ENVIRONMENTAL CHANGE, CLIMATE AND HEALTH

Issues and research methods

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CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK
40 West 20th Street, New York, NY 10011-4211, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain
Dock House, The Waterfront, Cape Town 8001, South Africa

http://www.cambridge.org

First published 2002

Printed in the United Kingdom at the University Press, Cambridge

Typeface Times 11/14 pt *System* $\LaTeX\ 2_\varepsilon$ [TB]

A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication data

Martens, Willem Jozef Meine, 1968–
Health impacts of global environmental change: concepts and methods / Pim Martens,
Anthony J. McMichael.
p. cm.
Includes bibliographical references and index.
ISBN 0 521 78236 8
1. Environmental health. 2. Environmentally induced diseases. 3. Social medicine.
I. McMichael, A. J. (Anthony J.) II. Title.
RA566 .M27 2002
616.9′88 – dc21 2001052884

ISBN 0 521 78236 8 hardback

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Global environmental changes: anticipating and assessing risks to health

ANTHONY J. McMICHAEL & PIM MARTENS

1.1 Introduction

The meaning of the word "environment" is elastic. Conventionally it refers to the various external factors that impinge on human health through exposures common to members of groups, communities or whole populations, and that are typically not under the control of individuals (i.e. the exposures are predominantly involuntary). Thus, "environmental exposures" are usually thought of as physical, chemical and microbiological agents that impinge on us from the immediately surrounding (ambient) environment.

The "environmental" roles of socioeconomic status in the determination of disease patterns, including aspects such as housing quality and material circumstances, have also claimed increasing attention from health researchers. This, however, requires a more inclusive definition of "environment" – one that embraces social and economic relations, the built environment and the associated patterns of living.

Note also that we typically view the environment as being "out there". It surrounds us, it impinges on us – but it is *not* us. This implied separateness reflects the great philosophical tradition that arose in seventeenth-century Europe as the foundations of modern empirical western science were being laid by Bacon, Descartes, Newton and their contemporaries. For several centuries this view helped us to manage, exploit and reshape the natural world in order to advance the material interests of industrializing and modernizing western society. In recent times, however, the magnitude of that environmental impact by human societies has increased exponentially. Consequently, in the light of the now-evident accruing environmental damage and the ongoing deterioration of many ecological systems, we must re-think our relationship to that "external world". We must recognize the essential dependency of human society and its economy upon the natural world. That dependency is manifest in the risks to human health that have arisen, or will arise, from the advent of these large-scale environmental changes – changes that are the current hallmark of the impact of the modern human species upon the ecosphere.

1.2 "Environment": the wider dimension

During the last quarter of the twentieth century we began to see evidence of a general disturbance and weakening of the world's life-supporting systems and processes (Loh *et al.*, 1998; Watson *et al.*, 1998). This unprecedented disruption of many of Earth's natural systems by humankind, at the global level (Vitousek *et al.*, 1997), reflects the combined pressure of rapidly increasing population size and a high-consumption, energy-intensive and waste-generating economy.

Global economic activity increased 20-fold during the twentieth century. Meanwhile, in absolute terms, the human population has been growing faster than ever in this past quarter-century, capping a remarkable fourfold increase from 1.6 to six billion during the twentieth century (Raleigh, 1999). The last three billion have been added in 14, 13 and, most recently, 12 years, respectively. While we remain uncertain of Earth's human "carrying capacity" (Cohen, 1995), we expect that the world population will approximate to nine billion by around 2050, and will probably stabilize at around 10–11 billion by the end of the twenty-first century.

In September 1999, the United Nations Environment Program issued an important report: *Global Environment Outlook 2000* (United Nations Environment Program, 1999). Its final chapter begins thus:

> The beginning of a new millennium finds the planet Earth poised between two conflicting trends. A wasteful and invasive consumer society, coupled with continued population growth, is threatening to destroy the resources on which human life is based. At the same time, society is locked in a struggle against time to reverse these trends and introduce sustainable practices that will ensure the welfare of future generations . . .
>
> There used to be a long time horizon for undertaking major environmental policy initiatives. Now time for a rational, well-planned transition to a sustainable system is running out fast. In some areas, it has already run out: there is no doubt that it is too late to make an easy transition to sustainability for many of these issues . . .

