Environment on the Edge

2004/05

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The United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC) is the biodiversity assessment and policy implementation arm of the United Nations Environment Programme (UNEP), the world's foremost intergovernmental environmental organization. The Centre has been in operation for over 25 years, combining scientific research with practical policy advice.

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CONTENTS

The day after tomorrow — 6
Sir Crispin Tickell

Oceans on the edge — 18
Dr Jane Lubchenco

Antarctica on the edge? — 33
Professor Chris Rapley

Biodiversity on the edge — 47
Dr Cristián Samper

Transport on the edge — 57
Dr Bernard Bulkin

The Day After Tomorrow

Sir Crispin Tickell

Environment on the Edge

It is a relatively new idea that among the hazards that attend the life of every human being is a global danger arising from the pressure that human activities are exerting on the environment. In one sense environment has always been on the edge, and always will be. It is just that the shortness of our lives and the narrowness of our perspective on Earth's history mean that we are mostly unaware of change, and until now have scarcely noticed the pressures on the environment.

The last couple of centuries have seen an extraordinary stretching of our understanding of space and time. We can now look beyond the solar system, beyond our galaxy, beyond billions of other galaxies – back to the big bang that initiated the universe we know. As for time, we can look beyond the last thousand years, beyond the beginnings of civilization, beyond the patch of warmth in the last 12,000 years, beyond the many spasms of the ice ages, beyond the multicellular, eukaryotic organisms, and further back still over more than 3 billion years to the origins of life itself.

During these almost unimaginable stretches of time, the environment has been on many edges. There have been big hits from space, the changing relationship between the Earth and the sun, the slow movement of tectonic plates on the Earth's surface, major volcanic eruptions, and not least the influence of life itself. The tightly linked living organisms on the Earth's surface work as a single self-regulating system, tending to create and maintain the environment most favourable to them. Over time the environment has tipped many ways, sometimes violently, to the detriment of this or that ecosystem. There have always been correctives; life itself is robust. Yet today one small animal species – our own – is tipping the system in ways whose consequences cannot be foreseen.

The idea may be hard to accept, but the Earth has never been in this situation before. In the words of the title of a recent book on environmental history, we confront *Something New Under the Sun*. These points were well brought out in a remarkable *Declaration* published by some 1,500 scientists from the four great global research programmes[1] in Amsterdam in July 2001. They stated squarely that human-driven changes to the Earth's land surface, oceans, coasts, atmosphere and biodiversity:

> *… are equal to some of the great forces of nature in their extent and impact.… Global change is real and happening now.*

1 International Geosphere-Biosphere Programme; International Human Dimensions Programme on Global Environmental Change; World Climate Research Programme; DIVERSITAS, the international programme of biodiversity science

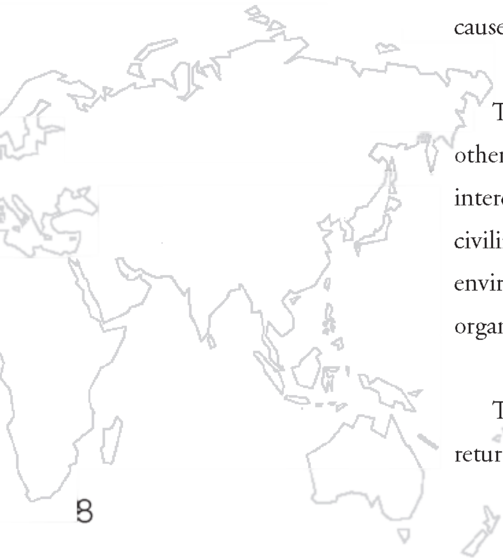
Environment on the Edge

… Human activities have the potential to switch the Earth System to alternative modes of operation that may prove irreversible and less hospitable to humans and other life.… The nature of changes now occurring simultaneously in the Earth System, their magnitudes and rates of change are unprecedented. The Earth is currently operating in a no-analogue state.

… The accelerating human transformation of the Earth's environment is not sustainable. Therefore the business-as-usual way of dealing with the Earth System is not an option. It has to be replaced, as soon as possible, by deliberate strategies of good management that sustain the Earth's environment while meeting social and economic development objectives.

The problem is almost on a geological scale. No wonder the Nobel Prize winner Paul Crutzen, with his colleague Eugene Stoermer, should have named the current epoch the "Anthropocene" in succession to the Holocene.

How did we get into this situation? Let us look at recent human history. At each stage in the development of current society, the impact has increased. Hunter-gatherers fitted easily enough into the ecosystems of cold and warm periods in the Pleistocene epoch. But farming with land clearance changed everything. With a vast increase in human population came towns and eventually cities. Tribal communities evolved into complex hierarchical societies. Before the industrial revolution, some 250 years ago, the effects of human activity were local, or at worst regional, rather than global. All the civilizations of the past cleared land for cultivation, introduced plants and animals from elsewhere, and caused a variety of changes.



This ability to influence other species has given us a profound conceit of ourselves. Yet our use of other species is coupled with an amazing ignorance of how natural systems work, their awe-inspiring interconnectedness, and our total reliance on natural services. There have been some 30 urban civilizations before our own. All eventually crashed. Why? The reasons range from damage to the environmental base on which they rested to the mounting costs in human, economic and organizational terms of maintaining them.

There has been a worsening conflict between humans and the rest of living nature. I have just returned from China, where this conflict is painfully visible. As one of my Chinese hosts remarked, we are exploiting natural resources on an epic scale. According to him: "During the 20th century humans consumed 142 billion tonnes of petroleum, 265 billion tonnes of mineral coal, 38 billion tonnes of iron, 760 million tonnes of aluminium and 480 million tonnes of copper." This depredation cannot continue indefinitely.

As for the future, some may have heard some remarkably gloomy predictions from the Astronomer Royal Sir Martin Rees. In his new book *Our Final Century* (the publishers removed the question mark after the title), he explores the dangers arising from human inventiveness, folly, wickedness and sheer inadvertence. The ramifications of information technology, nanotechnology, nuclear experimentation and the rest have still to be understood and explored. His conclusion is to give our civilization only a 50 per cent chance of survival beyond the end of this century. James Lovelock recently gave a comparable warning. He wrote:

> *We have grown in number to the point where our presence is perceptibly disabling the planet like a disease. As in human diseases, there are four possible outcomes: destruction of the invading disease organisms; chronic infection; destruction of the host; or symbiosis – a lasting relationship of mutual benefit to the host and the invader.*

It seems to me that there are six main problems that have pushed the environment to the edge. They arise from human population increase; degradation of land and accumulation of wastes; water pollution and supply; climate change; energy production and use; and destruction of biodiversity.

Of these factors, population issues are often ignored as somehow too embarrassing or mixed up with religion and the ideology of development. Most people are broadly aware of land and waste problems, although far from accepting the remedies necessary. Water issues, both fresh and salt water, have received a lot of publicity, and already affect most people on this planet.

Climate change, with all its implications for atmospheric chemistry, is also broadly understood, apart from by those who do not want to understand it. How we generate energy while fossil fuel resources diminish and demand increases is still a conundrum.

But damage to the diversity of life of which our species is a small but immodest part has somehow escaped most public attention. Yet according to IUCN–The World Conservation Union, current extinction rates are between 1,000 and 10,000 times greater than they would naturally be.

All these issues are interlinked, and all represent pressure on the environment. Coping with all or any of these issues requires two fundamental changes: first, recognition that they exist, and second – and eventually – readiness to do something about them. This process may take some time. The story of how ozone depletion was recognized, and international action followed, is a classic example of success. The story of climate change is only halfway there. Many in the Bush administration are still in a state of denial, but elsewhere in the United States attitudes are changing fast, and I believe that, in the end, concerted international action to limit the emission of greenhouse gases will be taken.

Nothing is more difficult than learning to think differently. The problem is wider than ozone depletion or even climate change, and goes to the roots of how we run our society. It relates to our value system. Any change in a system that gives primacy to market forces, exploitation of resources and ever-rising consumption will be uncommonly difficult.

At present we seem to want to attach monetary value to almost everything. But how do we give a monetary value to pollution of the atmosphere, acidification of the oceans, loss of a species or supply of such natural services as microbial disposal of wastes? Of course some rule-of-thumb method of assessing and comparing values would indeed be useful, not least in giving comfort to economists and more plausibility to their models. But somehow we have to bring in the factor of environmental costs. As has been well said, markets are superb at setting prices but incapable of recognizing costs.

Definition of costs requires a new approach towards economics and above all towards how we measure things. In addition to the traditional costs of research, process, production and so on, prices should reflect the costs involved in replacing a resource or substituting for it, and the costs of the associated environmental problems. Here the Chinese government has recently taken the lead. It has actually applied the principles of “clean green growth” in the province of Shanxi, with startling results.

Neither state-directed economics nor market economics can alone supply the right framework. Again, as has been well said, the economy is a wholly owned subsidiary of the environment. Governments have a particular responsibility to determine what is in the public interest, and to use fiscal instruments to promote it. But they can scarcely do so without public understanding and support.

It is also extremely difficult for governments to take action outside a broad international consensus. Such action can look needlessly damaging to the national interest unless others do the same. It is, for example, obvious that the current exemption of aviation and bunker fuel from taxation is absurd and profoundly damaging to the environment. It is one of many distortions of energy policy that still sees subsidies going to fossil fuel extraction (some $73 billion a year in the 1990s). Rhetoric about competitiveness as an excuse for environmental abuse fills the air in the United Kingdom as elsewhere.

The sad truth is that global institutions are still feeble. We seem to have an exaggerated expectation of what they, and international conferences, can achieve. Look at what happened – or did not happen – at the World Summit on Sustainable Development in Johannesburg in 2002. Perhaps the most damning comment came from Hugo Chavez, the president of Venezuela. He said: “Sometimes our heads of state go from summit to summit, while our people go from abyss to abyss.”

Most of the solutions to the problems we have caused are well known. Take human population increase. The overall rate is still rising, but in several parts of the world it is levelling off. The main factors are improvement in the status of women, better provision for old age, wider availability of contraceptive devices, lower child mortality and better education, especially for girls and young women.

Even so, according to the first UN Millennium Ecosystem Assessment report, if current trends are anything to judge by, in 2050 we may well have a population of 3 billion more people, bringing the total to around 9 billion. Yet when I was born, the population was around 2 billion. If this rate of increase was in swallows, spiders or elephants, we should be scared silly. But because it is ourselves, we accept it as almost normal.

Take degradation of land and water. We know how to look after them both if we try. We do not have to exhaust topsoils, watch them erode into the sea, rely upon artificial aids to nature, eliminate the forests with their natural wealth of species or poison the waters, fresh and salt. Take the atmosphere. We do not have to rely on systems of energy generation that will affect climate and weather in a fashion that puts an overcrowded world at risk.

But in order to concert action we need institutions for the purpose. The United Nations is basically an association of sovereign states, even if real sovereignty is leaking away from them all the time. Beyond and above the international debating society that is the UN General Assembly is the Security Council for the regulation of peace and war. Much of its role is reactive, and its scope for taking action to head off conflict is limited.

Then there are the International Court of Justice, to which few states now risk submitting their disputes; the various specialized agencies and associated bodies; then the multilateral corporations, the banks, the media controllers, the drug empires, the criminal syndicates and others essentially outside the current system; the non-governmental organizations which, though not accountable except to their members, try to represent citizens' interests; and now increasingly the information systems of the Internet and the world wide web, also outside the system.

There is a particular imbalance. On the one hand we have the World Trade Organization, the International Monetary Fund and the World Bank, which are all institutions with real mechanisms for influencing government policy. They are much stronger on trade and finance than on the environment, and tend to be driven by vested interests looking for short-term profitability. By contrast, the 200 or more environmental agreements are dispersed and poorly coordinated, have different hierarchies of reference and accountability, and look principally to the long term.

I have long argued for the creation of a World Environment Organization to balance – and be a partner of – the World Trade Organization. The last director of the World Trade Organization took the same view. If ever we are to cope with the consequences of the environment going over the edge, we shall need something of this kind.

So at the moment, neither public understanding of how and why environment is on the edge nor the mechanisms for coping with the results yet exist. Nor have we reckoned with the indirect effects.

High among them is the understandable desire of most poor countries to follow the industrial countries in exploiting natural resources to the full, raising living standards and participating in the consumer culture characteristic of the mindset of most modern societies.

Yet in many ways this is an impossibility. Over the last few years stock market indices may have risen, but the world's natural wealth, measured by the health of its terrestrial, freshwater and marine species, fell by no less than 40 per cent between 1970 and 2000. The World Wide Fund For Nature's *Living Planet Report* shows that the development on which so many countries are bent ignores ever-increasing human pressure on the biosphere. In 2001, humanity's ecological footprint exceeded the Earth's biological capacity by about 20 per cent. This underlines the need to avoid the misleading characterization, based on a false biological analogy, of "underdeveloped", "developing" and "developed" countries.

The division between the world's rich and the world's poor is a prime and growing source of insecurity for all. At present about 20 per cent of the world's people consume between 70 and 80 per cent of its resources. That 20 per cent enjoy about 45 per cent of the world's meat and fish, and use 68 per cent of electricity (most of it generated from fossil fuels), 84 per cent of paper and 87 per cent of cars. The division between rich and poor is not only between countries but also within them.

New elites in such countries as China and India are now acquiring similar purchasing power to the middle classes in industrial countries. For example, increased meat consumption by middle-class Chinese already threatens to perturb world grain markets as more cereal is needed for cattle feed. The contrast is increasingly between small numbers of globalized rich and large numbers of localized poor.

Some economists suggest that market forces will eventually bring their version of development to all. The trends in subsequent issues of the UNDP (United Nations Development Programme) *Human Development Report*, especially that of 1999, suggest the opposite. Living conditions have certainly improved for many people over the last 250 years, and most people are living longer. But with ever-rising population and increased pressure on resources, it is hard to see how this can continue.

Our ability to respond to change is constantly being diminished. More people than ever are fleeing poverty, water and food shortages, health problems, storms, floods and droughts, and by most reckonings the number of environmental refugees will greatly increase. In a world where the Internet lets knowledge travel ever wider, ever faster, inequalities in living conditions are becoming more generally known and felt.

