues in the theory of long-run growth. In asking when continued growth is possible in a world of finite resources, environmental economists have increased understanding of the roles of technical progress, factor substitutability and capital accumulation in long-run growth. We know, for example, that even if an exhaustible resource is essential to production, in the sense that output is zero when the input of this resource is zero, there are paths on which output remains positive for all time (Dasgupta and Heal 1979). This is not an obvious point.

Intertemporal welfare economics has also benefited from the work of environmental economists on sustainability. Most of what we know about the relative implications of Rawlsianism, Utilitarianism, and various other axiom sets relating to intertemporal justice and equity comes from the work of environmental economists. In particular, this work has shown that although Rawls's axioms are appealing and constitute a force for social justice in an atemporal context, their implications are more perverse in the long-run and can justify remaining forever at the status quo. And almost everything we know about valuing public goods comes from environmental economics. This is a field that will come to matter to other areas of economics, though people do not seem to realize this yet.

Recent Applications of the Hotelling Rule

Something that I find intriguing is the recent development of new applications for the exhaustibility paradigm of Hotelling. A true sign of a deep analytical structure is that it resurfaces in many contexts, and that seems to be happening with Hotelling's model. For example, recent work has noted that underground aquifers are exhaustible. Fossil water—water laid down in aquifers many years ago that is no longer being replenished—is an exhaustible resource, and one whose scarcity rent is growing and could become huge with the progress of climate change (National Research Council 2005). The capacity of the atmosphere to absorb greenhouse gases without radical change to the climate system has also been modeled as an exhaustible resource (Heal 1984). Climate scientists are finding it productive to say that for the rise in global mean temperature to be within 2°C, we cannot emit more than a certain amount of CO_2 (W. Broeker, personal communication). This, in effect, states that the problem of managing climate change is one of managing an exhaustible capacity.

Another related and interesting exhaustible resource is the capacity to store carbon dioxide in underground rock formations. According to some perspectives on climate change, this could be a vitally important—and exhaustible—resource over the next half century (Butt et al. 1999). A Hotelling-type analysis tells us something about how to schedule the use of this capacity over time. It also tells us that the social costs of using it comprise not only the obvious costs of collection and storage of the greenhouse gases, but also a scarcity rent. In the engineering studies that have been conducted to date, these insights into intertemporal scheduling and the full social cost have been omitted, but they make a real difference (Narita and Heal 2006). A very different recent application of this paradigm is to the study of drug resistance: Brown and Laxminarayan (2000) have modeled as an exhaustible resource the extent to which a drug can be used before resistance develops among the pathogens it is intended to kill. The world's stock of biodiversity can be seen as an exhaustible resource, too. Every time a species is driven to extinction, this stock falls in an irreversible way. We are depleting that stock and do not fully understand the consequences.

It is puzzling that in spite of its intellectual power and elegance, a key prediction of the Hotelling model gets little empirical support. The prices of exhaustible resources, net of extraction costs, do not seem to rise at the interest rate.[3] There are many possible explanations, perhaps the prime one being that in reality few resources are in fact exhaustible in the sense of the Hotelling model. Most have supplies of varying grades, with the lowest grades available in almost unlimited amounts. This implies a rather different relationship between prices and interest rates (Heal 1976), one that has not been tested empirically.

Obviously, resource and environmental economics is intellectually important: I have noted a few of the significant intellectual developments that originated in the field. It is clearly of practical import, too. Two of the headline grabbers of our times are the price of oil—a classic in the economics of exhaustible resources—and climate change, one of the largest manifestations of external costs and public bads of all time. Hardly a day goes by without either or both on the front pages. On both topics, a little environmental and resource economics goes a long way. Consider the following questions.

[3] Heal and Barrow (1980, 1981). For a dissenting view that does find support for the Hotelling rule in the case of oil, see Miller and Upton (1985).

Past and Future Oil Prices

What is the difference between the run-up in oil prices of recent years and that of 1979–80? The rise then was actually sharper than now, and to levels that are higher in real terms. Then too there was talk of the end of the oil era, of falling discoveries of new fields, and of the need to move to new technologies. Commentators were predicting oil costs rising to a hundred dollars a barrel (in 1980 dollars!). Oil majors invested billions in "synfuels," oil derived from unconventional sources such as shale and tar sands. Yet before too long, the price was down in the teens again and all the money invested in synfuels was wasted, written off in a sea of red ink. In all the discussions of today's high oil prices and what they mean for the future, none of the commentators seems aware of this recent history, and none can explain why things are different today, or why prices collapsed in the 1980s. There is virtually no well-informed discussion of the future of oil prices. Yet basic ideas from our field can bring a little clarity to these issues.