These are strong words. The report urges national governments everywhere to recognize the need for urgent, concerted and radical action. The report's assessment concurs with others, such as the detailed analysis of changes in major global ecosystems carried out by the World Wide Fund for Nature, leading to an estimation that approximately one-third of the planet's vitality, its natural resource stocks, have been depleted over the past three decades (Loh *et al.*, 1998). In Box 1.1 the main types of global environmental changes are addressed. It is of interest to review, as historical narrative, the changing profile and scale of human intervention in the environment. From that review, in Section 1.3, we can thus better understand how we have arrived at today’s situation.

BOX 1.1

The main types of global environmental change

The main global environmental changes, of a kind that were not on the agenda a short quarter-century ago, are summarized below.

Climate change

During the 1990s, the prospect of human-induced global climate change became a potent symbol of these unprecedented large-scale environmental changes. Since 1975 average world temperature has increased by approximately 0.5 °C, and climate scientists now think this may be the beginning of the anticipated climate change due to human-induced greenhouse-gas accumulation in the lower atmosphere (Intergovernmental Panel on Climate Change, 2001). Weather patterns in many regions have displayed increasing instability, and this may be a foretaste of the increasing climatic variability predicted by many climate change modellers.

Stratospheric ozone depletion

Meanwhile, higher in the atmosphere, a separate problem exists. Depletion of stratospheric ozone by human-made industrial gases such as chlorofluorocarbons (CFCs) has been documented over several decades. Terrestrial levels of ultraviolet irradiation are estimated to have increased by around 5–10 % at mid-to-high latitudes since 1980. This problem is now projected to peak by around 2010–2020. Simulation models estimate that European and North American populations will experience an approximate 10 % excess incidence of skin cancer in the mid-twenty-first century (Martens *et al.*, 1996; Slaper *et al.*, 1996). These changes in the lower and middle atmospheres provide the most unambiguous signal yet that the enormous aggregate impact of humankind has begun to overload the biosphere. The capacity of the atmosphere to act as a “sink” for our gaseous wastes has been manifestly exceeded.

Loss of biodiversity

The loss of biodiversity is another major global environmental change. As the human demand for space, materials and food increases, so populations and species of plants and animals around the world are being extinguished at an accelerating rate – apparently much faster than the five great natural extinctions that have occurred in the past half-billion years since vertebrate life evolved. The problem is not simply the loss of valued items from nature’s catalogue. It is, more seriously, the destabilization and weakening of whole ecosystems and the consequent loss of their products and their recycling, cleansing and restorative services. That is, we are losing, prior to their discovery, many of nature's chemicals and genes – of the kind that have already conferred enormous medical and health-improvement benefits. Myers (1997) estimates that five-sixths of tropical vegetative nature's medicinal goods have yet to be recruited for human benefit. Meanwhile, "invasive" species are spreading into new non-natural environments via intensified human food production, commerce and mobility. These changes in regional species composition have myriad consequences for human health. Just one example: the choking spread of the water hyacinth in eastern Africa's Lake Victoria, introduced from Brazil as a decorative plant, has provided a microenvironment for the proliferation of diarrhoeal disease bacteria and the water snails that transmit schistosomiasis (Epstein, 1999).

Nitrogen loading

Since the commercialization of nitrogenous fertilizers in the 1940s, there has been a remarkable, sixfold, increase in the human "fixation" of biologically activated nitrogen (Vitousek *et al.*, 1997). Humankind now produces more activated nitrogen than does the biosphere at large. The recent United Nations Environment Program Report (1999) suggests that disruption of the biosphere's nitrogen cycle may soon turn out to be as serious a problem as the better-known disruption of the world's carbon cycle. This increased nitrogen loading is affecting the acidity and nutrient balances of the world's soils and waterways. This, in turn, is affecting plant biochemistry, the pattern of plant pests and pathogens, and the species composition of ecosystems. Via the sequence of eutrophication of waterways, leading to algal blooms and oxygen depletion, nitrogen loading is beginning to sterilize coastal waters, such as Chesapeake Bay in Maryland, the Baltic Sea, and the Gulf of Mexico.