Accepting all the difficulties, we still need to work out what should be done. Looking over all the problems of the environment, I have my own list of priorities, for what it is worth:

- We need urgent action on climate change. Like Sir David King, the UK government's chief scientific adviser, I think that it represents "the most severe problem we are facing today, more serious even than terrorism". Global dimming from pollution has become an unexpected, even if temporary, counterpart of global warming. Urgent action on energy policy in all its aspects is now essential. So much has been said on this that I will not repeat it. But sucking up to car drivers or calling for new airports does not suggest that all politicians have yet understood what is at stake. I doubt whether technical wheezes – mirrors in space, windmill extractors, iron sprays in the oceans, cloud whitening and the rest – could ever do much to help. They would probably create more problems than they solved. But I am, of course, in favour of carbon capture and sequestration. I am also in favour of a government review of the true costs of all sources of energy, including nuclear.
- We need to do far more to educate public opinion, not least in the financial and investment communities. Here many initiatives are pending, with the support of the industries and businesses likely to be affected. The insurance industry is very much aware of the problems. I welcome the recent statement by the chief executive of BP that "paradigm shifts must occur across the economy".
- As I have already said, we need to look again at economics and the way we measure wealth, welfare and the human condition in terms of the Earth's good health.
- We need to apply the principles of common but differentiated responsibility, accepting that industrial countries have much bigger responsibilities for what has gone wrong as well as what has gone right, and should set the example in their domestic policies.
- For other countries, we need to help them make best use of their resources and particular circumstances, avoiding any universally applicable blueprint for improvement in their condition.
- We need to do far more to understand natural ecosystems and promote conservation. The Millennium Ecosystem Assessment should help.
- We need to make better use of technology and its myriad applications. We also need to understand

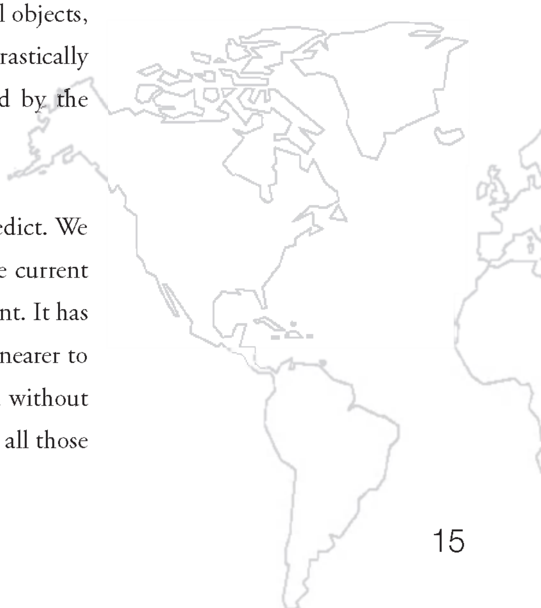
the hazards, particularly regarding pollution. Risks are hard to assess. The short term must not be allowed to defeat the long term.

- We need to focus on the needs and attitudes of coming generations – in short, give new direction to the educational process. The process in industrial countries, as in any other country, is rightly called capacity building.

All involve the ability to accept accelerating change, to learn to think differently and ultimately to behave correspondingly. We all suffer from the disease of what has been called conceptual sclerosis. Change is rarely linear. There are sudden breaks, unforeseen thresholds, uncomfortable shocks. In bringing about change we need three things: leadership from above; public pressure from below; and, usually, some instructive disasters to jerk us out of our inertia. There are many examples of all these: leadership on ozone depletion or climate change; pressure on disposal of industrial wastes, including oil rigs; and catastrophes over destruction of topsoils and their fertility.

This brings me to prospects for our future. If present trends continue, we may well push the environment over the edge with consequences that include potentially unfavourable conditions for ourselves. But let us assume that we survive this century. In peering further ahead, it may be useful to jump a few hundred years, accepting that our ability to look even 20 years ahead is extremely limited. If statistical projections from the past have value, there will certainly have been some sudden disruptions before 2500, whether volcanic explosions, earthquakes, impacts of extraterrestrial objects, or even destructive wars using unimaginably horrible weapons. Ecosystems will be drastically changed, as after extinction episodes in geological history. Human health will be affected by the development and spread of new pathogens.

How our successors, if there be such, will react to these new circumstances we cannot predict. We must always expect the unexpected. But it is hard to believe that there will be anything like current human numbers in cities or elsewhere. Their distribution will almost certainly be very different. It has been suggested that an optimum population for the Earth in terms of its resources would be nearer to 2.5 billion rather than – as now – 6.2 billion. Communities are likely to be more dispersed without the daily tides of people flowing in and out of cities for work. People may even wonder what all those roads were for.



There is also the possibility, however sinister, of differentiation of the human species. H.G. Wells invented Eloi and Morlocks (those up above and those down below), and at the time, more than a century ago, it seemed an amusing fantasy. No longer. Redesigning humans has become a real possibility. Through genetic manipulation, humans could split into distinct varieties and, over time, into subspecies. It is worth remembering how vulnerable even the Eloi were. Lee Silver explored some of these ideas in his 1998 book *Remaking Eden*.

Then there is the development of information technology. On the one hand humans may take enormous advantage from such technology and thereby be liberated from many current drudgeries. Soon cars will book themselves in for servicing, hospitals will consult online diaries before scheduling an appointment, and trawlers will sell their catch at market before reaching port. All this seems unimaginable while elsewhere others still trudge miles to collect fuelwood and water.

On the other hand, humans may become dangerously vulnerable to technological breakdown, and thereby lose an essential measure of self-sufficiency. Already dependence on computers to run our complex systems, and reliance on electronic information transfer, are having alarming effects. Here industrial countries are far more vulnerable than others. Just look at the effects of single and temporary power cuts. More than ever, individuals feel out of control of even the most elementary aspects of their lives.

The implications for governance reach equally wide. Already there is a movement of power away from the nation state: upwards to global institutions and corporations to deal with global issues; downwards to communities of human dimension; and sideways by electronic means between citizens everywhere. There is a wide range of possibilities, including forms of dictatorship and disaggregation of society.

The problems of politics will be as difficult as they are today: how to ensure greater citizen participation without creating chaos; how to establish forms of accountability to ensure that governance is by broad consent; and how to establish checks and balances to protect the public interest and ensure enforcement without abuse.

Let us hope that by then, humans will have worked out and will practise an ethical system in which the natural world has value not only for human welfare but also for and in itself. Humans may also be involved in spreading life beyond Earth and colonizing Mars or other planets. The opportunities for our species seem as boundless as the hazards.

Working together, we may merit our survival. But our long-term prospects cannot be assured. We may have to regard our present civilization as a failure, an experiment which did not work, or which sank under the weight of its own rapacity. There is a touching Chinese poem from the time of the Tang dynasty with a message of hope: “Thousands of boats pass by the side of the sunken ship. Ten thousand saplings shoot up beyond the withered tree.”

But supposing the boats do not pass and the saplings do not shoot up. How long would it take for Earth to recover from the human impact? How soon would our cities fall apart, soils regenerate, the animals and plants we have favoured find a more normal place in the natural environment, the waters and seas become clearer, the chemistry of the air return to what it was before we polluted it? Life itself, from the top of the atmosphere to the bottom of the seas, and even below that, is so robust that the human experience could become no more than an episode.

Above all, let us remember how small and vulnerable we are as creatures of a particular environment. We are like microbes on the surface of an apple, on an insignificant tree, in an insignificant orchard, among billions of other insignificant orchards stretching over horizons beyond our sight or even our imagining.

Sir Crispin Tickell GCMG, KCVO, DCL is Chancellor of the University of Kent.

Oceans on the Edge

Dr Jane Lubchenco

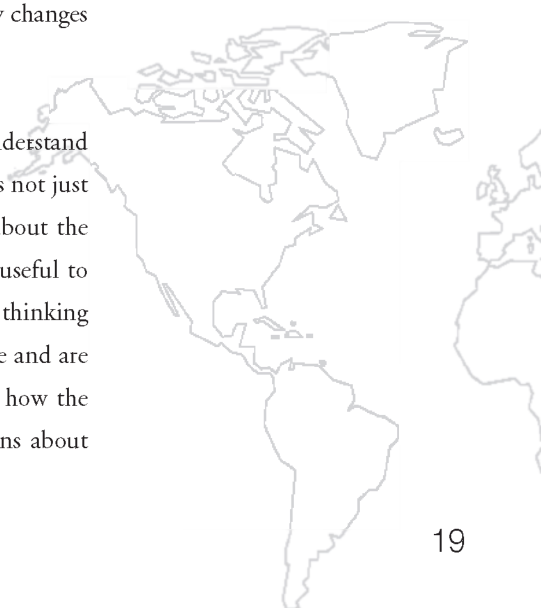
The aspect of the environment I am concerned with is the oceans, but I will begin with the role of science: both its broad role in today's world and its more specific role as we learn about changes in the oceans and consider how to respond to them. Then I want to set a broader stage for the global context and global changes that are under way. What is happening in the oceans is also, of course, happening on a larger scale, and we need to start with this big scale, then move to the only slightly smaller scale of oceans. Lastly I will discuss oceans at risk, the scientific knowledge we have about what is changing, the possible solutions, the choices that we have as individual citizens and as institutions, and the future.

The role of science

If you ask politicians around the world about the historical role of science, they usually focus on the economic or health benefits of investing in it, or on how it improves people's lives generally – extremely important reasons to invest in science and for citizens to value it.

Science has other roles in today's world which are not as commonly appreciated, in informing and helping us to understand, particularly with regard to change. Science plays a critical role in documenting changes that are happening, providing a neutral source of information that goes beyond assertions or observations that might just be correlations, and providing some historical records. From these we can gain information about whether an event represents a new development or whether it is something that just comes and goes. This is extremely important, as is understanding the consequences of any changes in light of how natural systems, social systems or natural-social systems operate and interact.

We can use our knowledge of how the Earth system and the climate system work to understand any changes that are occurring and to interpret their consequences. A critical role of science is not just to understand the past and the present but also to help us think about and make choices about the options in front of us, and their possible outcomes. In choosing to take Path A or B, it is useful to know the likely results of those decisions. So a hugely important role of science is to inform thinking about the trade-offs created by our choices – realizing that we do not have perfect knowledge and are looking ahead – grounded in our understanding of the changes that are happening and of how the systems work. And, finally, it is critically important for science to be part of the discussions about possible solutions to problems.



Global changes and their consequences

A few years ago, some colleagues and I published a paper in *Science*. We wanted to take a broad look at the global-scale changes for which there is valid scientific information published in the literature, and get away from any assertions that were being made about changes that might or might not be happening. Those we identified, ones which nobody much argues about, can help us gain a sense of some of the important global-scale changes that are under way and, in particular, the magnitude of the human contribution. The changes related to: climate, land use, biochemical cycles, water use, biodiversity and fishing.

Most of the changes directly caused by human activity have happened within the last 100 to 1,000 years. We know, for example, that humans have transformed about half of the Earth's land surface. That is a considerable amount, and most has happened relatively recently, mainly over the last 200 years. We also know that our activities have increased the carbon dioxide concentration of the atmosphere by 30 per cent since the beginning of the industrial revolution. We know that humans currently utilize about half of the available surface freshwater on the planet. We know that humans are responsible for about half of the nitrogen that is fixed on an annual basis, so we are modifying one of the major biochemical cycles of the planet by more than doubling annual nitrogen fixation. We know that we are moving invasive species around the planet. (As a non-global example, about 20 per cent of the species now in Canada are invasive.) We know that about a quarter of bird species have become extinct in the last 1,000 years, due directly or indirectly to human activities. And we know that two-thirds of the major marine fisheries are fully exploited, overexploited or depleted.

This gives us a starting point for saying that there is a broad sweep of environmental changes under way. The current time is different from any other in the history of Earth because of this footprint of human activity, and the consequences are multiple and complex. Put very simply, however, these changes taken together – climate, land transformation, disrupted biochemical cycles, water use, biodiversity and overfishing – are altering the functioning of the ecological systems of our planet, whether forests, coral reefs, wetlands or grasslands, and are in turn changing the delivery of ecosystem services to humanity.

Ecosystem services are the benefits that people receive from the functioning of intact ecological systems. The Millennium Ecosystem Assessment is a critically important new global evaluation of

the status of ecosystems and how they relate to human well-being. It categorizes ecosystem services in four general areas: provisioning services (food, water purification as it is filtered through an old-growth forest or a wetland, fuel); regulating services (climate, disease); cultural services (spiritual, inspirational, recreational, heritage, education); and supporting services (the ones that are critically important to providing those in the first three categories). The global-scale changes that are under way are modifying ecological systems and their functioning, which in turn impairs the delivery of many of these critical services. It is this connection between change, ecosystem functioning, ecosystem services and human well-being that focuses our concern on the changes that are taking place.

Loss of services has direct and indirect consequences for human well-being, and much of this is being explored in the Millennium Ecosystem Assessment. Put very simply, the connections to human well-being are very basic. Ecosystem services affect human health, basic materials for a good life, the security of people, social relations, freedom and choices.

Clearly, many different things are driving the changes that are under way, and it is this diversity and complexity that makes altering any of them a very daunting task. Nonetheless, the more information we have about the drivers of change, the consequences of change and how they affect people directly, the better position we are in to make informed choices and to try to redirect the changes.

Humanity is faced with a grand challenge unique to our time, and this is simply to make a transition to a world in which everyone's basic needs are met without compromising – and, in fact, while protecting and restoring – ecosystems and their ability to deliver the critical services upon which all life depends. That is a huge task, and it is one that we do not quite know how to go about. However, understanding the connections is a critical link in thinking through what the choices are and how we might do things differently.

Oceans at risk

I am going to turn now to ocean changes and their consequences, and some of the choices and possible solutions in front of us, concentrating particularly on four aspects: fisheries, climate change, coastal development and pollution.

Fishing is the single activity with the largest impact on ocean ecosystems today. We know that global fisheries, which were on a spectacular rise in terms of total landings throughout the last century, peaked in the 1980s and are now slowly but steadily declining. Thus, 67 per cent of global fisheries are now fully exploited, overexploited or depleted, according to UN Food and Agriculture Organization (FAO) categories. It is particularly sobering to think that this 67 per cent was only 5 per cent 40 years ago.

FAO data give a temporal sense of some of the changes. About midway through the last century, around half of fisheries were in an underdeveloped stage, but by 1970 there were none in this category. The second half of the century saw an increase in the number of fisheries in the mature or senescent stages.

Such dramatic changes in a short period of time are due to our technological capabilities to find, catch, preserve and deliver fish and seafood at rates which were formerly simply not possible. A paper by Myers and Worm, published in *Nature* in 2003, provided the startling information that about 90 per cent of the really big fish – tuna, swordfish, marlin, sharks, those icons of the oceans – have gone. Within 10 to 15 years of an industrial fishery getting under way, and before good baseline information has been taken, much of the fishery in terms of these large species is lost. So the oceans today are significantly depopulated.