Prices fell in the 1980s because of lags in the responses of demand and supply to prices: shortfalls in 1979 and 1980 sent prices up, and inelastic short-run demand let them stay there for a while. But over a few years, demand did respond through more efficient vehicle choices and other energy-saving measures—as it is doing today, as shown by the precipitate drop in the sales of large SUVs and pickup trucks. And supply responded too—the high prices of 1979 and 1980 created the North Sea, Mexican Gulf, and North Slope oil fields. Without those prices, they would not have come on line when they did. But with high fixed costs and low variable costs, oil fields are really vulnerable to hold-up problems: if the price drops to a level at which entry would not be profitable, production continues nevertheless because sunk costs are, after all, sunk. So, within a few years of high prices, there was a drop in demand and an increase in supply and with low short-run elasticities, the market needed a big price move to clear, downwards this time.

Is the same thing going to happen again? Predicting oil prices is of course risky: lots of experts have made fools of themselves in trying. Retrodicting the 1980s is a lot safer! But even without sticking one's neck out too far, it is easy to see what issues have to feature in an analysis of the future. Demand for oil is growing fast, and the supply is not. Demand growth could cool but will nonetheless almost certainly continue to outpace the growth of conventional oil deposits. This should push prices up.

But here we need to bring in a concept that loomed large in the exhaustible resources literature of the 1970s—the backstop technology. This is a technology that can replace conventional oil with a large supply of something equivalent, a supply with a horizontal supply curve. If it exists, it pegs the price of oil. At this point, it appears that there may be some backstops available. One is the conversion of coal to oil for a cost in the range of forty to fifty dollars per barrel. Another is the extraction of oil from tar sands—as in the Athabasca Tar Sands in Canada or in the Orinoco Basin in Venezuela—also at a cost of forty dollars. A third is gas-to-oil technology, which converts natural gas into gasoline, again at a cost said to be in the forty-dollar range. This is attractive in places where gas is abundant and where there is no local market. Between them, these three sources could provide a lot of oil. Canada, for example, is talking about matching Saudi output within a decade. So perhaps this abundant supply of a substitute at a price in the range of forty dollars will force the price of oil back down to that range. But there is a complication: oil from coal, and oil from tar sands, requires massive investment, in the billions.[4] If there is a chance of the price of oil dropping sharply after the investment is made, rational investors should not invest. So there is scope here for a game in which producers of conventional oil try to scare off investors in backstop products by establishing a credible threat of prices dropping. I am sure that they are thinking in these terms. So far they have not made the threat credible, although the possibility of a price drop is clearly the main factor holding several oil majors back from investing heavily in these backstop technologies. Resource and environmental economists studied exactly these issues back in the 1970s.

This doesn't amount to a forecast of oil prices, but I think it clarifies what the issues are. It doesn't go beyond chapter one of a basic resource economics textbook, but generates insights that are starkly absent from today's discussions.

Climate Change Policies

Can we offer easy insights into climate change policies? Again, the answer is certainly yes, but to a greater degree they are already out there in the debate. The fundamental mechanism of the Kyoto Protocol—cap and trade—is one of our great success stories. Unless you are an environmental economist, it appears to be a fundamentally implausible approach. Recall all the hostility of environmentalists to issuing ''rights to pollute'' that came with the first large-scale use of cap and trade in the 1990 amendments to the Clean Air Act? And the hostility to the use of carbon offsets in the Kyoto Protocol? It's far from obvious that setting up a market in a new-fangled and rather abstract property right will cure pollution or climate change, so we need to congratulate ourselves on developing the idea and getting it out there into application. Another one of our achievements in this area is just raising the idea that we need to compare the costs of reducing climate change with the costs of allowing it to occur, although this basic insight is still not as widely shared as one might wish. If we could get more of the debate focused on this issue, we would make a lot of progress.

Another simple insight that we seem to have gotten across is that there is a discount rate in this problem and it matters. In other words, some of the intertemporal welfare economics that I alluded to above is now being applied in discussions of climate change policies. Personally, I would like to see more and more intelligent discussions of uncertainty and how that features in climate change policies. There is good literature on this, some of course based on the real option value frameworks that I mentioned before (for a review, see Heal and Kristrom 2002). Although the basic science of climate change is robust, there are uncertainties, particularly in the analysis of the social and economic implications of an altered climate. What will it be like to live in a world where it is on average four or five (or more) degrees hotter? Until recently, most of us probably thought that it would not be very different. I am beginning to change my mind on this; evidence seems to be accumulating that quite small changes in climate—those already in hand—can produce noticeable effects, mostly negative. So I would want to give some probability to the event that a warmer world is really very much less pleasant than the one we have now, though I would not treat this as a certainty. It should be possible to explain this to the general public.

[4]It also requires a vast amount of water, which could prove a constraint on the development of these technologies.