Terrestrial and marine food-producing systems

Meanwhile, the ever-increasing demands of agricultural and livestock production are adding further stresses to the world's arable lands and pastures. We enter the twenty-first century with an estimated one-third of the world's previously productive land significantly damaged by erosion, compaction, salination, waterlogging or chemical destruction of organic content, and with about half of that damaged land showing reduced productivity (United Nations Environment Program, 1999). Similar pressures on the world's ocean fisheries have left most of them seriously depleted. These changes compromise the capacity of the world to continue to provide, sustainably, sufficient food for humankind.

Freshwater supplies

In all continents, freshwater aquifers are being depleted of their "fossil water". Agricultural and industrial demand now often greatly exceed the rate of natural recharge. Water shortages are likely to cause tensions and conflict over coming decades (Homer-Dixon, 1994; Gleick, 2000). For example, Ethiopia and the Sudan, upstream of Nile-dependent Egypt, increasingly need the Nile's water for their own crop irrigation. Approximately 40 % of the world's population, living in 80 countries, now faces some level of water shortage. India has seen its per-person supply of freshwater drop from 5500 cubic metres per year in the 1950s to around 1800 cubic metres now, hovering just above the official scarcity threshold. By 2050 India's supply will be around 1400 cm per person – and, further, the slight drying due to global climate change that is projected by climate modelling would exacerbate this further (Cassen & Visaria, 1999).

Persistent organic pollutants

Many long-lived and biologically active chemicals have become widely distributed across the globe (Watson *et al.*, 1998). Lead and other heavy metals are present at increasing concentrations in remote environments. More worrying, various semi-volatile organic chemical pollutants (such as polychlorinated biphenyls) are disseminated towards the poles via a remarkable sequential "distillation" process through the cells of the lower atmosphere (Tenenbaum, 1998). Consequently, their concentrations are increasing in polar mammals and fish and in the traditional human groups that eat them. Their immunosuppressive effect has been demonstrated in seals, other marine mammals and rodents (Vos *et al.*, 2000). Current epidemiological studies in the Faroe Islands and elsewhere may soon tell us if humans are similarly affected.

1.3 Six phases of human ecology over the past 100 millennia

The story of human health and disease in relation to environmental conditions has deep roots in human prehistory and history. The profile of contemporary western diseases would have been as unrecognizable to your average Palaeolithic hunter-gatherer, early agrarian or nineteenth-century urban citizen as would their day-to-day procession of diseases be to our eyes. Over the past 100 millennia, humans have undergone an accelerating succession of environmental and cultural changes: dispersal, tool-making, patterns of social cohesion, agriculture, urbanism, sea-faring, and, latterly, industrialization. Six main phases can be identified, each ushering in new patterns of disease and death. Because these phases provide the backdrop to much of what follows in later chapters it may help to outline them here.

1.3.1 Hunter-gatherers

For most hunter-gatherers, the primary causes of death were physical trauma, infection or, less often, starvation. As with other animals, human life expectancy was that of young adulthood – only a successful or lucky minority completed a full reproductive lifespan. Fossil bones suggest an average lifespan of around 25 years.

The bones yield some evidence of trauma and malnutrition. The types of infections would have been limited to those compatible with small mobile human populations, probably including bacterial infections of skin, ears, nose and throat, various parasitic intestinal worms, and incidental infection with the malaria parasite and the African sleeping sickness trypanosome – both of which diseases were circulating in wild animals.

1.3.2 Agriculture, settlements and cities

Two important new influences on health emerged with agriculture, animal domestication and settlement: chronic nutritional deficiencies occurred and various "crowd infections" began to appear in urbanizing populations. Agrarian dependence on a restricted range of staple foods, with reduced meat intake, led to nutritional deficiencies. Early agrarians were distinctly shorter than their immediate hunter-gatherer predecessors. Agriculture, while greatly increasing local environmental carrying capacity, does not eliminate famines: they have persisted throughout most of history. Meanwhile, new contagious infections such as influenza, dysentery, smallpox and measles arose as mutated versions of long-established infections in newly domesticated animals or rodent pests. As villages became towns, and towns became cities, the magnificence and might of urban life unfolded, along with the crowding, oppression and squalor. Great civilizations came and went, often largely in response to the exhaustion of local agricultural systems or surface water supplies – as seemed to be the case, for example, with the 2000-year success story that once was Mesopotamia. Infectious disease epidemics occurred, sometimes in response to, and sometimes as a precursor of, great social and political upheavals.