Off the coasts of Oregon, we have seen a situation typical of many places around the world. We are all familiar with cod numbers, but we can also look at figures for landings of rockfish off the US west coast over the last few decades. Early on, there was a significant increase in landings and then, as is typical, an abrupt decline. There were serious pressures to continue fishing and a lack of appreciation of the fact that many rockfish are slow growing, long lived and not able to reproduce at the rate originally thought. A number of specific species of rockfish which used to be relatively abundant became so overfished that the largest fishery closure ever in the entire world was declared in 2002 – 8,000 square miles off the west coast of the United States is now closed to groundfish fishing because of the depleted nature of these stocks.

Not only do these kinds of changes disrupt marine ecosystems and specific populations, they also have significant economic and social consequences. In addition to fishery collapses and crashes, the removal of biomass from the oceans results in a number of unintended outcomes, ones that we need to understand in order to manage fisheries better. It is these factors which collectively have had such a huge impact on marine ecosystems.

First and foremost, the removal of top predators has huge consequences. Many are keystone species, apex predators. Removing them triggers cascading changes throughout the ecological system. Some kinds of fishing activities significantly alter habitat – dredging and trawling, in particular, are among the more destructive, eroding the sea floor and, in many cases, destroying very long-lived, three-dimensional structures that provide nursery areas for fish. This compounding influence makes it difficult for fisheries to recover after the habitat has been altered so significantly. By-catch – the incidental take affecting anything from other fish to turtles, marine mammals or birds – is a significant problem and often serious. It alters the size, age structure and sex ratios of the target species.

All these factors are beginning to be better understood and need to be incorporated into fisheries management. This is one of the reasons for thinking about ecosystem-based management, not just management of individual species, individual targets or clusters of similar species.

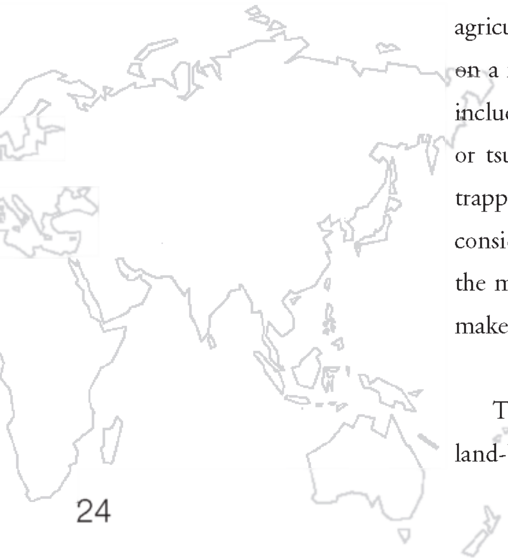
Many people think that with the oceans so depleted, fish and shellfish farming will solve the problem. In fact, the fastest-growing segments in the food production industry – salmon, shrimp and other carnivorous species of fish – depend very critically on wild-caught fish made into fishmeal, and the conversion ratios are such that continuing to catch small pelagic fish to rear salmon, shrimp, cod and so on is contributing to the depletion of wild cod species, not just relieving pressure on wild cod fisheries. Food production is critically important for the future, and we need to think how to do it more sustainably than at present. Current pressures are pushing it in an unsustainable direction, so we face a huge challenge.

Climate change is another phenomenon with enormous ramifications for ocean ecosystems. It is not only the temperature of the water and of the air that is changing. Increased water temperature affects coral reefs, for example, and we have seen significant bleaching and increases in bleaching events throughout the tropics. Rising sea levels also influence the erosion of coastal areas. And we are seeing some unanticipated and possibly very important changes in the pH of oceans. Much of the increased carbon dioxide has been absorbed by the ocean and that, in turn, will be likely to affect the rates at which corals and many phytoplankton can build their skeletons, and will impact other shell creatures in the oceans, from mussels, scallops and clams to snails. Anything that has a calcium carbonate shell is affected by the pH in oceans.

Climate change is also likely to affect the intensity of coastal upwelling – areas where many of the major fisheries are located. Upwelling is driven by winds that are a function of the difference between the temperature of the land and the temperature of the water, so as we change those temperatures, we are altering the intensity of the winds and the intensity of upwelling. These are some of the many changes that we are only beginning to be aware of with respect to how climate is affecting oceans and ocean ecosystems.

About half of the world's population lives in coastal areas, and the proportion is increasing as more and more people move to the coast. Coastal development is happening at a frantic pace, is usually based on local decisions and has very serious consequences for coastal marine ecosystems. It affects the flow of water, nutrients and sediment to the ocean, and it changes the chemistry of the atmosphere and habitat for coastal species.

One example occurs with mangroves, a critically important habitat in coastal areas around the world. About half the world's mangroves have been converted to land for human settlements or agriculture, or for shrimp ponds – an example of land transformation. For mangroves it is happening on a massive scale with wide-ranging effects. As the mangrove is transformed its ecosystem services – including the provision of fish nursery areas, the provision of food, buffering of shores against waves or tsunami, detoxification of pollutants as they come from the land and flow into the ocean, and trapping of sediments so that they do not smother downstream coral reefs – are lost. There are considerable trade-offs to be considered in balancing the pros and cons of coastal developments, and the more information we have to enable us to understand these trade-offs, the better able we are to make appropriate choices.



The last factor that is having a strong influence on coastal oceans, in particular, is a result of land-based activities and has to do with nutrient pollution. Nitrogen is the primary factor in this, but there is an element of phosphorus as well. The nitrogen in the atmosphere is not in a form that can be utilized by plants; it has to be chemically changed or fixed. Naturally – before or without humans – about 100 teragrams of nitrogen are fixed globally on an annual basis on the land by natural sources (algae and bacteria, a little bit by lightning). Over the last century, this figure has more than doubled because we are making fertilizers, planting legumes over a larger area than they would occupy naturally, and burning fossil fuels, with fixed nitrogen as one of the unintended by-products. This huge amount of nitrogen resulting from land-based activities ends up either flowing off agricultural areas, via rivers and streams, into coastal zones, or being transported by the air and deposited in the oceans.

The flow of nitrogen and phosphorus to coastal areas is having a significant impact and disrupting marine ecosystems, especially in coastal waters. As a result, two things are happening. First, we are seeing "dead zones", which are essentially the result of a bloom of phytoplankton. The herbivores in the system cannot keep up with the phytoplankton, the phytoplankton die and begin to decompose, and that uses up all the oxygen. In the United States for example, much of the nitrogen used in the Mississippi drainage basin to grow corn and soybean as cash crops is being deposited in the Gulf of Mexico. At the mouth of the Mississippi river, there is a zone of low oxygen, or hypoxia, which is growing larger and larger each year and is now about the size of the state of Massachusetts.

These are global effects. There are around 50 hypoxic zones around the world, most of which have appeared in the last 30 to 40 years, and most of which are at the mouths of areas that drain major agricultural areas.

Another outcome of nutrient pollution is the stimulation of certain types of plankton which contain toxins or are otherwise harmful. We are seeing more and more harmful algal blooms around the world, some of which can cause massive death of fish as well as affect human health.

It is sobering to look at these different effects. The oceans are changing at unprecedented rates, the complex result of multiple factors. There is no one silver bullet: it is not just climate, it is not just commercial fishing, it is not just recreational fishing, it is not just agriculture. It is all those things together, acting in concert and often exacerbating one another. This presents an enormous challenge.

Part of the reason this is occurring is because we have not been tracking what is happening, or paying it much attention. Most citizens are not aware of the changes; most political leaders are unaware of most of them, or if they are aware there is no set of solutions available; and there are vested interests promoting business as usual.

Possible solutions and choices for the future

Let us turn to the choices that are available and some of the solutions that are being explored. I have divided the choices into those for which the scientists have been actively engaged in providing new understanding, those on which governments are working, and those on which citizens' groups are concentrating.

We will start with two areas where science is providing possible solutions. One is trying to understand large marine ecosystems and how they work. There is increased talk about ecosystem-based management, but we have never really studied ocean ecosystems at that scale. On land, there are studies of forest ecosystems, wetlands and grasslands, but the infrastructural and technical capabilities to properly study ecosystems in the oceans have not been available.

There are some 64 large marine ecosystems around the world. The one I will focus on is the California Current Large Marine Ecosystem off the west coast of the United States. This is formed by an oceanographic current that comes across the Pacific and splits into two when it hits Vancouver Island, Washington. One part, the Alaska Current, goes north while the California Current goes south to define a large marine ecosystem. It is at this scale that we need to be thinking, in part because a current transports larvae throughout that system and a wide variety of creatures move around in it. Even though it has not actually got a fence around it, it is a cohesive ecological unit that needs to be better understood. PISCO (the Partnership for Interdisciplinary Studies of Coastal Oceans) is a new model for the study of large marine ecosystems, and there are various study sites up and down the coast focusing on the nearshore portion of this one.

Typically, the study of ecosystems, particularly in the United States, has been very atomized. We have different bodies – such as the National Science Foundation (NSF) or the other government foundations – funding oceanography on the one hand and marine ecology on the other. There are different groups that fund fisheries, or economics, or disease, or sociology. This atomized approach is beginning to change, but it has been the historical pattern.

It has been very difficult to conduct integrated studies that are interdisciplinary or cover more than just a couple of years, the duration of most NSF grants. The PISCO research programme is designed to be very different: to be long term, to integrate across many different disciplines, to be responsive to management needs and to have fundamental links to policy.

It involves four different universities along the west coast, and the principal investigators at each university have agreed to use uniform ways of carrying out research and monitoring. We are all collecting data in the same way up and down this coastline: data for oceanographic information, physiological information (looking at genetics and biological physiology), ecological information, policy and management.

The idea is to understand the dynamics of the large marine ecosystem, focusing on that nearshore ocean. This has historically been a no-man's area – ocean-going vessels are too large to come in close to shore, and marine ecologists only stand on the shore or perhaps dive in kelp forests – and we are working to integrate the nearshore ocean, the area that actually bears the brunt of both ocean-based activities such as fishing, mining and drilling, and land-based activities that are impacting the area. There will be an intense focus on this nearshore ocean, both for research and monitoring, and for training students in an interdisciplinary manner, as well as providing information for policy and management.

We are excited about what we are doing. It is a challenge to keep up with all the new findings, and I think we are going to be seeing some very remarkable progress in building the knowledge base to help inform ecosystem-based management.

I want to turn now to some of the scientific programmes that concentrate on understanding what many have suggested is the most powerful new tool at our disposal to help recover the bounty that has been lost from the oceans – marine reserves. A marine reserve is an area of ocean that is fully protected from destructive or extractive activities on a permanent basis, except as needed for evaluation or monitoring. These are "no-take" areas. Marine reserves are not a new concept but one we have had little information about until relatively recently.

A marine reserve is not the same as a marine protected area. A marine protected area is managed for some conservation purpose. It might prevent drilling for gas and oil but allow everything else. It might not allow fishing for a particular species but allows other fishing. At the furthest end of the spectrum in terms of restricted areas are marine reserves, and it is this type of management that is going to have the most benefit, though of course marine reserves have to be part of a larger context of marine protected areas and better management.

The kinds of questions asked about both marine protected areas and marine reserves are: where should we put them, how big, how many, what are the trade-offs if we are closing areas to fishing; and do they work?

A working group on the science of marine reserves operated for about three years out of the National Center for Ecological Analysis and Synthesis in Santa Barbara, California, an interdisciplinary group of scientists from around the world. It resulted in a number of products both for scientists and for the public: a special issue of *Ecological Applications* and a series of papers and journals. Some of the results relate directly to our topic here, particularly what happens inside and outside the reserve as well as network design. We made a comprehensive analysis of changes when an area becomes a marine reserve, using studies and data from more than 100 reserves examined and 80 analysed, representing about 23 nations. I want to emphasize that the total area of all the marine reserves in the world adds up to far less than 1 per cent of the surface area of the ocean – just a drop in the bucket.

The analysis showed what happens to key biological measures – biomass, density, size and diversity – in terms of percentage increases. Generally there is a huge increase in biomass because there is no fishing and nothing is removed. There is a huge increase in density and a significant increase in average individual size and diversity. Reserves vary considerably one to another but, in general, species are more abundant, more diverse and larger inside reserves, and they reproduce more. Reserves also protect habitats. In the oceans there are many kinds of habitat – sandy, rocky, ridge, boulder, the sea floor –

and each is important because in protecting habitats we are protecting species. It is not surprising that there are clear conservation benefits from marine reserves.

Next we looked at what happens outside a reserve, and whether there are any benefits to fisheries. Obviously the goal of conservation was to have a reserve large enough for young to be produced in the middle of the reserve, not outside it, thereby minimizing export. In contrast, for fishery benefits you want to maximize export.

When different species of fish are tagged inside a reserve we can monitor how far they swim outside the reserve. There is spillover from reserves as things get crowded in there, but these fish do not go far, usually to the general area around the reserve. Other changes which are likely outside a reserve are potentially much more important and more difficult to measure, such as the export of larvae. Individuals in the reserve get big and produce young. Zygotes or larvae are transported in ocean currents away from the reserve, over varying distances. This is much more difficult to document as they are not marked, but we can calculate the number of young produced by the number remaining in the reserve.

When fish are allowed to get big and fat, the reproductive benefit is immense, and is directly related to the size of the individual. Take the vermilion rockfish. One that is 37 centimetres long produces about 150,000 young, while a fish that is 60 centimetres long produces 1.7 million young. Allowing fish to get bigger in reserves therefore brings tremendous benefits. Since this study was undertaken, it has been found that in some fish, not only do the fat females produce more young, they produce higher-quality young which do well when less food is available.

A network of marine reserves is a series of reserves connected by the movement of larvae, juveniles and adults within a large marine ecosystem. Because species spend time in different habitats – a larval habitat, a juvenile habitat, an adult habitat – it is important to think comprehensively and holistically in this large ecosystem context. In addition, an important function of reserves is to provide insurance against mismanagement or unanticipated consequences. Much of our management of fisheries historically has been on the edge: when something unexpected happens, it triggers a crash.

Reserves also have an important role as scientific reference areas, shedding light on the results of fishing and other pressures outside the reserve, looking at both direct and indirect human impacts.

The conclusion of the study is that reserves can offer important benefits in protecting local areas. Individuals grow larger in protected habitats, there are immediate benefits outside the reserve and a likely larger fishery benefit, although that varies from one species to another and is a function of local conditions.