To digress slightly, let me talk more about the hostility to the idea of trading carbon emission permits in the context of the Kyoto Protocol. For the last two and a half years I have been actively involved with the Coalition for Rainforest Nations (CfRN).[5] This is a group of countries with large tropical forests that are seeking to harness the 1997 Kyoto Protocol to generate incentives for forest conservation. Under Kyoto's Clean Development Mechanism (CDM), there are incentives for reforesting land from which forests have been cleared and for afforesting land that was never forested. The reforestation and afforestation incentives under the CDM work as follows: by growing a new forest and providing a carbon sink, countries generate carbon credits that can be sold to entities subject to the Kyoto Protocol to offset their emissions, so-called Certified Emission Reductions (CERs). But, perversely, there are no similar incentives for conserving existing forests. As deforestation is one of the largest of all sources of greenhouse gas emissions, accounting for about 20% of the total (for comparison U.S. emissions are about 25 percent of the total),[6] this makes no sense at all. In the original Kyoto Protocol, conserving forests was treated the same way, but in the 2001 Marrakech meeting of the Conference of the Parties, it was ruled out in an amendment. This in spite of the fact that by conserving forests we also conserve biodiversity—forest clearing is the largest driver of species extinctions, giving us a real "two-fer" here: cutting back deforestation can reduce one of the largest sources of carbon emissions as well as conserve threatened species. It can also preserve traditional lifestyles and cultures that are threatened by large-scale tropical logging.

With so much going for it, you would expect that environmental groups would be enthusiastic about using the Kyoto Protocol to promote reductions in deforestation. Yet, in fact, they were the ones who really killed this idea when it first surfaced. Some of them are opposed to it even today. This is all a part of their objection to providing firms in industrial countries with the opportunity to purchase offsets rather than reduce emissions directly. They see this in moralistic terms rather than in terms of economic efficiency: they feel that we "ought" to reduce emissions in high-cost areas, almost in the same way that friars in the Middle Ages felt that penitence was not real unless accompanied by self-flagellation. "No pain, no gain" could be their motto, playing directly into the hands of the interest groups who argue that the costs of reducing emissions are unbearable for the industrial economies. A little bit of environmental economics could go a very long way here!

This opposition notwithstanding, the CfRN is making real progress. The 2005 Montreal Meeting of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed that deforestation is a major contributor to climate change and set in motion a process for investigating how financial mechanisms can be used within the Kyoto Protocol to provide incentives to reduce deforestation.[7] The obvious option is to treat deforestation like any other emission and agree that reducing it generates credits. For this to happen, the members of the CfRN would assume positions in the protocol similar in some respects to those of the industrialized countries: they would agree to emissions limits and would then be entitled to credits for remaining within these. The involvement of a large

[5] See www.rainforestcoalition.org.

[6] See the IPCC's Third Assessment Report at www.ipcc.ch.

[7] The motion to this effect was proposed by Papua New Guinea, supported by Costa Rica. I had the honor of being a member of the delegation from Papua New Guinea.

group of developing countries in such a Kyoto mechanism would be a politically salient development.

My close involvement in this process has served to reinforce my belief in something that I always tell my students—a little economics (in this case of the environmental kind) goes a very long way. Working on the research frontiers tends to make us undervalue the most basic principles of our subject, but in fact they are very powerful and represent a way of thinking that adds tremendous value to what otherwise seems to be common sense.

Let me try to summarize my thoughts on what we have contributed to the analysis of climate change. There is a real danger of feeling frustrated that we don't have any single simple clean solution to offer, and of feeling that because of this we have not contributed as much as we should have. But, in fact, we have had a huge and beneficial impact on the terms in which this debate is conducted, and steered politicians and environmental groups away from some very serious mistakes. Our ideas have probably reduced the overall costs of attaining any level of emissions reductions by at least a half and probably much more. Our most basic insight, that the emission of greenhouse gases is an external cost that has to be internalized, is of course the most fundamental one in this area. If we could only get the prices of energy sources to reflect their social costs, we would be a long way towards a solution.

Biodiversity and Ecosystems: A New Paradigm

Another major environmental problem is biodiversity loss. I mentioned it above in the context of climate change and deforestation, and it is true that deforestation links the two because it is a driver of both. But logically the two are separate. I think that as a profession, we have had some difficulty in articulating why biodiversity loss matters, and in finding tools that allow us to address this in a fully satisfactory way. However, in recent years, we have made a lot of progress. I want to quote something that Ed Barbier and I said recently in *The Economists' Voice* (Barbier and Heal 2006):

> A new paradigm is emerging in environmental economics. It views the natural environment as a form of capital asset, *natural capital*. This is fully in keeping with what is happening in other areas of economics, where alternative forms of capital are central to analyses that have become influential—human capital, intellectual capital and social capital being notable examples.
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> Natural capital consists not only of specific natural resources, from energy and minerals to fish and trees, but also of interacting *ecosystems*. Ecosystems comprise the abiotic (nonliving) environment and the biotic (living) groupings of plant and animal species called communities. As with all forms of capital, when these two components of ecosystems interact, they provide a flow of services. Examples of such ESS include water supply and its regulation, climate maintenance, nutrient cycling and enhanced biological productivity.
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> This newly emerging area of environmental economics is concerned with the identification and analysis and valuation of these ESS. What are they? How do they affect human societies? How do the actions of human societies affect them? In short, what are the *values* arising from ESS and why should humankind care about these values?