1.3.3 Commerce, conquest and microbial confluence

Much later, as trade routes opened up, and as conquering armies spread their reach, so infectious diseases spread more widely. Smallpox and measles, unknown in Greece, reached Rome because of trade with the Middle East and Asia during the middle years of the Roman empire. The bubonic plague first arrived in cataclysmic fashion in the Roman Empire in the sixth century AD and in China shortly after. Bubonic plague (the Black Death) returned to Europe, again from the east, in the mid-fourteenth century, immediately following a devastating outbreak in China. The Spanish conquistadors in the early 1500s took measles, smallpox and other acute infectious diseases to the Americas, where, inadvertently, they proved to be terrible weapons of microbiological and psychological warfare. Relative to the genetically selected and immunologically battle-hardened Eurasian populations, Amerindians, Australian aboriginals and Pacific island populations were immunologically naive and were consequently devastated by these infections. The dissemination of many infectious diseases continues today, as poverty persists, as human mobility and trade increase, and as Third World populations urbanize.

1.3.4 Industrialization

The advent of mechanized agriculture in the eighteenth and nineteenth centuries, along with sea-freight and refrigeration, increased the food supplies to western countries. Europe's population expanded and spilled over to the Americas, southern Africa and Australasia. Industrialization and imperialism brought material wealth and social modernization to Europe. In the latter decades of the nineteenth century, improvements occurred in sanitation, housing, food safety, personal hygiene and literacy. These, in turn, led to control of infection. Later, immunization and antibiotics consolidated a new era of human supremacy over infectious diseases. Industrialization, meanwhile, also intensified the contamination of local environments with chemical pollutants. From early in the twentieth century, occupational exposures to hazardous chemicals and to ionizing radiation became more frequent.

1.3.5 Modern times: urban consumerism

Since World War II, human lifestyles in western countries have changed radically. Changes in food choices, dietary habits, smoking behaviour, alcohol consumption and physical inactivity have caused increases in various chronic noncommunicable diseases (and decreases in some others). Changes in sexual, contraceptive and reproductive behaviours have also greatly influenced patterns of infectious and noninfectious diseases – including human immunodeficiency virus and acquired immunodeficiency syndrome (HIV/AIDS), other sexually transmitted diseases, breast and ovarian cancers and cardiovascular diseases. Meanwhile, the introduction of life-saving public health and medical technology to Third World countries has reduced the childhood death toll from infectious diseases. Because this mortality decline has so far only been partially offset by a subsequent fall in fertility, rapid population increases have occurred in many of those countries in recent decades, creating additional demographic and resource pressures.

1.3.6 An increasingly full world: the advent of global environmental change

Today, the aggregate impact of the human population size and economic activity on various of the world's biophysical systems has begun to exceed the regenerative and repair capacities of those systems. Such overload has never before occurred globally; this is a historical "first". *Homo sapiens* now accounts for approximately

40 % of the total terrestrial photosynthetic product (actual or potential): by growing plants for food, by clearing land and forest, by degrading land (both arable and pastoral), and by building or paving over the land (Vitousek *et al.*, 1997).

This unfamiliar, historically unprecedented, situation of humankind overloading Earth's carrying capacity presents a special challenge to science. How can we best estimate the likely consequences for human health (or other outcomes) of the plausible future scenarios of environmental change (see Box 1.1 for an overview of the main global environmental changes affecting human health)? This question warrants careful consideration. It poses a number of challenges, some of them unfamiliar, to population health scientists. However, let us first review the recent history of evolving priorities in the topic area of "environment and health."