Until very recently the ocean was replete with *de facto* marine reserves – areas where it was too far, too deep or too rocky to fish. These have essentially disappeared now. Fishing can take place almost everywhere, and many are of the opinion that marine reserves offer a huge opportunity to recover some of what has been lost.

Much of the information from this working group on the science of marine reserves was summarized in a booklet, *The Science of Marine Reserves,* as well as a 15-minute video, so there is an active effort to communicate the results of this project to fishermen, citizens' groups and others interested.

Turning to governments, a few have taken the step of creating ocean policies that set out a distinctly different future. Canada and Australia have done this. We have had no policy changes in the United States but there have been two national commissions that have recommended sweeping changes. I had the pleasure of serving on the Pew Oceans Commission; it was independent and the first comprehensive review of ocean practice and policy in over 30 years. We were a collection of 18 individuals – elected officials, business leaders, fishermen and conservationists – and we spent three years going around the country talking to citizens. We also commissioned studies by scientists to inform our deliberations.

Looking at the United States as an economic zone, we realized that the area of oceans over which the United States has jurisdiction is about 1.5 times larger than the area of the US continent, a huge responsibility that we have not yet grasped. The conclusion of the Pew Oceans Commission was that this public domain should be managed as a public trust, and although we are a long way from that, we have made a series of far-ranging recommendations[1]. Essentially, if people want healthy fisheries,

1 America's Living Oceans: Charting a Course for Sea Change

vibrant coastal economies, abundant wildlife, clean beaches and healthy seafood, they have to have intact, functional ecological systems. Therefore one of the commission's strong recommendations was to make protecting and restoring the ecosystems that provide this bounty and these services a goal of all ocean policy and practices in the country.

This approach was taken up by the national US Commission on Ocean Policy (USCOP) appointed by Congress, which reported to the president[2]. Both this and the Pew commission are in line in terms of their conclusions, highlighting the importance of stewardship, regional governance, ecosystem-based management, working out how to link the land and sea, science and education. The power of these two commissions is going to be significant. There will be much activity in the next few years as we begin to share the results and publicize them more widely. The recommendations have significant policy implications. I have already mentioned the primary emphasis on protecting and restoring the ocean ecosystems and having clear institutional responsibility. There are currently over a dozen federal agencies dealing with oceans and more than 140 congressional laws that regulate them. The left hand does not know what the right hand is doing, and there is a huge gap in the middle. Institutional responsibility and governance changes are highlighted by both commissions – as are changing the regional Ecosystem Management Council's structure and investing in monitoring and research.

It is a new dialogue, and I think there is beginning to be increased awareness on the part of political leaders. But it is very early, and there is a huge amount yet to be done. It is encouraging that the debate is being informed by science, and that scientists are playing such an active role in it.

Much of the science is also informing citizen action. There is a wealth of activity on a global scale through a variety of non-governmental organizations, but also on a local scale. There is increased interest in the oceans, and in individuals using the power of their own choices to help make a difference. Choosing sustainably caught or farmed seafood is gaining currency, but it is still in the very elementary stages. There is considerable momentum for creating networks of marine reserves and marine protected areas, working for governance changes and individuals creating their own environmental preferences. There are a number of citizens' action groups in the United States focused on making choices at the market or restaurant in favour of sustainably caught or farmed seafood. In

2 An Ocean Blueprint for the 21st Century – USCOP

Europe the Marine Stewardship Council is a lot more active than it is in the United States; there are similarities and differences.

In summary, then, marine systems are exceedingly challenging, more so than most of what is happening on land, and that is challenging enough. The fact that most people do not come into contact with the oceans is a huge barrier to increasing public understanding and creating political will. However, a new awareness is emerging and is beginning to trigger some bold new actions. The state of California took the Pew Oceans Commission's report and actually passed a law – the Californian Ocean Protection Act – which does exactly for the state what we recommended for the United States as a whole. California also passed the Marine Life Protection Act, which mandates the creation of marine reserve networks. In Australia, under the Great Barrier Reef Marine Park Authority, about a third of the park is now marine reserves. Other countries are taking similar actions.

I think the time is right for meaningful change; it is not soon enough, but it is happening. The oceans are vast, historically very bountiful, and also dangerous and mysterious. These are the impressions people have. The oceans are home to billions of creatures and essential for all life because they provide critical ecosystem services. This is what is at risk, and human well-being is at risk because of the changes taking place in the oceans. The current choices we are making in terms of energy, agricultural practices, coastal development, horticulture and fisheries are all unsustainable and leading to an impoverished future, but this is not inevitable. It is not too late to change, although it will be exceedingly difficult. I believe there is both urgency and hope in making this transition. We can choose a different future informed by science that understands the consequences of trade-offs, science that leads to a better set of options for more individuals.

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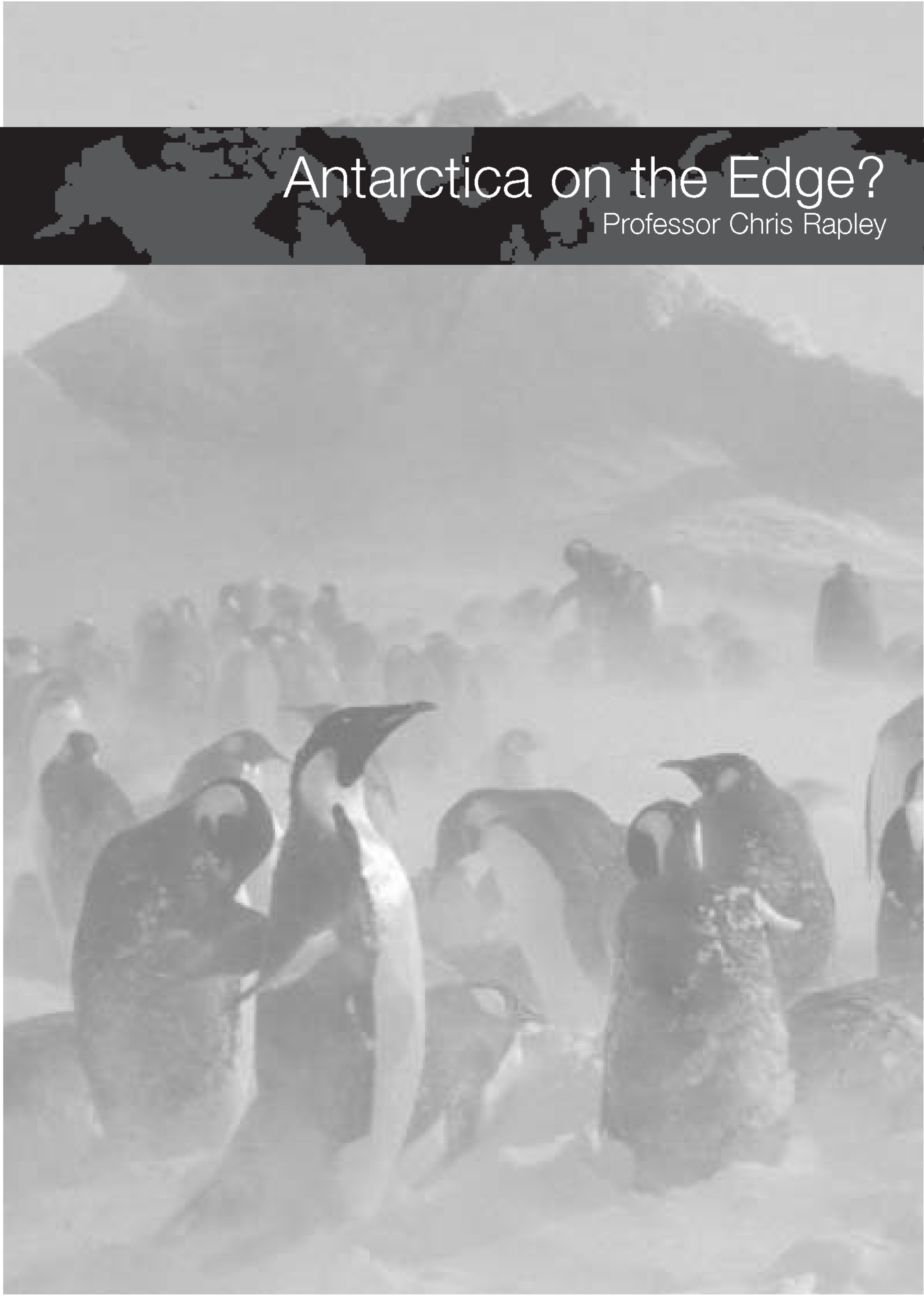
and Distinguished Professor of Zoology, Oregon State University.

Antarctica on the Edge?

Professor Chris Rapley



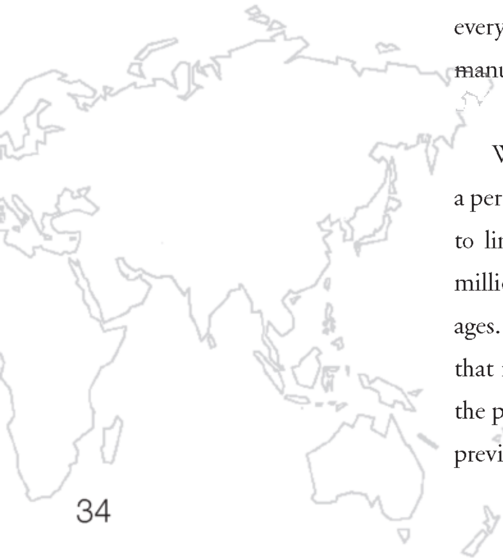
Environment on the Edge

The question mark at the end of the title – Antarctica on the Edge? – is important, as we will see. But let us start with the most complex object in the universe, and one in which we are rather interested because we live on it: the Earth. From the point of view of scientists interested in systems analysis and the way systems function as a whole, the Earth is the most fascinating object because it is the most complex. The Earth has geology, physics, chemistry, biology – which as far as we know is not prevalent in the universe – and, of course, it has an advanced technological civilization, for which there is also no evidence elsewhere. It is the interaction of all these elements that makes the Earth so interesting to study.

The Earth as a system

We can start by making a few comments about the Earth as a system, a highly complex and interconnected one. We can break it up into the geosphere (the solid part that is most of the Earth), the ocean, the atmosphere, the ice, the life and the humans. That is six interconnected compartments, and because six things can be connected six times five over two ways, we already have 15 interconnections, without even starting to break down the different spheres. This complex Earth functions as an integrated whole, which means that the traditional scientific approach of studying the smaller pieces that make up the whole is not sufficient.

The Earth provides what are known as ecosystem services – freshwater, fresh air, food, shelter, energy – upon which life depends. The Sun provides the primary source of energy that drives everything, the movement of the fluids and the energy supply to the life forms. There is no user manual, there are no spare parts – and human impact is leading us into uncharted waters.



We can look at carbon dioxide trace from the Vostock ice core record drawn from the Antarctic for a period of 450,000 years. It fluctuates periodically, but under the natural control of the planet it tends to limit at a lower level of about 180 parts per million and an upper level of about 280 parts per million, the upper level being during relatively brief warm periods and the lower level being during ice ages. There have been four ice ages during the last 450,000 years, although we have ice core records that run further back. Current carbon dioxide levels are about 370 parts per million, showing that in the past 100 years (measured directly over the past 40 years and taken from bubbles in ice cores for the previous period), human burning of fossil fuels has increased the carbon dioxide content of the atmosphere by as much as the normal change between an ice age and an interglacial, and it has done so at a very, very fast rate – the fastest rate of change the planet has seen for at least millions of years.

Where carbon dioxide levels are going in the future is a moot point, but based on a variety of projections of the continuing growth of human population, human activity and use of carbon-based fuels, levels at the end of this century will end up significantly higher than they have been for the last 500,000 years, and in fact significantly higher than they have been for the past 200 million years. This has consequences. Everyone knows that the Earth's surface is warmer than it would otherwise be because of the presence of greenhouse gases in the atmosphere, mainly water vapour. But carbon dioxide is a factor, and if you enhance the greenhouse effect, which helpfully stops us from freezing over, then you increase surface temperatures unless there are feedbacks to prevent it.

There are other consequences of increasing the carbon dioxide content of the atmosphere. It makes the oceans more acidic, as we are already measuring. It has a big impact on marine ecosystems. It fertilizes the land biosphere. So it is important not to become obsessed solely with the enhanced greenhouse effect. These effects begin to interact and cascade, so that although the land biosphere is taking more carbon dioxide at present because it is being fertilized, when it gets warmer respiration will increase, and at some point the land biosphere will become a source of carbon rather than a sink.

There is a whole community of people trying to predict what the future impact of carbon dioxide increase will be on climate, and a great deal of uncertainty. Prevalent among them are the numerical modellers, many of whom have come from the world of meteorology, where they have been very successful. They are trying to build simulations, or numerical models, of the Earth. Then there is another community of people who say that if climate did change, and temperatures did increase, and acidification of the oceans did happen, how serious would it be? What would be the impacts? The question everyone is interested in – because it was set at the 1992 Earth Summit in Brazil where Article 2 said, to paraphrase, that humans should not affect the climate in a dangerous way – is: what do we mean by dangerous, and what does that mean in terms of climate change and carbon emissions and the trajectory we need to take into the future? Is a change of 4°C, 3°C, 2°C, or 1°C dangerous? That is the question that Sir David King posed, with the support of the UK prime minister, to the Exeter conference "Avoiding Dangerous Climate Change" in February 2005: What constitutes dangerous climate change?

Antarctica: a description and history

Now we must move on to Antarctica, an important player in this game. In the 1770s Captain James Cook had been instructed by the Admiralty to find the southern continent. He struggled to do so and was beaten back by the elements. He said: “Should anyone possess the resolution and fortitude to push yet further south than I have done, I shall not envy him the fame of his discovery but I shall make bold to declare that the world will derive no benefit from it.” There is an air of sour grapes about this statement because he did not see the continent. Then he set sail for Tahiti and was killed in Hawaii.

Cook was proved wrong rather quickly because his own journals immediately started off the sealing trade. Many people benefited from exploiting the southern oceans in this way, which of course also led to the whaling trade.

I once had the pleasure of taking four new UK Members of Parliament onto the *James Clark Ross* research vessel in Stanley Harbour in the Falklands, and when we showed them a map it was clear that they did not have a clue about Antarctica. Here are some basic facts. It is the fifth largest continent; it is completely surrounded by ocean; it is the highest, windiest, coldest and driest place on Earth; it is 99.7 per cent ice covered and holds 90 per cent of the world’s ice, although there is a lot elsewhere. The volume of the ice sheet is roughly 30 million cubic kilometres, and it is on average 2.2 kilometres thick – 4.5 kilometres at its maximum. The ice is so heavy, it weighs down the Earth’s crust beneath it by about a kilometre.