In grappling with biodiversity loss and how and why it matters, we are forced to think about ecosystems: biodiversity is a fundamental part of an ecosystem, and its loss is thought by biologists to affect mainly the robustness and productivity of ecosystems. We can think of ecosystems as capital assets. Ecosystems matter economically because they provide services that are of great value to human societies.

This new natural-capital–based paradigm sees the environment as a source of services that improves human wellbeing: these services are ESS and the ecosystems that support them are a part of our stock of natural capital.[8] The ESS are a return on the natural capital: they are what we get in return for investing in rebuilding or conserving this capital. For example, when New York City invested over $1 billion in restoring the Catskills watershed, this investment yielded a continuing flow of ESS of great value to the city (see Heal 2000 and National Research Council 2005). If we invest in conserving a wetland, then the wetland is natural capital and the services that it provides, such as water cleansing and wildfowl support, are the services that we get as a return on our investment. According to the Millennium Ecosystem Assessment, "ecosystem services are the benefits people obtain from ecosystems" (Millennium Ecosystem Assessment 2003, p. 53). Such benefits are typically described as follows (Daily 1997, p. 3):

> Ecosystem services are the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life. . . . In addition to the production of goods, ESS are the actual life-support functions, such as cleansing, recycling, and renewal, and they confer many intangible aesthetic and cultural benefits as well.

This vision of ESS and associated natural capital is important analytically because it is very productive: it allows us to bring to bear on the economics of the living environment a set of techniques from mainstream economics, including welfare economics and capital theory. Prior to the development of this paradigm, it was difficult to bring the analytical techniques that characterize much of modern economics to focus on issues arising from our interactions with the living world. Environmental economics was bifurcating into two separate spheres, "brown" and "green." The brown sphere contained issues relating to the management of pollution and the regulation of polluting industries, and was rigorous and formal. The green sphere, though no less important, was until recently characterized by a less quantitative approach and an inability to measure the concepts that were key to its operation. I see this as an exciting development because it opens up to analytical economists an area that was previously frustratingly closed. It also provides a natural framework for collaboration between economists and ecologists in understanding how and why biodiversity and its associated ecosystems matter to us.

Because there are no markets for most ESS, the issue of how to value them jumps to the fore. To value natural capital, we need to be able to measure and value the services it provides. In recognition of the importance of these issues and of the absence of widely accepted answers to most of the pertinent questions, the National Academy of Sciences–National Research

[8] See Daily (1997) for an exposition of the ecological perspective here, and Heal (2000) for a summary of the relevant economics.

Council (NAS/NRC) in 2002 set up a Committee on the Valuation of Ecosystem Services, composed of economists, ecologists, and a philosopher: its report was published last year[9] and provides a review of the techniques available for valuing ESS and their strengths and limitations. Valuing the services it provides is of course a prerequisite to valuing natural capital. One of the main conclusions was that regardless of exactly how one defines and categorizes ''ecosystem services,'' ''the fundamental challenge of valuing ecosystem services lies in providing an explicit description and adequate assessment of the links between the structure and functions of natural systems, the benefits (i.e., goods and services) derived by humanity, and their subsequent values'' (see National Research Council 2005, p. 2). Collaboration across disciplines is essential to this task.

Although the NAS report found that, to date, there has been good progress on establishing this ''mapping'' from ecological function to economic valuation for certain well-defined single ESS of aquatic systems, valuing multiple ESS typically greatly increases the difficulty of evaluation and as a result has yielded fewer successes. In fact, understanding how the biochemical state of an ecosystem affects its ability to provide services and so how human changes to that biochemical state affect service is one of the most important research topics in the conservation field right now. As economists, we can typically describe how economic activity will affect an ecosystem physically, but neither we nor our ecology colleagues have the tools needed to understand how this translates into a change in the services an ecosystem supplies and the value of the natural capital that it represents.

National Income Accounting and Sustainability

Thinking of environmental systems as natural capital, as one of several types of capital that drive a nation's economy along with intellectual, human, social, and built capital, lets us talk in a productive way about sustainability. There are many different interpretations of sustainability, and this article is not the place to review them. However, one interpretation that is certainly attractive is that sustainability involves maintaining intact the value of a nation's total capital stocks. This interpretation of sustainability allows us to deplete some kinds of capital, provided that we compensate by building up others. Maintaining the total value of capital stocks intact is not an arbitrary choice for the benchmark for sustainability: one can show that if a country maintains the value of its capital assets intact, then it can also maintain living standards intact over the long run. The precise statement is as follows: the present discounted value of welfare along an optimal path is increasing, constant, or decreasing as the value of capital stocks is increasing, constant, or decreasing.[10] This result gives us a close connection between capital stocks and long-run living standards and has given rise to a spate of work trying to assess the sustainability of the growth patterns of different countries. The World Bank (2005) has been one of the drivers of this work, with its conclusions to date summarized in its recent book *Where is the Wealth of Nations?* This shows very clearly how the composition of total wealth varies from poor to rich countries, with the former having a larger share of natural capital and the latter larger shares of human

[9] The report is available online at http://www.nap.edu/books/030909318X/html/.