1.4 Environment and health: recent developments

At the 1972 United Nations Conference on the Human Environment, in Stockholm, concern was focused on the increasing release of chemical contaminants into local environments, the prospects of depletion of certain strategic materials, and some aspects of the modern urban environment. There were environmental hazards resulting from western industrial intensification, the rapid, programmed and often profligate industrialization in Soviet bloc countries, and the poorly controlled and increasingly debt-driven industrial and agricultural growth in newly-independent Third World countries. In consequence, the world experienced various serious episodes of air pollution (e.g. London in 1952), organic mercury poisoning (Minamata in 1956), heavy metal accumulation (especially lead and cadmium), pesticide toxicity and scares from environmental ionizing radiation exposures.

Today, similar toxicological environmental problems persist widely around the world. Since 1972, we have had Bhopal, Seveso, Chernobyl, and in 1999 the fatal reactor accident at Tokaimura in Japan. Air pollution is an increasing, often dramatic, problem in many large cities in the developing world.

Meanwhile, a further, unfamiliar, set of large-scale environmental problems has begun to emerge. Indeed, by the 1992 United Nations Conference on Environment and Development, in Rio de Janeiro, they were moving centre-stage. The World Commission on Environment and Development had, in the late 1980s, put "sustainable development" on the world's agenda. There was nascent recognition that we were beginning to live beyond Earth's means, that limits had been breached, and that the continuing increase in the weight of human numbers and economic activity therefore posed a new and serious problem – including risks to human health. Life-support systems were coming under threat at a global level.

These global environmental changes are a manifestation of a larger pattern of change in the scale and intensity of human affairs. Global climate change is one of the most widely discussed of these global environmental changes. In 1996, the United Nation's Intergovernmental Panel on Climate Change (IPCC) concluded that human-made changes in the global atmosphere were probably already beginning to change world climate (IPCC, 1996). During 1997 and 1998, global temperatures reached their highest levels since record keeping began in the mid-nineteenth century, and 1999 was also well above the century's average temperature. Overall, ten of the 12 hottest years of the twentieth century occurred after 1988. Around the world, during the late 1990s and turn of the century, it seemed that world weather patterns were becoming more unstable, more variable. In 2001, the IPCC firmed up its conclusion that human-induced climate change was already occurring, and raised its estimation of the likely range (1.4–5.8 °C) of temperature increase during the twenty-first century (IPCC, 2001).

The prospect that climate change and other environmental changes will affect population health poses radical challenges to scientists; fortunately, this has arisen at a time of growing interest among epidemiologists in studying and understanding the population-level influences on patterns of health and disease. These strivings to understand population disease risks and profiles within a larger contextual framework – be it social, economic, cultural or environmental – will, hopefully, be mutually reinforcing. After all, they share a recognition that there are complex underlying social, cultural and environmental systems which, when perturbed or changed, may alter the pattern of health outcomes. In this respect they recognize the *ecological* dimension of disease occurrence – that is, as changes occur in the systems that constitute the milieu of human population existence, so the prospects for health and disease are altered.

The exploration of these systems-based risks to human health seems far removed from the tidy examples that abound in textbooks of epidemiology and public health research. Yet there are real and urgent questions being posed to scientists here. The wider public and its decision-makers are seeking from scientists useful estimates of the likely population health consequences of these great and unfamiliar changes in the modern world. Illustrative of this expectation is that the World Health Organization's second estimation of the "global burden of disease", conducted during 2000–2001, included an estimation of the burden attributable to climate change scenarios over the coming decades. Similarly, the United Nations Development Program, in seeking to identify "global public health goods", has paid particular attention to large-scale environmental changes as manifestations of losses in fundamentally important "public health goods" – losses of common-property environmental assets that are likely to impact most on the world's poor and vulnerable populations, and are likely to compound over the coming generations.

Clearly, there is a major task for health scientists in this topic area. This book seeks to identify the nature and scope of the problem, and to explore the conceptual and methodological approaches to studying these relationships, modelling their future realization, providing estimates of health impacts and communicating the attendant uncertainties. The next section of this opening chapter overviews the strategies available for studying and estimating the health impacts of climate change.

1.5 Challenges to population health research

The great majority of researchers are *empiricists* by training and tradition, studying the past and the present by direct observation. By definition, empirical methods cannot be used to study the future. To the extent that the advent of global environmental change obliges scientists to estimate future impacts, should current or foreseeable trends continue, then empiricism must be supplemented by predictive modelling. Epidemiologists, whose primary task is to identify risks to health from recent or current behaviours, exposures or other circumstances, are not much oriented to asking questions about health impacts several decades hence. That is beyond the time horizon and methodological repertoire of the standard textbook.