Antarctic ice exerts a major influence on southern hemisphere weather, ocean circulation and climate. If we melted it all, which would require much energy and time, then it would raise global mean sea level by 57 metres, which means that Cambridge, for example, would be under water. I am often asked why the United Kingdom should worry about this remote, distant and difficult-to-reach part of the planet. One thread of reasoning says Antarctica is remote but relevant: London needs protection against flooding, and as sea levels inexorably rise – 1.8 millimetres per year – the Thames barrier will ultimately become insufficient. Antarctica will have a role in that sea level rise in future.

Let’s go back about 200 million years, or 4 per cent of Earth’s history. There is a place called Fossil Bluff, which is one of the four staging posts of the British Antarctic Survey (BAS), where you can find beautiful fossils of ferns and plants. Two hundred million years ago the Antarctic was the hub of the Gondwana supercontinent and Antarctic temperatures were considerably warmer than they are now. About 35 million years ago there was a major cooling and formation of a dynamic ice sheet. About 15 million years ago came the large permanent ice sheet which fluctuates in size, and that cooling is reckoned to be linked to the configuration of continental fragments and the opening of ocean gateways. Today we have a circumpolar ocean with Antarctica set squarely over the south pole with a big ice sheet on it.

When we compare proxi-temperature records with carbon dioxide and methane records, we see that there have been clear fluctuations driven by periodic variations in the Earth's orbit, so there have been subtle changes in the way heat is accumulated onto the Earth before it is radiated into space again. Marine sediments show us there have been 46 cycles in the last 2.5 million years over the ice core record, with 120,000-year cycles over the more recent period. The earlier cycles were shorter with roughly 10°C temperature variations, and are very closely correlated with carbon dioxide and methane variations.

This is an important point because in many comparisons of temperature and carbon dioxide, climate temperatures change and carbon dioxide does not. There are reasons for this: for example, the input from the Sun varies slightly, or the atmosphere can be upset by volcanic eruptions. But there is no place in the record where carbon dioxide moves and temperature does not, and that is an important fact to use in the argument with sceptics about the impacts of carbon dioxide change today. Over an even shorter period, the last 18,000 years, sea levels around the world have risen by 120 metres. Again, the current rate is about 1.8 millimetres per year, but past rates were ten times greater, largely due to loss of the northern ice sheets but also due to change in the southern ice sheets.

Recent changes in ice sheet

To familiarize ourselves further, we can divide Antarctica into three broad areas. East Antarctica is the ice sheet bedrock, mainly above mean sea level, with the bulk of the ice 52 metres sea level equivalent. West Antarctica sits on bedrock up to 2 kilometres below sea level, with a smaller equivalent water mass, 5 metres global sea level equivalent. Then there is the Antarctic Peninsula, a mountain chain extending towards South America joining the tip of the Andes, which is only 7 per cent of the area, and only 0.3 metre sea level equivalent, but an important area, where BAS does much of its work for logistical reasons.

We will first look at the input side of the ice sheet, the snow coming in. Most of the snow is dumped by the moist marine air around the coast, while the large central area of the continent has low snowfall and is technically a desert. It is the peninsula and the area slightly to the west of it that gets the highest annual snowfall. Total accumulation is equivalent to a significant 6 millimetres of sea level per year, and in the peninsula it is about 0.4 millimetres of sea level equivalent.

On the output side, ice deforms and flows under its own weight downhill, forming fast-moving ice streams. The velocity of ice movement depends on the thickness and the friction at the base. If there is water at the base, ice slides, but if it is frozen it deforms. There are 33 major drainage basins, and the ice creeps like porridge. It is the ice streams that transport the bulk of the ice towards the coast, like a network of tributaries. The flow rates are 10 metres per year or less in the interior, reaching 1 or 2 kilometres per year at the coast. Where a lot of the ice extrudes over the ocean, it lifts off and starts floating; the thickness of these ice shelves ranges from hundreds of metres to tens of metres. There are two particular areas where this happens, each larger than the area of France: the Ronne Filchner ice shelf and the Ross ice shelf. As Archimedes could have told us, the transition from grounded ice to floating ice is where it displaces its own weight of water, raising sea level.

Ninety per cent of ice loss from Antarctica is through these ice shelves; the rest is blown off the continent by the winds. The loss is either by iceberg calving at the edge, when they float off north, break up and melt, or by basal melting in which the ocean erodes the underside of the ice shelf and carries water away. The first process is very sensitive to air surface temperature and the second to ocean temperature.

Humans have been active on the Antarctic continent for only 100 years, and active scientifically, in respect of monitoring what is going on, only for the past 50 years. Even these monitoring data are very sparse and intermittent. There are temperature data from a number of places around the continent, most of which do not show a statistically significant signal. The only strong signal is one of a warming over the Antarctic Peninsula of the order of 2.5°C in 50 years. That is five times the global mean change over the same period. Is this human induced, the fingerprint of human beings? We are not completely sure, but the evidence is growing that the answer is yes. There is a strong association with the intensified flow of westerly winds around the Antarctic, which, when they hit the peninsula, move more warm air south. The intensified westerlies appear to result from the regional effect on sea ice of greenhouse warming – which results from human activities. Although we realize there are strong connections between the polar part of the southern hemisphere and the equatorial parts of the Earth through the atmosphere and through the ocean, they are only now being unravelled.

The impact of the warming has been very evident, and there has been much recent media interest in a comprehensive study by BAS of the behaviour of 244 glaciers over the last 50 years. This study, involving thousands of aerial photographs and satellite images, has shown that 87 per cent of glaciers have retreated over the last 50 years, even though at the beginning of that period they were not retreating. It is clear that this phenomenon has built up over 50 years, and that it has swept further south as the period progressed.

At the tip of the peninsula is an island where over the last century the thick ice shelf has disappeared, and ice shelves down both sides of the peninsula have gone. The discovery that some huge ice shelves have just shattered and disappeared in a matter of days has been quite a shock. There is a current of strong evidence and understanding that these ice shelves become damaged by the presence of significant summer melt waters – surface water which drains down cracks, damages the fabric and causes the ice shelf to be susceptible to breaking up. That line has been steadily moving south.

Once an ice shelf has gone, a ship can go in – which could not happen before – and sample marine sediments underneath. Both BAS and the United States have done this, and what we are finding is that the northern ice shelves went quite naturally 2,000 to 5,000 years ago in a slightly warmer period. It is therefore perfectly possible for ice shelves to disappear through natural fluctuations in regional or global climate without intervention from humans. But the evidence on the last large collapse is that it was not a recent one, and we are now entering areas that have not been opened up for millennia.

At first, the consequences of ice shelf losses were open to speculation because the important point is what happens to the glaciers that feed them when the ice shelves collapse. Using satellite data it has been found that wherever an ice shelf has gone, the feed glaciers have speeded up and lost significant volume close to the coast. In cases where the ice shelf is still in place but subjected to identical climatic conditions, the glacier is unaffected. This is quite strong evidence for the cork-in-a-bottle analogy: if the cork is removed it causes the glaciers to accelerate, and that does add to the annual increase in global mean sea level. On the other hand, evidence is beginning to emerge that perhaps that acceleration is not being sustained, and that there is a readjustment of those glaciers. We must wait and see how they settle down.

Next let us consider the West Antarctic marine ice sheet, much of which you remember is grounded on bedrock well below mean sea level. It has been suggested for a long time that this is unstable. In particular, it has been suggested that as global mean sea level rises there is a hydrostatic lift that attempts to raise the ice sheet, allowing very high-pressure water at the grounding line to force its way underneath. Once there is wet water under the ice sheet, the ice can slide much faster than when it is frozen to the bedrock, and hence the suggestion of a positive feedback that could make the ice sheet unstable. This has been proposed as a possible explanation for global mean sea levels appearing to be 5 metres higher at the last interglacial, which was also a couple of degrees warmer than it currently is.

Using expensive pieces of radar equipment which bounce signals off the surface of the planet – and these work particularly well with ice-sheet surfaces that are flat and featureless – a number of scientists are trying to find out more about the surface of the ice sheet. The impressive fact is that you can measure, from 700 kilometres away, the position of the surface of the ice sheet to an accuracy of a few centimetres.

From these scientists' data, we find some areas where there has been no significant change in ice sheet, while some are going down significantly. From aircraft data and *in situ* work by the United States, it seems the ice streams that feed into the Ross ice shelf are stagnant or growing and have a positive ice balance. Another area is losing ice, and the three drainage basins are losing ice rapidly. The synchronism suggests that the cause is connected with ocean warming, which has removed the buttressing ice shelves and led to an acceleration in ice loss. Certainly the air temperatures in the far south indicate that this is not a surface-melting issue.

Earlier this year in *Science Express,* an important paper from Kurt Davis and his colleagues in the United States reported the findings from processing hundreds of millions of radar echoes from the Antarctic ice sheet during the period from 1992 to 2004. The West Antarctic ice sheet is losing ice at 1.6 millimetres sea level equivalent per year. The East Antarctic ice sheet is growing, and this is because the warmer atmosphere carries more moisture and the marine air masses penetrating the area are dumping more snow onto the ice sheet. David Vaughan at BAS sets out in an unpublished paper his belief that the peninsula is losing a net amount of ice into the ocean of a similar order. Duncan Wingham at University College London (UCL), too, has an unpublished paper with similar findings.

So what is the Antarctic ice sheet contributing by way of global mean sea level rise? Five years ago, the Intergovernmental Panel on Climate Change, which is a consensus process for summarizing the best understanding of system issues, said the following:

- Ice sheet reaction times are thousands of years.
- On a hundred-year time scale, the ice sheet is likely to gather mass because of greater precipitation (and the Davis paper shows that this is true).
- On the basis of really thin evidence, but largely the fact that numerical models could not make it happen, the West Antarctic ice sheet is very unlikely to collapse in the 21st century.

A BAS study came to this last conclusion, too, but based on very little hard evidence. The projected mean sea level rise over the next 100 years – there are many terms in this equation, such as ocean expansion and loss of Alpine glaciers – was estimated as in the order of 11 to 77 centimetres. The Antarctic contribution could range from negative, because of the growth of East Antarctica, to just slightly positive, because of the loss of ice from the peninsula and the West Antarctic ice sheet.

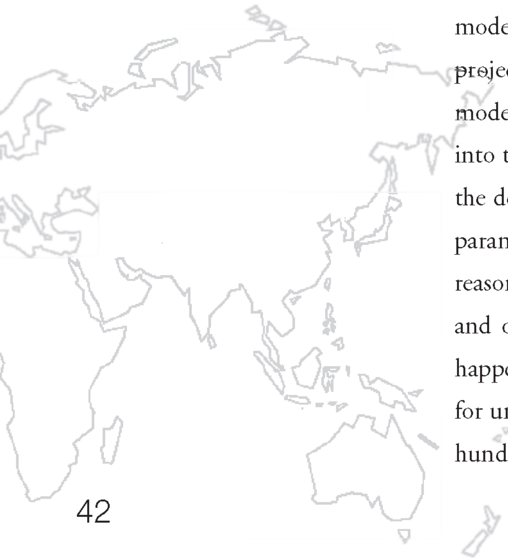
To summarize what we have learned since, there have been some surprising examples of rapid significant regional change. The sensitivity of ice flow down ice streams to ice shelf loss is greater than previously assumed. Another radar-sensing technique allows the detection of incredibly small motions of the ice sheet deep in its interior, and the network of feed streams reaches far deeper than previously thought. This implies that if those accelerate, then they have a greater grasp on the bulk of ice in the interior, and that makes modelling the dynamics difficult.

What is the critical threshold for the West Antarctic ice sheet to collapse? We do not know, but the issue has been reopened by the facts: if you take away the ice shelf, then things start to happen quite quickly. The accumulation over East Antarctica has been confirmed, but over the long term it may not be enough to balance the other losses. The fact is that we have some very large numbers with a wide range of accuracy, and the Antarctic contribution to mean sea level rise now and in the future needs reassessment. Some people have talked of a dangerous climate threshold of 2ºC or 4ºC, but we believe these are no more than guesses.

Modelling the future

Despite the difficulties in taking measurements, we must try to make the most of our knowledge of the physics, chemistry and biology of the Earth's systems and use computer models to predict what will happen as all these different elements interact with each other. We know world temperature change over the last 50 years, and we have predictions for the next 50 years from data used in what is widely regarded as the best numerical climate model, the Met Office model. But the significant point is that the peninsula warming I mentioned, which is one of the strongest warming features on Earth in the past 50 years, is not represented in this terrific model – so how much can we trust its predictions in the southern hemisphere? Its general predictions may be reasonably accurate, but not so its regional predictions.

What about ice sheet models? There is a mass of information that goes into a numerical ice sheet model, including physics and data, and these are used both to integrate existing sets of data and to project into the future. Ice sheet models also need, of course, to be coupled to general circulation models, which, as I have said, do not work very well in this area. A huge amount of effort has gone into these models, and they are increasingly sophisticated, but not one of them is yet able to represent the deglaciation since the last glacial maximum *and* the observed current variability. You can tune the parameters to make them do it separately, but they cannot do it simultaneously. Although that is no reason for giving up, we are not yet at a point where we have reliable models – either of the atmosphere and ocean in the southern hemisphere or of the ice sheet – to be able to forecast what is going to happen in the future. We need an action plan. More fieldwork in the West Antarctic ice sheet is crucial for understanding what is going on: perhaps the ice loss will stop, or perhaps it will go on for another hundred years, and maybe it will significantly raise global sea level over that time period.



We have precious little data about the atmosphere in the Antarctic and virtually no data at all about its ocean temperatures and circulation. We are just beginning to run submersibles under the ice shelf – the United Kingdom has in fact this year lost one under the ice shelf – and there is a great deal of satellite and aircraft remote sensing going on. Cryosat, which Duncan Wingham and the UCL team have masterminded, will be launched shortly and represents a big step forward from current radar space systems by way of monitoring ice sheet mass balance.

We definitely need more work on the models, and a five-year timescale is essential to make progress. On a positive note, BAS and the University of Texas acquired 100,000 kilometres of radio echo-sounding flight lines in the 2005 season, and these radio echo-sounding data penetrate right inside the West Antarctic ice sheet and cover 30 per cent of it, including the area that is currently active. This large amount of data will reveal a great deal about what is going on, and what we might expect to continue to go on, in this tricky area.