[10] This is proven in several places. One is Heal and Kristrom (forthcoming). Another is Dasgupta and Mäler (2000).

and intellectual capital. It also shows that for most countries total wealth is constant or rising, though less rapidly than measured national income because of the environmental and resource costs of growth in fast-growing countries such as China. In addition, it shows that for some unfortunate countries, total wealth is falling: their paths are unsustainable and their living standards, in many cases already low, are going to fall.

Take Botswana as an example. It is a relatively prosperous, stable, and fast-growing country in southern Africa. In fact, it is one of the little-known political and economic success stories of the last half-century. Much of its wealth comes from diamond mines. Clearly diamond mining is not sustainable by any definition: diamonds are an exhaustible resource. But Botswana has used its revenues from diamonds to build up other forms of capital and offset some of its resource depletion so that its real total wealth per capita has more than trebled since 1980, in spite of the depletion of its diamond reserves (Lange 2004). Neighboring Namibia, however, while also rich in exhaustible resources as well as renewable ones through its rich ocean fisheries, has been more profligate, and its path is therefore less sustainable. Its per capita real wealth has fallen by about 30 percent over the same period.

Tables 1 and 2 show a more general set of results in this spirit from Arrow et al. (2004). Table 1 shows the results when we compute the rate of change of total capital for a wide range of countries, including two rich industrial countries (the United States and the UK), two rapidly growing developing countries (India and China), one very poor developing country (Bangladesh), one very poor developing region (sub-Saharan Africa), and one oil-exporting region (the Middle East and North Africa). The data cover the period 1970–2001.[11] The first numerical column shows domestic net investment, which is the starting point for the calculations and an estimate of investment in physical capital. To this is added expenditure on education, an indicator of investment in human capital. We then add investment (usually disinvestment) in various types of environmental capital. The third numerical column shows an estimate of the social cost of CO_2 emissions, the fourth shows the depletion of energy resources (particularly large for the Middle East and North Africa), and the next is forest depletion, large for Nepal and zero for the United States, where there has actually been regrowth of forests over the period of interest. The final column gives the sum, an estimate of total investment in all forms of capital as a percent of national income. Following the World Bank, we call this genuine investment (GI).

Clearly there are many shortcomings here, and I shall talk about correcting some of them shortly. Among the shortcomings that we do not correct are the inadequacy of educational expenditure as a measure of investment in human capital and the incompleteness of the list of categories of environmental capital whose depletion we include. Both could be serious sources of error, but it has not been possible to obtain data to take this process further. Nonetheless, the numbers that emerge make some intuitive sense. For example, for the Middle East and North Africa, a domestic net investment of +14.72 percent turns into

[11]To be precise, the coverage is as follows: Bangladesh 1973–2001, India 1970–2001, Nepal 1970–2001, China 1982–2001 (without 1994), Sub-Saharan Africa 1974–1982 and 1986–2001, ME and NA 1976–1989 and 1991–2001, United Kingdom 1971–2001, and United States 1970–2001, and are taken from the World Bank (1997).

Table 1 Derivation of genuine investment as % of GDP

	Domestic net investment	Education	CO_2	Energy	Mineral	Forest	Genuine investment
Bangladesh	7.89	1.53	0.25	0.61	0.00	1.41	7.14
India	11.74	3.29	1.17	2.89	0.46	1.05	9.47
Nepal	14.82	2.65	0.20	0.00	0.30	3.67	13.31
Pakistan	10.92	2.02	0.75	2.60	0.00	0.84	8.75
China	30.06	1.96	2.48	6.11	0.50	0.22	22.72
Sub-Saharan Africa	3.49	4.78	0.81	7.31	1.71	0.52	−2.09
Middle East and North Africa	14.72	4.70	0.80	25.54	0.12	0.06	−7.09
UK	3.70	5.21	0.32	1.20	0.00	0.00	7.38
United States	5.73	5.62	0.42	1.95	0.05	0.00	8.94

Source: Arrow et al. (2004)

Table 2 Genuine investment corrected for total factor productivity growth and population growth

	Genuine investment	Growth of genuine wealth (GW)	Population growth	Growth of GW per capita	TFP growth	Final growth genuine wealth per capita	Growth GDP per capita
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	2.06	1.13	0.59	2.21
China	22.72	3.41	1.35	−3.05	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 and							0.74
North Africa	−7.09	−1.06	2.37	−3.43	−0.23	−3.82	0.74
UK	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

Source: Arrow et al. (2004)

a total savings rate of −7.09 percent after allowing for the depletion of energy resources. These results draw attention to the fact that this part of the world lives unsustainably by depleting an exhaustible resource and is not compensating for this by building up its other capital stocks. Sub-Saharan Africa is also shown to be living unsustainably, a tragic and not surprising result. Allowance for the impact of HIV/AIDS on human capital would probably make its total investment number even worse. The remaining countries all appear from these numbers to have positive total investment and so to be meeting one of the criteria for sustainability, namely that the present value of future welfare obtainable from capital stocks be nondecreasing.