Western science has long set great store by *reductionism* – the assumption that one can understand the working of the whole by studying the component parts. Further, western science classically conducts such studies, preferably by deliberate experiment, by holding constant the context (i.e. other background factors) so as to more clearly describe and quantify some specific relationship. However, we cannot meaningfully study a complex dynamic system, such as an ecosystem or the world's climate system, by reducing it to a set of parts, assuming that each part is amenable to separate study.

Yet, these contextual difficulties aside, population health scientists must find ways to estimate the potential health consequences of current social and environmental trajectories. Not only is this an interesting scientific task, but – crucially – it will assist society in seeking a sustainable future. Clearly, elucidating these risks to population health from environmental changes such as long-term changes in global climatic patterns, depletion of stratospheric ozone and biodiversity loss poses a special research challenge (see Chapters 2 and 3). For a start, these environmental changes entail unusually large spatial scales. They also entail temporal scales that extend decades, or further, into the future. Some entail irreversible changes. While some direct impacts on health would result – such as the health consequences of increased floods and heatwaves due to global climate change, or increases in skin cancer due to ozone depletion – many of the impacts would result from disruption of the ecological processes that are central to food-producing ecosystems or to the ecology of infectious-disease pathogens. That is, many of the causal relationships are neither simple nor immediate.

1.5.1 Concepts

A fundamental characteristic of this topic area is the pervasive combination of complexity and uncertainty that confronts scientists. Policy-makers, too, must therefore adjust to working with incomplete information and with making "uncertainty-based" policy decisions. They must jettison misplaced assumptions that scientists can provide final and precise truths. Relatedly, society at large will have to come to terms with the Precautionary Principle, in order to minimize the chance of low-probability but potentially devastating outcomes. When the science is uncertain or infeasible and the stakes are potentially high, better to be safe than sorry. While scientists dislike "false positives" (hence their reflex invocation of statistical significance tests), society's interest lies in not being caught out by science's "false negatives".

Several aspects of the complexity and uncertainty of this research domain are dealt with specifically in three of the subsequent sections. Those aspects are: (i) complexity and surprises, (ii) uncertainties, and (iii) determinants of population vulnerability, and adaptive capacity, to these environmental changes.

1.5.1.1 Complexity and surprises

Predicting the impact of a changing world on human health is a hard task and requires an interdisciplinary approach drawn from the fields of evolution, biogeography, ecology and social sciences, and it relies on various methodologies such as mathematical modelling as well as historical and political analysis (see later). When even a simple change occurs in the physical environment, its effects percolate through a complex network of physical, biological and social interactions, that feed back and feed forwards. Sometimes the immediate effect of a change is different from the long-term effect, sometimes the local changes may be different from the region-wide alterations. The same environmental change may have quite different effects in different places or times. Therefore, the study of the consequences of environmental change is a study of the short- and long-term dynamics of complex systems, a domain where our common sense intuitions are often unreliable and new intuitions have to be developed in order to make sense of often paradoxical observations (see Chapter 4).

1.5.1.2 Uncertainties

The prediction of environmental change and its health impacts encounters uncertainties at various levels. Some of the uncertainties are of a scientific kind, referring to deficient understanding of actual processes; for example, knowing whether increased cloud cover arising from global warming would have a positive or a negative feedback effect. Some of the uncertainties refer to the conceptualization and construction of mathematical models in which the specification of linked processes may be uncertain or whose key parameter values are uncertain (see also Chapter 8). For example, what is the linkage between changes in temperature, humidity and surface water in the determination of mosquito breeding, survival and biting behaviour? Some uncertainties are essentially epistemological, referring to what we can and cannot reasonably foresee about the structure and behaviour of future societies, including for example their future patterns of greenhouse gas emissions. And, finally, there is of course the familiar source of uncertainty that arises from sampling variation, and which leads to the need for confidence intervals around point estimates.