Sea ice

I have concentrated on the ice sheet because it is of the greatest interest. But we have 20 years' worth of satellite data on Antarctic sea ice, showing the shrinkage through the summer and regrowth as the following winter sets in. This is sea ice freezing because it gets dark and very cold indeed, so the top of the ocean freezes because of the radial imbalance but also because of cold winds from the dome shape of the Antarctic continent. This dataset has given us much to think about and be amazed by – huge icebergs spinning round the coast being carried by the very strong ocean currents, for instance. It is the biggest seasonal change on the planet, and it has a huge impact on the albedo (the reflectivity) of the southern hemisphere, as well as being important for other reasons. When you generate sea ice – when you freeze saltwater – you expel the brine, which makes already cold dense water even more dense. This cold dense water rolls off the edge of the continental shelf into the abyss, and warm water is sucked in to replace the cold.

About 40 per cent of the world's oceans are chilled by the Antarctic; the Antarctic is the refrigerator of the world's oceans. The Southern Ocean, which surrounds the Antarctic, is a productive ocean, having a relatively simple food web. The upper parts depend on krill, and that marine ecosystem draws down carbon dioxide from the atmosphere. In the southern Indian Ocean and the eastern side of

South America, the Southern Ocean is very actively absorbing carbon dioxide. The marine ecosystem sits in this conveyor belt being whizzed around the Antarctic in a "jet-stream" current, and the biological and physical dynamics are completely entwined. Krill that are spawned under ice at the tip of the Antarctic Peninsula are carried – and carry out two life cycles on their way – to South Georgia, where seals, penguins and albatrosses are waiting. If anything changes either in the biology or in the physical dynamics, then the waiting creatures starve, and their populations have periodic crashes when something happens in the delivery system. It also, of course, means that the capacity of the Southern Ocean to absorb carbon dioxide varies.

So what has happened to Antarctic sea ice? There is a 20-year trend showing overall growth and strong regional differences associated with the general warming of the atmosphere. Areas of reduced sea ice have, it is believed, led to the observed significant decrease in krill stock in the Weddell Sea area, and this has had an ongoing major impact on the Southern Ocean ecosystem. But the impacts on ocean circulation and the carbon drawdown are simply not known because we do not have the data.

If we move inshore, the shallow-water marine ecosystem around the Antarctic is as rich as a tropical reef. The marine creatures there exist in very low temperatures, and those temperatures have been constant over evolutionary timescales. The organisms that live in warmer waters are capable of handling quite large temperature variations, but those that exist in very cold waters have given up that capability in order to be able to survive there. That is evolutionary adaptation, so they can only tolerate very small temperature excursions. Even a rise of 1°C or 2°C would have major consequences on individuals and therefore on those species, and if there were to be ocean temperature rises of this order then we would see major ecosystem shifts and some mass extinctions. We have some insights as to what is happening and what will happen, and we are concerned, but to predict what will happen in 100 years is impossible.

Future research in Antarctica

We need an enormous range of scales both in distance and time to study and understand how the Earth functions as a system. We have to study microscopic changes and changes right the way through to the scale of the planet, and so we need microscopes and macroscopes, the nice term that has been coined for the satellite instruments that allow little us to see big things in a way we can comprehend. But the world science capability is finite. The United States spends about half the world's investment in understanding how the planet works, perhaps $1-2 billion a year. Europe spends about half that, and the rest of the world together spends the same as Europe.

There is no infinite capability of brainpower or equipment or infrastructure, and so we need to marshal what we have carefully. We need to identify and focus on the key components of this system. When we do, reductionism is not enough; it is no use taking the thing apart and figuring out how the little bits work and putting it together again. It requires unprecedented levels of interdisciplinary research and unprecedented worldwide organization and collaboration, as well as a sense of urgency. Scientists on the whole resist being rushed and move at a pace they think suits the quality of their outputs, but policy makers need some answers quite quickly. The science community therefore needs to be persuaded that it is better to come up with something less than perfect soon, rather than come up with the perfect answer too late.

At the British Antarctic Survey, we have been taking this very seriously in the way that we have developed our new science programme, which we will be carrying out over the next five years. It addresses many of the major issues I have been describing. We have also been working closely with the International Council for Science's Scientific Committee on Antarctic Research. In the past they tended to study lots of little bits, but they are now pursuing five flagship projects, and three address the sort of big questions I have been outlining.

Fifty years on from the International Geophysical Year, we have been very successful in raising worldwide interest in having an International Polar Year – IPY 2007-2008, which will actually take place between March 2007 and March 2009. It will be an intensive burst of international, coordinated, interdisciplinary scientific research and observations focused on the Earth's polar regions, Arctic and Antarctic. It has six themes: current status of the polar regions; change in the polar regions; global linkages; new frontiers; polar regions as vantage points; and, especially for the northern hemisphere, the human dimension. To date we have had 900 expressions of interest worldwide.

I have not been able to give you answers about what constitutes dangerous climate change from the point of view of the Antarctic, but what I hope I have shown is that we are making progress

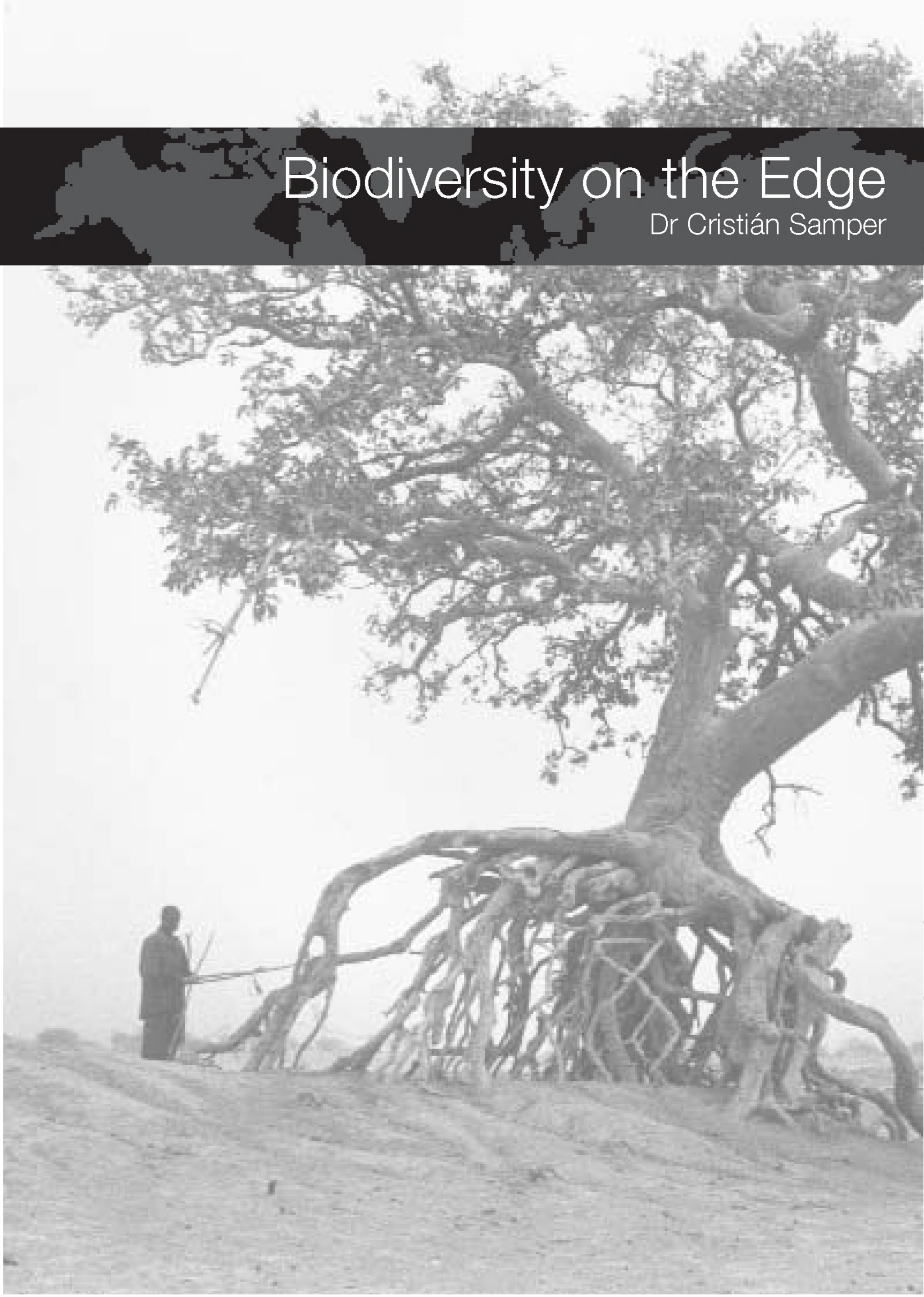
considering how far away the Antarctic is; how difficult it is to operate in; how remote and challenging it is in many ways; and that we do have the tools to make progress and are marshalling them seriously to do so. I hope, in five years' time, I might be able to tell you more.

Samuel Butler pointed out that "all progress results from the ineluctable desire of every organism to live beyond its means". That is what we are all doing, collectively, and overcoming this will be the real challenge if we are to find a sensible balance between human endeavours, human well-being and the planet.

Professor Chris Rapley CBE is Director of the British Antarctic Survey, and was Chair of the International Planning Group for the IPY 2007-2008.

Biodiversity on the Edge

Dr Cristián Samper



We have been, as biologists, interested in discovering and exploring this planet for 200 years, documenting and describing species, from coral reefs and the depths of the oceans to forests all over the world. In that process we have described, catalogued and collected many of the species that make up the biological diversity of this planet. We have been fascinated by these species for scientific reasons, especially in order to understand the very complex interactions that exist between them, and to understand how many of these groups have co-evolved over millions of years.

But it is also important to remember that this biodiversity, this planet and life on Earth, has been the backdrop to human evolution. We see this all around the world and going back through the ages. For example, there are pre-Colombian paintings from the Amazon that are several thousand years old and remind us that humans were interacting with nature in many ways, as hunter-gatherers and through the process of crop domestication. Recent work shows that we were already starting to see early domestication of certain crops in the Middle East as far back as 20,000 years ago.

But what is clear is that over the decades, as human population density has increased and practices changed, the footprint we humans have made on the environment continues to become greater and greater, to the point where we have settled, built cities and seen the impact of our activities spreading all over the globe. We see far-flung effects such as invasive species or, in some areas, the process of deforestation driven by overseas markets. The environmental impact of activities in the United Kingdom, for example, is now felt as far away as Indonesia. These changes have been expanding very rapidly.

These are just some findings from a recent project, the Millennium Ecosystem Assessment. Since 1960 the human population has doubled from 3 billion to 6 billion. The size of the global economy has increased sixfold. Food production has increased by 2.5 times, the demand for water for human consumption has doubled and the amount of water that is impounded by dams has quadrupled. The flow of chemicals such as phosphorus used in fertilizers has tripled, and all this in a matter of 40 years. These activities are clearly having an impact.

During that time we have made important scientific advances: for example, describing some 1.75 million species and setting aside protected areas – about 11 per cent of the world's terrestrial ecosystems are protected. We have seen increases in human health and longevity, decreases in child mortality, incredible increases in agricultural productivity, increased awareness of environmental issues among people all over the world, and development of multilateral agreements relating to the environment. Some of the best known, such as the Convention on Biological Diversity, resulted from the 1992 Earth Summit in Brazil.

The fact is, despite all this progress and achievement, we know that biodiversity is declining in many areas of the world, and that many people are still living in poverty – more than a billion people live below minimal thresholds. Most importantly, we see that there are still inequities in the distribution of the benefits of biodiversity among people and among countries, and that many of these inequities seem to be getting worse. You may have seen the striking figures – that the total assets of the three richest men in the world are greater than the total size of the economies of the 50 least-developed nations worldwide. The paradox is that many of the richest countries in terms of biological diversity are the least developed economically. Much of the capacity and information about that biodiversity is in a few countries like the United Kingdom, the United States and others, and most of the biodiversity is in countries where the scientific and technical capacity is still developing.

How can we bring the best of our science to inform policy and benefit society? I will address this question primarily from a biological perspective, covering three topics: first, the current status and frontiers of our understanding of biodiversity; second, focusing on conservation, threats, status and trends; and finally, what this means for human well-being.

How much do we know?

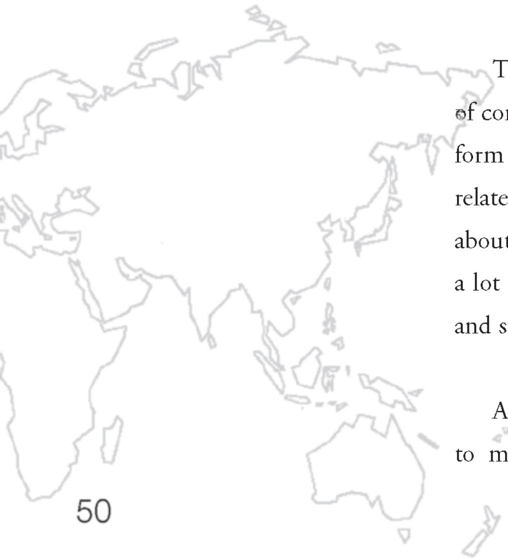
As biologists we ask a whole range of questions about biological diversity, including:

- What is this species? (taxonomy)
- How are species related to each other? (phylogenetics)
- Where are they found? (biogeography)
- How do they interact? (ecology)
- How did they come to be? (evolution, paleontology)
- How are they used by people? (ethnobiology)
- What is the impact of people? (conservation biology)

As an example of how little we still know, last year a scientist in a deep-sea submersible took a photograph of a giant squid more than ten feet long. It had never been collected, and this was the first time it had been seen, although it is a very large animal. Likewise, only last year, a scientist at the Smithsonian described a new species of whale.

But it is not only the large creatures. The frontier of our understanding is very often in the small organisms. When Betsy Arnold and Helen Herre at the Smithsonian began to examine leaves of cocoa trees in the Isthmus of Panama, and took cultures of the fungi that grow inside the leaves, they found 600 species of endophytic fungi growing inside the leaves of one species of tree. Given these kinds of numbers, our understanding of how things operate and what is out there is really just incipient. Furthermore, they have found that the presence of certain endophytic fungi confers resistance to some kinds of disease. Another extreme in this area is the current tally of the number of different micro-organisms found inside the mouths of human beings – more than 600 to date.

We have new tools to describe and understand what is around us. The National History Museum in London is talking about DNA bar-coding to use molecular techniques to unveil some of this diversity and to find new, cryptic species. You may have read some papers we have produced in the United States. Paula Hebert and colleagues at the Smithsonian have been using DNA bar-coding with groups of birds in North America. Four new species of birds have been found this way, as have cryptic species of butterflies in Costa Rica, and other organisms.