However, all of these numbers omit two factors that could be important: one is population change, a real issue in several countries, and the other is technical change. A higher rate of population growth will presumably increase the level of investment required to maintain constant living standards. This means that the numbers in table 1 will overstate the extent of sustainability with a growing population and vice versa. Technological progress will act in the opposite direction, allowing humans to extract more welfare from a given set of resources. Neither population growth nor technological progress was a part of the theory that has been developed in this area, and indeed as far as I am aware there is little or no discussion of either of these issues in the literature on sustainability or on optimal growth with environmental resources. Yet intuition suggests that they are important, and the numbers in Arrow et al. (2004) confirm this, indicating a lacuna in the theory developed so far. So we have made two modifications to the data in table 1 to adjust for population growth and technological progress.

Table 2 shows the results of these modifications. The first column is the last column from table 1, our preliminary estimates of genuine savings as a percentage of GDP. The second column gives an estimate of the growth rate of genuine wealth (GW) derived from the previous column using an assumed GDP/wealth ratio, and the fourth gives the growth rate of GW per capita, using the population growth rate given in the third numerical column. This is followed by an estimate of the growth rate of total factor productivity and then the growth rate of per capital GW adjusted for total factor productivity growth. For comparison purposes, the last column gives the conventional figure for growth of GDP per capita. Only two estimates of the growth of total wealth per capita are negative, the same two as before, but many others are probably not significantly positive. The high population growth rates of Bangladesh, Nepal, and sub-Saharan Africa all act to reduce their countries' rates of genuine savings.

Although the methodology differs in some technical details, our results are very consistent with those of the World Bank (2005), although the Bank does not allow for technical progress and covers a much greater range of countries. The Bank concludes that most resource-dependent countries are not replacing the capital that they deplete in extracting their resources and are therefore reducing their long-run welfare potential. In other words, they are living unsustainably.

This type of work, setting out a nation's balance sheet in a way that lets us see the evolution of its assets over time, brings a powerful combination of economic theory and national income accounting to bear on the concept of environmental sustainability and shows that this attractive but elusive concept can be made precise and indeed can be measured.

Market-Based Approaches to Environmental Conservation

Thus far, I have spoken of some of the intellectual contributions we have made and how these have influenced policy debates. But there is another element to our impact that is not associated with specific policy issues but is more general and almost philosophical in nature. This is the introduction of market-based approaches to environmental conservation. I believe that some years ago, Bob Solow described most environmental policies as Stalinist. I can't find the exact reference, so the story may be apocryphal, but nonetheless it's too good not to use. The point is that apocryphal or not, it is absolutely correct: far too many environmental policies have relied on telling people exactly what to do and what not to do. They have been classic command and control policies.

An example that comes immediately to mind is the Endangered Species Act (ESA) (Brown and Shogren 1998). One of the most important pillars of conservation in the United States, the ESA is also arguably one of the most controversial, and this controversy has a lot to do with its command and control nature. The central mechanism through which the ESA operates is the listing of a species as endangered. Once a species is listed as endangered, government agencies, mainly the Fish and Wildlife Service, have the power to ensure that nothing is done to further threaten the status of that species. In particular, they can prevent changes in land use that have negative effects on the species, which gives them the right to prevent development of the land or to prohibit any use of the land that is prejudicial to the species. While at first sight rational, and representative of how environmental groups typically think about such an issue, this clearly places all the costs of conserving the species on the owner of the land on which it lives, even though he or she may bear little responsibility for the species' predicament. To me, the ESA is a classic of command and control legislation, the antithesis of a market-based approach. Not surprisingly, landowners and the property rights brigade have had this act in their gunsights ever since it was passed, and the current administration is giving them the chance to get some shots on the target.

Just imagine if an enlightened economist had designed this legislation, instead of the environmental lobby. What might it look like? Its central feature might be an incentive to conserve an endangered species. Instead of triggering all kinds of limitations on land use, it might instead trigger payments for the support of the species—so much per animal or per breeding pair per year on your land. The more endangered animals you have on your land, the more the Fish and Wildlife Service pays you. If the payment were high enough, there would be an incentive to encourage and assist the endangered species. Indeed, one can even see landowners lobbying for listing, rather than against, as it would represent an alternative source of income for them. Actually, we have come quite close to this in some cases, cases in which mitigation banking has been applied to endangered species.