Human societies have, of course, some experience of uncertainty-based policy-making. We avoid locating housing developments around nuclear power plants because of the recognized finite but unquantifiable risk of serious accident. We have taken various actions to prevent the final extinction of many species of plants and animals, in part because of concerns about likely but uncertain knock-on consequences for the functioning of ecological systems. Yet it is also clear that many such decisions are delayed or otherwise hampered by a lack of information about quantifiable risks, and hence, also, a lack of information about the likely economic costs to society. There is a need to reduce the gap between these two domains, the risk-based and the uncertainty-based policy-making. At least that need will exist while we come to terms with the as-yet unfamiliar inevitability of a substantial amount of uncertainty, as a property of the systems and processes in which changes are occurring (see Chapter 12).

1.5.1.3 Vulnerability and adaptation

Human populations vary in their vulnerability to health hazards. A population's vulnerability is a function of the extent to which a health outcome is sensitive to climate change and of the population's capacity to adapt to the new climate conditions. The vulnerability of a population depends on factors such as population density, level of economic development, food availability, local environmental conditions, pre-existing health status, and the quality and availability of public health care.

Adaptation refers to actions taken to lessen the impact of the (anticipated) climate change. There is a hierarchy of control strategies that can help to protect population health. These strategies are categorized as: (i) administrative or legislative; (ii) engineering; or (iii) personal (behavioural). Legislative or regulatory action can be taken by government, requiring compliance by all, or by designated classes of, persons. Alternatively, an adaptive action may be encouraged on a voluntary basis, via advocacy, education or economic incentives. The former type of action would normally be taken at a supranational, national or community level; the latter would range from supranational to individual levels. Adaptation strategies will be either reactive, in response to observed climate impacts, or anticipatory, in order to reduce vulnerability to such impacts (see Chapter 11).

1.5.2 Research methods

Next to the conceptual challenges we have to face, the assessment of the risks to population health from global environmental change requires several complementary research strategies. Research into the health impacts of these environmental changes can be conducted within three domains, and there is a variety of methods that can be used within each domain (see Chapter 5). The three categories of research are:

(i) The use of historical and other analogue situations which, as (presumed) manifestations of existing natural environmental variability, are thought likely to foreshadow future aspects of environmental change. These empirical studies help to fill knowledge gaps, and strengthen our capacity to forecast future health impacts in response to changing environmental–climatic circumstances.
(ii) The seeking of early evidence of changes in health risk indicators or health status occurring in response to actual environmental change. Attention should be paid to sensitive, early-responding, systems and processes.
(iii) By using existing empirical knowledge and theory to model future health outcomes in relation to prescribed scenarios of environmental change. This is referred to as scenario-based health risk assessment.

1.5.2.1 Analogue studies

Empirically based knowledge about the relationship between climate and health outcomes is a prerequisite to any formal attempt to forecast how future climate change is likely to affect human health. In fact, we cannot know in advance the exact configurations of the future world. Indeed, we should assume that in some respects the future will be unlike the present, both in its overall format and in the component relationships between now-familiar variables which, in future, will occur at unfamiliar levels. (For example, will the rate of evolution of drug resistance in malarial parasites increase as temperatures rise and generation time shortens? Will new pests and pathogens emerge in agriculture, thereby reducing harvest yields, as climatic conditions change? And will the North Atlantic deep-water formation system – part of the heat-transferring oceanic "conveyor belt" – weaken as ocean temperatures rise several degrees centigrade?) Nevertheless, our best guide to foreseeing the future is to have studied and understood the past and present (see Chapter 6).

1.5.2.2 Empirical studies of early health effects

If recent global climate trends continue, and it becomes more certain that this process is the beginning of anthropogenic climate change, then epidemiologists must seek early evidence of impacts on health. Such things as patterns of heat-related deaths, the seasonality of allergic disorders, and the geographical range and seasonality of particularly climate-sensitive infectious diseases can be expected to begin to change.