These new technologies are helping us to unveil biological diversity and also helping in the process of constructing the tree of life. Hundreds of scientists around the world are involved in this, trying to form a tree where every branch is a different species, and where we can see where different kinds of related organisms are found on the tree, encompassing all 1.75 million known species. It is not all about knowing about the species and their interactions, about how these things are operating in nature; a lot of this fundamental understanding is essential for scientific curiosity as well as for conservation and sustainable use.

At the other extreme of technology, we have important advances in remote sensing that allow us to monitor different ecosystems, and by combining observations we can start gaining a better understanding of the distribution of biological diversity. Maps from the UNEP World Conservation Monitoring Centre show different patterns of species richness, such as the diversity of families of flowering plants and their highest concentrations. Not surprisingly, the areas of tropical forests in Southeast Asia and Central America as well as the Andes are some of the most diverse. The pattern changes from one group to another. Different pictures emerge for terrestrial vertebrates and for freshwater fish. The maps are updated all the time and are important for synthesizing our knowledge and setting priorities for conservation.

How are things changing?

But how we can conserve the diversity, and what are the main threats? If you look at a map of terrestrial wilderness areas, which are relatively intact ecosystems, they are found in the Amazon rainforest, the African deserts, and tundra in Asia, North America and other places. If you then compare this map with one of human population, you can clearly see that the highest and densest settlements of populations are where the biggest impacts on, and transformations of, the ecosystems have happened.

The Millennium Ecosystem Assessment study has found that in 2000, 25 per cent of the Earth's terrestrial surface was under cultivation, a substantial figure. Most change has happened in the last 40 to 50 years, and looking ahead we can see that in some areas the agricultural frontier is likely to expand, for example in South America, and in others it will most likely contract, as in parts of Europe and North America.

A global analysis has looked at how biomes have been affected in terms of percentage loss, taking the loss before 1950, the loss between 1950 and 1990, and projections for the future using Millennium Ecosystem Assessment scenarios. Six kinds of biomes have lost close to 50 per cent of their original area: Mediterranean forests, temperate broadleaf forests, tropical forests, grasslands, savannahs and coniferous forests. Change in some of these biomes has been more rapid in the last 40 years, primarily in the savannah ecosystems, coniferous forests and tropical dry forests. The projection for many of these ecosystems or biomes is that the total area will change more, except in temperate forests, where we expect to see a net gain in total area due to soil regeneration and reforestation. But some of the areas will lose an important part of their total surface area, depending on the scenarios and models used. For some tropical forests we estimate that 20 to 25 per cent might be lost over the next 50 years.

It is not only the terrestrial systems that are suffering. Data for marine fisheries are expanding, and a reconstruction from the Millennium Ecosystem Assessment provides a model of how fishing pressure has changed over 50 years. It shows that the fishing industry has expanded to the point where there is no corner of the oceans that is not under some pressure at this time.

We know that ecosystems are changing rapidly, and that in every area species are changing. A yellow-eared parrot, an endangered species from the Andes once thought to be extinct, has been rediscovered in the forests of central Colombia. Like the parrot, thousands of species of animals and plants are endangered all over the world. The best approximation we have is the IUCN *Red List*, which gives different kinds of data: taxonomic groups, the numbers of described species, those assessed, those threatened and the percentage of species assessed actually under threat. Our current knowledge is limited, as only 38,000 species have been assessed, mostly birds and mammals, with a small percentage of fish. Of those that have been assessed, those threatened under IUCN criteria include 23 per cent of mammals, 12 per cent of birds, 32 per cent of amphibians, 61 per cent of reptiles, 46 per cent of fish, 57 per cent of invertebrates and 70 per cent of plants. These are very high percentages, although one should bear in mind that many study groups have focused on species known to be endangered. We all recognize that there is a problem, and that we need to do something about it.

The current tally of extinct species documented worldwide is 784, and this is a reliable figure. Around 60 species have become extinct in the wild but have been saved in botanic gardens and zoos. The data show that the extinctions have not been random. IUCN analyses have found that high numbers of the extinctions have occurred in oceanic islands, many of which historically we know have had very small populations of endemic species prone to extinction. In addition, many species extinctions appear to have taken place in parts of North America, where aquatic, freshwater and terrestrial ecosystems have been transformed, but also have better data.

Over the last 500 years, the number of documented extinctions has, not surprisingly, been going up steadily, and many extinctions have happened in the last 150 years. The main causes of extinction are exploitation of the species, habitat degradation and invasive species. The latter is an increasingly serious problem for many groups of plants and animals, one that will get worse as commercial trade increases.

We all recognize that extinction happens, and the figures I have quoted are recent, for the last 1,000 years. From fossil records we know that there were hundreds of thousands of species that became extinct. But how do you distinguish between a natural extinction and one that is human induced? And is the rate different? The fossil record for marine groups shows that 95 to 98 per cent of all marine species have already become extinct. The question is, what is the background rate of extinction?

We know, of course, that there have been massive episodes of extinction – classic extinctions such as the Cretaceous/Tertiary boundary. If we look at extinction rates based on fossil records both for marine species and Pleistocene mammals, the background rate of extinction seems to be one species for every million species per year. But over the last century the estimated rate of extinction for mammals, birds and amphibians is about ten species per million species per year – ten times higher. Models may differ, but projections for certain groups suggest the rate of extinction in the next 50 to 100 years is likely to increase substantially. It varies within taxonomic groups, but all in all there is consensus in the scientific community, and it is recognized by the Millennium Ecosystem Assessment, that the rate of extinction now seems to be significantly higher than the background rate.

Another example I want to cite is the black-footed ferret. These animals used to be widespread on the prairies throughout North America, from the plains of northern Mexico to southern Canada. In the Natural History Museum of the Smithsonian Institution, where I work, we have several hundred specimens. We have found the historical collections extremely useful in these days of modern technology, using DNA analysis to reconstruct the genetic diversity of populations of black-footed ferrets. We have skulls collected as far back as 200 years ago, and we can gather DNA samples and look at the genetic variability within and between populations. We can also document the genetic bottleneck that has happened for this species. As the unpublished work of Samantha Wiseley, a postdoctoral fellow at the Smithsonian National Zoo, has shown, the genetic diversity for black-footed ferrets 150 years ago was substantially higher. The black-footed ferret is a success story in terms of conservation: the population was reduced to only a few individuals, but a captive breeding programme in zoos around the world has brought the population back to more than 1,000 today.

This shows how we need and use historical data for the planning and management of species *in situ* and *ex situ*. Protected areas are an important measure for conservation. Data from UNEP-WCMC, IUCN and other partners show that the total area set aside for protection of terrestrial ecosystems has increased exponentially, currently to 11 per cent. This is good news for terrestrial ecosystems, but the bad news is that for marine and coastal ecosystems it is less than 1 per cent at this time. This bias was one of the elements under discussion at the World Parks Congress of IUCN and the Convention on Biological Diversity. There are many areas where basic science will be important for conservation. Maps identifying critical areas to establish protected areas for conservation; basic research in reproductive biology and restoration ecology; understanding the impact of invasive species and their introductions and interactions; the impact of sustainable harvesting – these are all areas that need a lot of work.

What does this mean for human well-being?

We cannot just approach this issue as environmentalists, saying these things are going extinct and we need to save them, if we do not also realize they are fundamental to the lives of people around the world. It is not fair to think people on the edge of poverty in developing countries, where livelihoods are endangered, are going to put biodiversity conservation on top of their priority list. We must recognize that biodiversity and human well-being are inextricably linked.

The Millennium Ecosystem Assessment's sub-global assessments have made this point clearly, such as in the villages in the Western Ghats in India. As it turns out, the population in India has increased dramatically in the last two decades, and demand for fuelwood in the Western Ghats has likewise increased. As people have moved into the forest and cut the trees, the canopy cover has decreased to the point where grass is moving in. As grass moves in, the cattle from the villages range further into the forests and reach areas where they come into contact with monkey ticks, which carry a disease that can be passed on to humans. As the cattle go further from the villages to forage, they are bringing the disease back to the population in the Western Ghats, and the incidence of this tick disease has increased as a result of deforestation.

In parts of Africa the lack of fuelwood and inability to boil water has an impact on livelihoods through disease. There are many ways in which we are dependent on biodiversity in our livelihoods, either directly for food or through ecosystem services that are often not measured – such as having access to clean water.

In the Millennium Ecosystem Assessment the main focus was trying to understand the ecosystems and how they affect livelihoods. These were grouped in four categories:

- provisioning services, like food and fibre;
- regulating services, such as climate regulation and water regulation;
- cultural services, including aesthetic and spiritual values;
- basic supporting services, like primary productivity.

We recognize that these services affect different dimensions of human well-being, from health to cultural security, economic security and equity. The presence of people is, in turn, driving factors like population growth, markets and political issues, and these in turn affect a series of proximal drivers like climate change, land-use change and others. We are trying to understand how the various drivers affect the ecosystems and services they provide, and to identify response options. The assessment over four years has tried to quantify some of these factors. When the different kinds of biomes and main kinds of drivers like habitat change, climate change, invasive species, overexploitation and pollution are compared, the main drivers for each biome can be identified. Not surprisingly, we find that for areas like islands the main driver is invasive species, whereas for tropical forests it tends to be habitat change.

Once we understand the main drivers of ecosystems, we can design different kinds of response options. The fact is that all these drivers are interrelated in complex ways, so we know climate change can affect the supply of freshwater, which in turn can affect the biodiversity present, which in turn can affect forest productivity. This complex web of interactions is what decision makers are confronting on a day-to-day basis. The different responses, and the findings of the Millennium Ecosystem Assessment recently released, are in five main categories:

- institutional responses;
- economic responses;
- social and behavioural responses;
- technological responses;
- knowledge responses.

The Millennium Ecosystem Assessment also developed a series of scenarios for looking ahead – we know what the historical changes have been, but we also want to know how things will change over the next 50 years. How are they going to affect the different services? There are four main future scenarios:

- global orchestration – better cooperation and coordination between countries;
- order from strength – becoming isolated and self-dependent;
- the adaptive mosaic – developing local management practices;
- the techno-garden scenario – having technology solve your problems.

Clearly there are some scenarios where we can make disastrous decisions, and others that would have better trade-offs in terms of ecosystem services. Issues related to adaptive mosaics, such as developing local sustainable management practices, can work very well. Technology, too, can be very helpful in some areas. But clearly this is an interconnected world, and building on order from strength seems to be an unreliable possibility for the future.

We have to recognize that biological diversity is essential for everything we do; for our livelihoods. We as humans rely on biodiversity, and we have a profound impact on it. The choices we have before us will fundamentally alter the future. It is in our hands to try to decide, based on the knowledge we have, what the best options are for moving forward. Biologists are committed to strengthening our knowledge base so that we understand the diversity and how it is responding to changes, and so that we can use basic scientific information to improve the lives of people around the world. We need to create awareness and make this an important issue, one that is discussed at all levels from village halls and city councils to the United Nations, everywhere from academia to the private sector. If we all pool together the information we have, and there is increasing awareness, then we can really look out for the future, because that future is in our own hands.

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Transport on the Edge

Dr Bernard Bulkin

In the register of environmental issues, transport looms large. It is an urban, suburban, rural and international problem. It contributes to problems of local air quality, regional air quality, global climate change, land take, noise, congestion and loss of human life. It is not surprising that challenges to transport today are being driven by environmental issues above all others. However, other key drivers of change in the energy world are also important for transport: security of supply, diversity of supply, price – both absolute and its stability – and cultural changes in our society.

Road transport dominates the environmental issues but we note that, at least in the European Union (EU), air transport is the fastest-growing mode and represents an increasingly difficult problem in the battle against global climate change. Here I am concentrating on the technological opportunities for road transport, and on the policy implications of those technologies.

To introduce the subject of transport, it is useful to step back and put it in the context of the total picture for energy in the world. In this regard, we see that transport, though much talked about, accounts for only about 20 per cent of world primary energy. By far, industrial, domestic and agricultural uses of energy are the largest, and the energy used for generation of electricity also goes to these consumers.

But transport has one characteristic that is unique: it is essentially all fuelled by oil. Indeed, as oil has declined as a fuel for power generation, and is used less and less for home heating and industrial uses, we have been approaching a situation where the dominant use of oil is in transport. So transport policy must deal not just with the emissions issues around oil-fuelled vehicles, but also with the great fluctuations in the price of oil, the political issues affecting security of supply and the vulnerability inherent in a crucial infrastructure component that relies on a single fuel source.

Up until 1973, oil production followed the growth in gross domestic product (GDP). The dramatic change in the price of oil that occurred that year and the supply disruptions of 1978-79 changed this. There have been a number of years in the past quarter-century where oil production (and consumption) has decreased. Although the trend is clearly upwards, the rate of increase has been much slower than that of GDP. In the past decade, the growth of light trucks, sports utility vehicles (SUVs) and less fuel-efficient vehicles, particularly in the United States but also in the EU, has been moving the curve up. This has been further aggravated in the past five years by growth in demand from China and, to a lesser extent, from India. While they still represent only a small portion of demand (in 2000 there were three times as many private cars in Los Angeles as in all of India), the growth rates are very rapid.

So oil represents an important part of the energy picture for our society. Our overall primary energy in the United Kingdom is more than one-third oil. It is interesting to contrast this with Ethiopia, at the other extreme of development, where burning of biomass dominates. Even here, however, oil is in second place, used to supply the small number of cars, taxis and buses.

Fuel for road vehicles

Before we look at changes to the vehicle, we should therefore ask whether there are viable alternatives to oil as road transport fuel. And there are some. There has been, over the past few decades, a lot of interest in using liquefied propane/butane, usually sold as LPG (liquefied petroleum gas) or Autogas as a fuel for vehicles. In the United Kingdom, the government has provided tax incentives for this, and more than 1,500 stations now offer it. Many small fleets, such as vehicles from local councils, have converted to LPG. This has now probably peaked, as other alternatives come in. Independent tests have shown that for most vehicles there is little advantage in emissions reduction from LPG compared with ultra-low-sulphur gasoline or diesel. Similarly, compressed natural gas (CNG) has been used in some places, particularly where there is a surplus of gas with no good market for it. The cost of compression will always make this an expensive alternative.