Mitigation banking was first introduced in connection with wetlands under the Clean Water Act of 1977 and has now spread to other types of habitat. The essence of mitigation banking is that developers are allowed to use habitat that is threatened and protected, provided that they mitigate by ensuring the conservation in perpetuity of a compensating amount of equivalent habitat elsewhere. The choice of what is a compensating amount and what is equivalent is determined by the appropriate conservation authority. In particular, compensation may be at a rate of more than one for one, which means that more than one acre of land is set aside elsewhere to compensate for the use of one of the original acres. A developer may, in addition, conserve more equivalent land than required and hold this excess to sell to others who want to develop yet do not want to be involved in finding and conserving equivalent space. This process of creating equivalent conserved land in excess of immediate requirements to hold for future sale to others who need to mitigate is mitigation banking and is now a well-developed practice in some areas.[12] Landowners as a group probably neither gain nor lose, but there is a redistribution within the group (Heal 2006).

The classic example of mitigation banking is the red-cockaded woodpecker, so let me explain what happened there. The red-cockaded woodpecker, *Picoides borealis*, is endangered and nests in forests owned by International Paper (IP). IP and the Fish and Wildlife Service agreed on a target number of breeding woodpecker pairs. Provided that this target number is attained or exceeded, IP will be regarded as complying with the ESA, whatever use they

[12]See for example www.wildlandsinc.com as an illustration of a company in the mitigation banking business.

make of the land (for details, see Bayon 2002, Bonnie 1999, and Bonnie and Bean 1996). Further, the agreement provides that any surplus breeding on the land can be "banked," that is, used by IP to offset ESA requirements with respect to red-cockaded woodpeckers elsewhere. It is also possible that title to surplus could be sold to other landowners and used by them to gain some measure of exemption. This ability to store or sell the surplus over the amount required by regulations is mitigation banking. As the excess of nesting pairs over a target is saleable, IP now actually has an economic incentive to encourage the endangered species, something it never had with a strict interpretation of the ESA. A few years ago, IP was able to sell banked breeding pairs for about $100,000 per pair. If several pairs can nest on each acre, this means that the value of land for breeding woodpeckers is greatly in excess of its value as a source of timber.

It is encouraging to see some economic rationality creeping into the ESA,[13] but it may well be too late for the Act to survive. It would have been so much better if someone had thought about incentive compatibility before the Act was drafted, rather than several decades later.

There are many advantages to market-based policies, and incentive compatibility is certainly one of them. I'm no expert in political economy, but it seems to me that there are political advantages to having a system that works through incentives. It is much harder to work up opposition to a provision that can give people money than to one that prevents them from making it or takes it away from them. If there is such a thing as the political sustainability of legislation, then I think it must come in part from offering options to people rather than taking them away. This is the old lesson about subsidies being hard to remove, but in another form. We should learn from the political durability of subsidies. But the main advantages of a market-based approach are the ones we all know and take for granted—efficiency under the right conditions, cost-effectiveness, and, of course, decentralization. By giving people incentives to do what society wants and then leaving them to choose how to do this, we enlist their knowledge of specific circumstances (as so lucidly explained in von Hayek's [1945] classic, "The Use of Knowledge in Society"), and also give them an interest in developing better ways of reaching the social goal. The market for SO_2 emissions, established as a part of the 1990 Amendments to the Clean Air Act, illustrates the same point. The costs of removing SO_2 from power station flue gases fell rapidly once the emissions-trading regime was in place, reflecting the incentives established to find less expensive ways of meeting or exceeding target emissions (Carlson et al. 2000). Markets aren't a panacea, but under the right conditions they work efficiently and with little bureaucracy, and they represent low-maintenance solutions.

Textbooks will tell us that two key shortcomings of markets are their failure to allocate public goods efficiently and the fact that the interests of future generations are not represented. The public good point has to be taken seriously, as so many ESS are public goods. But the cap and trade systems that we have discussed, both for CO_2 under Kyoto and SO_2 under the 1990 Clean Air Act Amendments, are set up to deal with public goods. Atmospheric quality, after all, is unambiguously a public good. It is interesting to understand what has happened here. We have not solved the fundamental problem of incentive compatibility in the provision of public goods: a cap and trade mechanism leaves the decision about the level at which a public good is to be provided to the political process. This is the cap, and it

[13] The NGO Environmental Defense played a major and constructive role here.

is the fundamental resource-allocation decision where incentive-compatibility issues arise. Once the cap is chosen, we use the market to decide how best to meet it. So the role of the market here is limited, but nevertheless important and constructive. Thus, with cap and trade systems, we are allocating goods with a mix of economic and political mechanisms.