There is evidence that the global climate change over the past quarter-century has begun to affect patterns of plant growth and distribution, particularly at mid-latitudes and in many mountain regions, e.g. the Alps (Grabherr *et al.*, 1994). There is also good evidence of climate-related changes in the distribution and behaviour of animal species both within Europe and elsewhere. For example, the northern limit of the distribution of tick vectors for tick-borne encephalitis moved north in Sweden between 1980 and 1994. Further analysis shows that changes in the distribution and density of that tick species over time have been correlated with changes in seasonal temperatures and human disease (Lindgren *et al.*, 2000; 2001).

There is little evidence yet of changes in human population health that can be attributed to the observed recent changes in climate (principally the warming that has occurred over the last 20 years). The debate has primarily focused on malaria in the highlands (Epstein *et al.*, 1998; Reiter, 1998; Hay et al., 2002). Although many highland regions, particularly in Africa, have experienced a resurgence of malaria, the existence of many co-varying factors (e.g. land-use change, population movement) and too few time-series datasets has impeded formal assessment of the climate–malaria relationships. So, too, has the variable and often poor quality of the available data (see Chapter 7).

1.5.2.3 Modelling

Modelling is often used by epidemiologists to analyse empirical data; for example, to gain insights into the underlying dynamics of observed infectious-disease epidemics such as HIV. The estimation of the future health impacts of projected scenarios of climate change poses some particular challenges, because of both the complexity of the task and the difficulties in validating the model against relevant historical datasets and, relatedly, in then calibrating it against external observations. Several modelling approaches are used, particularly empirical-statistical models, process-based models and integrated models. The choice of model depends on several factors, such as the purpose of the study and the type of data available (see Chapters 4 and 8).

1.5.2.4 Geographical Information Systems and remote sensing

Remote sensed (RS) data from weather satellites can be used to monitor changes in temperature and precipitation in order to predict continental and global patterns of disease outbreaks. Higher resolution satellite data can been used in a landscape epidemiological approach to model patterns of disease-transmission risk at local to regional scales. A comprehensive model of disease risk due to, for example, climate change should incorporate the temporal aspects of the climate models integrated with the spatial forecasting made possible by the use of Geographical Information Systems (GIS) technologies and spatial analyses. RS and GIS technologies provide unprecedented amounts of data and data-management capabilities (see Chapter 9).

1.5.2.5 Monitoring

A range of national, regional and international organizations routinely collect relevant data, most obviously those monitoring environmental conditions, and (usually separately) health status. While these systems constitute a potentially powerful resource, most were implemented for purposes other than studying environmental change effects on health. Monitoring is “the continuous or repeated observation, measurement and evaluation of health and/or environmental data for defined purposes, according to prearranged schedules in space and time, using comparable methods for sensing and data collection.” Environmental change/health monitoring should be directed towards the following aims: (i) early detection of the health impacts of global environmental change; (ii) improved quantitative analysis of the relationships between environment and health; (iii) improved analysis of population vulnerability; (iv) prediction of future health impacts of environmental change, and validation of predictions; and (v) assessment of the effectiveness of adaptation strategies. From the above it becomes clear that monitoring will also be an important component in the other methods mentioned earlier (see Chapter 10).

1.6 Conclusions

The advent of global environmental change, with its complexities, uncertainties and displacement into the future, brings new challenges and tasks for science, the public and policy-makers. The advent of this research task also poses a political and moral dilemma. We already face many serious and continuing local environmental health hazards. Poor populations around the world are exposed to unsafe drinking water, which is microbiologically contaminated or, in the case of Bangladesh, contains toxic levels of arsenic. Environmental lead has been widely dispersed in the modern world, via industry, traffic exhausts and old house-paints; it continues to blight child intellectual development. Urban populations face continuing hazards from air pollution. All of these environmental health issues must continue to command our attention. Yet, now, we must also extend the agenda of research and policy advice to include the larger-framed environmental change issues as emerging hazards to the health of current and future populations. This, as has been made clear in this book, will entail not just an expansion of effort but a widening of the repertoire of science.

We are entering a century in which science must increasingly engage in issues relating to the processes and consequences of changes to ecological systems, be they the systems of the natural biosphere, the biophysical systems of global climate, or the increasingly large and complex social systems in which we live our lives. While we do our best as scientists and policy-makers to understand and ameliorate the present, we must, increasingly, look to the need to anticipate the future – and seek a socially and ecologically sustainable path to it.

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