Natural gas does offer possibilities, however. The most useful is the conversion of natural gas to liquid fuel, usually diesel. The set of chemical transformations to do this, known usually as gas to liquids or GTL, has been around since the 1930s, developed in Germany. A related process, converting coal to a gaseous mixture and then on to diesel or gasoline, was used by Germany during the war, and more recently in South Africa. Until fairly recently these processes were very expensive. Recent developments both in the catalysts and in the chemical engineering of the reactors have changed that situation, and new plants are being built, especially in Qatar, where there is a huge gas resource. The diesel fuel that results from this process, often known as FT diesel (the German inventors were Fischer and Tropsch), is very high cetane and virtually zero sulphur, so can be claimed to be the best diesel available.

Biofuels are also important, and will be more important in the future. Today's technology is mainly about making ethanol as a gasoline additive, usually up to 15 per cent, from corn, sugar beet or cane. It is widely used in the United States as an agricultural subsidy for corn growers, and in Brazil. But it is being investigated in places like the east of England, where there is a substantial sugar beet crop. Diesel fuel is also made from rapeseed oil, other seed oil crops, and used vegetable oils. All of this is today's technology for using biomass. But it is, for the most part, not a sensible approach in the long term, because it takes land away from food to use for fuel.

To understand how biofuels could work in the future, it is useful to go back to the gas-to-liquids process. The modern way of looking at this is called polygeneration, a term that I believe was first coined by Robert Williams of Princeton and NiWei Dou from Tsinghua University. In polygeneration, gas, coal or heavy oil is converted to a mixture of carbon monoxide and hydrogen known as synthesis gas, or syngas. Coal syngas was burned in homes for generations in the United Kingdom, where it was known as town gas, and it is still in use in this form in Chinese cities today. Syngas can be converted to diesel fuel, used for power generation or heat, or made into high-value chemicals. By generating energy in all these different forms, and being able to vary the quantities of each, we optimize the economic possibilities for the process.

Now consider the same approach for biofuels. If we start with corn, instead of just getting food or ethanol, we take a polygeneration view. Most of the life of the corn plant is devoted to growing stalk and leaves. Modern corn cultivation produces only one ear of corn per plant. The stalk and leaves are waste, known as stover, and have a negative value as they have to be taken away. What we need for biofuels to be viable are biotechnological processes that convert stover to fuel components such as ethanol, speciality and bulk chemicals, and energy. Then we will really have something of value to society.

To summarize the alternatives to gasoline and diesel derived from oil:

- Fuels such as LPG and CNG may survive in small niches, but they are unlikely to be important for the long term. They require vehicle conversions or specialized vehicles, and do not offer very big advantages to the environment. Policy should really abandon these to the market.

- Gas to liquids can mean very clean diesel fuel as far as local emissions are concerned. It offers no special advantage on carbon emissions. Because costs have come down, plants will be built to take advantage of “stranded” gas and bring it to market. Development of GTL commercially offers a form of diversification for road transport fuels, opening up new suppliers competing for the market. It needs no special policy encouragement.
- Biofuels today are expensive, requiring considerable subsidies, which some governments have been willing to provide, mainly to support farmers. But it is possible to foresee how the tools of biotechnology could lower these costs dramatically, and make it possible to utilize a variety of agricultural waste products, such as stover, rice straw and even fen cuttings, to produce fuel. Where food and fuel can be co-produced, the carbon cost of fertilizer and cultivation can be spread across the products, and there is an overall positive impact on climate change.

New kinds of vehicles

But what about the vehicles themselves? What technologies can we expect that might make an impact on the environmental and supply issues associated with road transport? We will look at several alternatives, but especially at hybrid vehicles and fuel-cell vehicles, and will explain how all of these work. A good place to start is the all-electric battery-powered vehicle.

Schematically, a battery-powered vehicle draws its power from the electricity grid, uses that to charge batteries carried on board the vehicle, and then draws down on the batteries to drive electric motors that turn the wheels. Power technology allows the energy from braking to be captured by a generator and to feed the batteries as well. This is known as regenerative braking.

While there has been improvement in battery technology over the past few decades, it has not been possible to achieve the energy densities required to build a vehicle that has the power and range expected by customers. In other words, we need too much battery per car, and the result is that all electric vehicles are good for is driving batteries around in. This has occurred despite fairly massive research programmes and, in California, government mandates requiring electric vehicles (mandates that have had to be modified or withdrawn because of lack of technological progress). The overall environmental impact of the battery electric vehicle depends on the mix of fuels used to generate electricity for the grid. So at this time, and for the foreseeable future, battery electric vehicles are not the answer.

A much more important approach is the hybrid electric vehicle. This is similar to the battery electric vehicle, except that the grid is replaced by an internal combustion (IC) engine, powering a generator to charge the batteries. At first glance one might ask what the benefit is; we still have gasoline or diesel as the fuel, and all the associated emissions. But there are several reasons why the hybrid is a good solution.

- Electric motors are efficient and, coupled with the energy captured from regenerative braking, give a good benefit to fuel economy.
- The internal combustion engine can be smaller – probably half the size of the engine required for today's cars.
- Because acceleration can draw down more on the batteries, it is possible to run the IC engine at constant rpm (revolutions per minute), choosing a range where it is at its most efficient.
- When the car is stopped in traffic or for any other reason, or any time the batteries are fully charged, the IC engine can be shut off.

All of these aspects of a hybrid vehicle mean a significant improvement in fuel economy and a reduction in emissions. Improvements of greater than 50 per cent are possible for vehicles of comparable size and equipment. The improvement achieved will depend on the mix of city and highway driving, on external temperature, on driving style and many other factors, but generally the more adverse the conditions the better the hybrid fares by comparison with the IC-engine car of today.

What has been described is the so-called series hybrid. There is also a parallel hybrid, in which both the electric motors and the IC engine can give power to the wheels. Some vehicles and driving conditions will favour the series version, some the parallel version.

Hybrid vehicles are here today. They are commercially available, although they represent a small percentage of the market. The most widely sold to date is the Toyota Prius, but other models from Toyota, Honda, Ford and General Motors, representing different sorts of hybrids, are also available.

The display on the driver's dashboard in a Prius shows fuel consumption, of course, but it also shows when the driver is capturing energy through braking. The reason for showing this is important: if you brake hard to stop, the generator does not have the capacity to capture the energy, while gradual

braking allows much more to be regenerated. This display gives the driver feedback that leads to an alteration of behaviour. Another display available to the driver indicates what mode the engine, battery and braking system are using. At very low ambient temperatures, -25°C, the car can still achieve more than 40 mpg (less than 7 litres/100km), whereas normal IC-engine cars would almost certainly be below 10 mpg (28 litres/100km) in such conditions.

Hybrids are not just useful for cars – they are important for buses and other urban heavy-goods vehicles as well. Indeed, the urban bus or garbage-collection vehicle is probably the best use of the hybrid design. We have already indicated that the advantage of the hybrid is that the IC engine can run at constant rpm, avoiding the inefficiencies that come in acceleration and deceleration.

Urban buses and garbage collection vehicles are always running in this inefficient portion of the cycle, so they derive maximum benefit from hybridization. A number of US cities, including Seattle and New York, have already made big investments in hybrid buses and are reporting improvements in fuel economy of 40 per cent, and even bigger reductions in emissions of nitrogen oxides and particulates. China has also started a programme to develop and implement hybrid buses for its major cities.

So to sum up on hybrid vehicles:

- Hybrids are the right choice for urban buses, rubbish-collection vehicles, other urban fleets and private cars. They give benefits for local and global air quality.
- The specification of these vehicles is an area of control for government, usually at the local or regional level, and should be pursued aggressively to maximize the benefits.
- Hybrid cars are commercial today, and policy measures – whether incentives to purchase or to use (such as the exemption from the congestion charge that hybrids enjoy in London) – could bring them into the car population more rapidly.
- Hybrids are a big win. With a combination of hybrids and biofuels, a 50 per cent reduction of carbon emissions from road transport is a realistic goal in the medium term.

Now I want to turn our attention to fuel cells, the final technology to consider. There is a similarity with electric and hybrid vehicles. Once again, we have electric motors driving the wheels, and a regenerative braking system. Now, however, instead of the internal combustion engine of the hybrid, we have a fuel-cell stack powered by hydrogen. But the design concept is similar.

What is this fuel-cell stack, and how does it work? A fuel cell is just the reverse of the experiment we are familiar with from school, namely the electrolysis of water. In that experiment, electricity is passed through water and converts the water to hydrogen and oxygen. In a fuel cell, hydrogen and oxygen (from air) are combined across a membrane so as to allow the energy that is released to be captured as electricity. A platinum catalyst coats the membrane so as to lower the energy barrier for the reaction to take place. The only by-products of generating electricity in this way are air depleted of some of its oxygen, water and a small amount of heat.

To use this concept in a vehicle, a number of these fuel cells are assembled into a stack, and in this way powers of up to 100 kilowatts may be generated. Some time ago Toyota showed that all the components required for a fuel-cell vehicle could be fitted into the chassis of a conventional vehicle. Toyota, Daimler-Chrysler, Ford, General Motors and others have since built such prototype vehicles. But simply taking a vehicle based around a 100-year-old concept and putting a new powertrain in it is not very interesting. A more exciting concept is that shown by General Motors in its concept car, the Autonomy, and in a more recent version called the Sequel. This vehicle completely redesigns the car based on the idea that it will be powered by a fuel cell and use electricity for all its systems.

In the Autonomy concept, the fuel, fuel-cell stack, and all the motors and accessories are in the base, called the skateboard. The top contains the seats and upper chassis shell, and plugs into the base to connect to the driver's controls and displays. In this way, an owner could choose to change tops periodically, at modest cost, leaving the same base. Manufacturing would be efficient, as only the tops would vary from model to model.

All of the components fit inside the base, including tanks for storing hydrogen under high pressure. Because the vehicle is completely electric, there is no need for mechanical linkages between the driver and wheels, as we have in today's steering-wheel-driven vehicles. Rather, this car is completely drive-by-wire, and can be steered, speeded up and slowed down using a joystick.

It is logical at this point to ask where the hydrogen will come from. There is lots of hydrogen in the world; unfortunately most of it is attached to oxygen or carbon. We need to get it free from them and into the form of H_2 gas. Today, hydrogen made for chemical processes is generally produced from natural gas, using the same process we discussed earlier, via syngas. Ideally we would make the hydrogen from solar power via electrolysis of water, but to do this today is prohibitively expensive. Either efficiencies of solar cells have to increase or the costs must come down dramatically before we could start to do this commercially. Moreover, we still have a long way to go to get fossil fuels, and particularly coal, out of the power generation mix. From a policy point of view, it would seem that it will be several decades before we would want to divert any of our renewable energy to making hydrogen. An alternative to this view is that the solar power used to produce hydrogen for Europe could be in, for example, the Sahara desert. There the hydrogen could be liquefied and transported to Europe. This solution does somewhat overlook the shortage of freshwater in the Sahara for electrolysis, and would, today in any case, be extremely expensive.

There has also been considerable discussion of production of hydrogen from nuclear power – either from electricity by electrolysis, or by thermal splitting of water. Neither of these seems likely in the short to medium term, given the difficulty of building nuclear reactors for power generation, but it might be a longer-term outcome.

Fuel cells are much more expensive than internal combustion engines, and the biggest factor in this is the cost of platinum. To achieve the power required, fuel-cell stacks in the vehicles that have been built to date use 100 to 200 grams of platinum, which is 50 to 100 times more platinum than is used in a catalytic converter. Manufacturers have a goal of getting this down to 20 grams, still ten times more than in today's vehicles. And of the 155 tonnes of platinum produced every year, mainly in South Africa, 50 already go into catalytic converters. Some of the rest goes to other industrial processes, such as petroleum refining, and a lot goes for jewellery. The demand for platinum has been driven by increasing wealth in China, where platinum jewellery is much favoured.

What all these numbers mean is that even as few as a million fuel-cell cars (there are 800 million vehicles in the world today) would take two-thirds of current platinum production. While this production could surely be increased, one wonders by how much. And while ultimately the platinum would be largely recycled, it would be at least ten years before this started to happen in any significant amounts.

A significant barrier therefore remains to fuel-cell vehicles becoming important in the market today. We have discussed some parts of this barrier, but not all the components. The technology is not all there yet. True, companies have built vehicles and driven them on the road. There are two fuel-cell-powered buses operating in London and some in a few other cities. But there are still unresolved issues, such as operation of the vehicles in sub-freezing weather, for example – especially where the car is left on the street for a week between use, as many urban motorists do. Fuel cells operate wet and cannot be subjected to repeated freeze-thaw cycles.

Cost continues to be a problem – it is 10 to 100 times greater than for the comparable IC-engine powertrain (less for the total vehicle, of course). I have heard one auto industry technology leader state that the last fuel-cell vehicle they built cost $500,000. Mass manufacturing will help with this, but some of the costs do not go down as they are fixed parts of the vehicle. As mentioned, a big part of this is the platinum content, which takes us back to a technical problem.

Even if we have working vehicles at reasonable cost, we still need a fuelling infrastructure for the hydrogen. This probably means stations with cryogenic distribution and storage, with high-pressure dispensing, so as to get sufficient hydrogen on to the site and into the vehicle to give a reasonable range (say 300 miles without refuelling). And there is the whole infrastructure for production and distribution, all of which is new. Generally, infrastructure is not an interesting issue. It is mainly a question of money, but a lot of money, say $1.7 billion for London alone. It is not possible to build a business model for this investment that has a reasonable return. Studies at Argonne National Laboratory in the US have shown that the cost of distribution is also likely to be very high, at least $1/kg just to distribute the fuel.

Finally there is the challenge of reliability and durability of the vehicles. When you buy an IC-engine vehicle today, you are buying 100 years of evolution of the technology, and the last 25 years have been spectacular in terms of reliability and durability. Customers do not expect a car to break down, and they are rarely disappointed. Fuel-cell vehicles need to achieve this immediately, or customers will turn against them. This is a very tough challenge for the manufacturers.

Today, there is more investment in new powertrain technologies that could be alternatives to the internal combustion engine than there has been since spark ignition and diesel engines came to dominate the scene. It seems likely that for the next 30 years, hybrids will be the technology with the greatest chance of making it big in the road transport market. Fuel cells will come later, at least in the EU and United States. In China, things might be different, as problems of air quality, a desire to lead in a new technology, lower power requirements for vehicles (as eight-speaker stereos and air conditioning are not demanded) and the need to build a new infrastructure for fuelling make fuel cells somewhat more attractive.

In any case, customer expectations are high, and it will not be easy for new technologies to meet them. Hybrids allow a role for biofuels in the fuel mix, and combined, these two solutions can have a very big impact on carbon emissions and local air quality. In all of this there remain many scientific challenges as well as big opportunities to contribute to step changes in what we drive.

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