Representing the interests of future generations raises hard issues. Analytically, our profession has thought a lot about this: much of the literature I have mentioned on sustainability and intertemporal welfare economics focuses on defining and striking the right balance between the present and the future. But is this something that we can expect a market to implement, or do we need some other form of governance to manage this well? This is not clear. It seems like a very hard problem. One argument is that the present generation naturally thinks about the interests of their successors, their children and grandchildren. To the extent that this happens, the interests of the future are reflected in current choices. There are also groups that see representing the interests of future generations as an explicit part of their mission: some environmental nongovernment organizations see themselves in this light. An interesting example is the UK's National Trust, whose motto is "For Ever, For Everyone." The National Trust's aim is to conserve land and property of outstanding value "For Ever, For Everyone," that is to acquire and hold and manage it so that it is broadly accessible and will be preserved in perpetuity.[14] It has significant purchasing power and can act to buy and to receive gifts, and has been effective in its stated aim of representing the future. At a more empirical level, several authors, such as Kay and Mirrlees (1975), have noted that in the history of industrial societies, the present has never obviously short-changed the future: each generation has been better off than its predecessors. Investment in physical capital and intellectual capital always seems to have passed on to the next generation a capacity to exceed current living standards. Progress has been continuous and cumulative. But there are counterexamples outside the world of industrial societies, as Jared Diamond's (2005) book *Collapse* illustrates. And the central concern in the sustainability literature is that as the stresses we impose on the environment grow almost exponentially, the past may not be a good guide to the future.

Fisheries Management

The last topic I want to talk about is fisheries. This is a very frustrating topic: there is probably no other area of environmental and resource economics where there is so great a gap between real-world performance and what might be achieved if our recommendations were followed. The statistics on the state of the world's fisheries are intensely depressing. Sensible estimates suggest that the biomass of fish in the world's oceans is today perhaps one tenth of what it was half a century ago, and is declining.[15] Even if there is a significant margin of error in this estimate, it is shocking. We are extracting fish from the seas at a rate greatly in excess of the reproduction rate. The stock is falling, and this has been so for a long time. No model of optimal fisheries management would support this.

There are some shortcomings in the standard models of fisheries management, and we need to work on these. Perhaps the main shortcoming is that they model the management

[14]See its web site at http://www.nationaltrust.org.uk/main/.

[15]For a survey see the Report of the Pew Oceans Commission available at www.pewoceans.org. See also Worm et al. (2006).

of a unique species in isolation, whereas in reality fish are part of complex ecosystems, with their dynamics being governed to a large degree by the predator-prey interactions. Typically, these interactions are omitted from our models.[16] This suggests that our models may have been overly generous in predicting acceptable take levels, but the sad fact is that actual levels have been vastly in excess of what our models suggest as reasonable. This is easy to see: with a long-run optimal policy, stocks should be constant, whereas they have fallen very significantly.

It is in fisheries more than any other area that one has to confront the political limitations on adopting rational economic policies. The difficulties here seem to be even greater than with climate change, which, for all the deliberate obstruction and obfuscation from some energy companies, is nevertheless firmly on the world's agenda. Fishing industries are able to block sensible policies every time they are considered, and few governments feel a need to implement even the limited fisheries protection measures that they have in place. Within the last few years, two major commissions, the Pew Oceans Commission and the United States Commission on Oceans Policy, have both written extensive and persuasive reports indicating the need for major reforms to U.S. fisheries management legislation and institutions,[17] yet until very recently none of their recommendations had been adopted.[18] Given the importance of fish as a source of protein, especially in developing countries, the long-term human consequences of current policies could be very costly indeed.

Final Reflections

Many environmentalists, when asked how to resolve our pressing environmental problems, reply that we need a new vision of the relationship between humans and nature. Only with a radical new vision of how we relate to the natural world can we save the planet from the forces of modern technology and economic growth, they argue. Few go on to offer any persuasive details of this new relationship, except to talk about renewable energy, greater energy efficiency, less consumption, and perhaps a new appreciation of the value of nature. Because of the lack of specificity, these visions, while alluring to some, rarely have much practical impact.

My concluding point is that if we want a practical vision of a new and more harmonious relationship between humans and nature, we can find it in environmental economics. Just imagine, for a moment, a world in which all of our recommendations are in place. All external effects are internalized. The importance of natural capital and the services it provides are recognized and feature in national income accounts and in public decision-making. The public good nature of many environmental services is acknowledged, and institutions are in place to manage their provision. Adequate weight is given to the interests of future generations through the roles of interest groups and the selection of discount rates.

In such a world, there really would be a harmonious interaction between human society and the rest of the natural world. Environmental problems, in the sense in which we in economics think of them, would be solved. Our field provides a blueprint for the harmonious

[16] An exception is Carson et al. (2006).
[17] www.pewoceans.org and http://www.oceancommission.gov/.
[18] In December 2006 Congress reauthorized the Magnuson Stevens Act and included in the new bill some of the recommendations of the two commissions.

relationship with the natural world that so many wish for yet are not able to describe in any detail. There is a powerful vision behind environmental economics, a vision that can resolve the environmental tensions and problems that concern so many. We need to articulate this more clearly.

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