The Greening of Global Warming

The Greening of Global Warming

Robert Mendelsohn

The AEI Press

Publisher for the American Enterprise Institute

WASHINGTON, D.C.

1999

Available in the United States from the AEI Press, c/o Publisher Resources Inc., 1224 Heil Quaker Blvd., P.O. Box 7001, La Vergne, TN 37086-7001. To order, call toll free 800-269-6267. Distributed outside the United States by arrangement with Eurospan, 3 Henrietta Street, London WC2E 8LU England.

ISBN 0-8447-7132-5

1 3 5 7 9 10 8 6 4 2

THE AEI PRESS
Publisher for the American Enterprise Institute
1150 17th Street, N.W., Washington, D.C. 20036

Printed in the United States of America

Contents

Foreword

This volume is one in a series commissioned by the American Enterprise Institute to contribute to the debates over global environmental policy issues. Until very recently, American environmental policy was directed toward problems that were seen to be of a purely, or at least largely, domestic nature. Decisions concerning emissions standards for automobiles and power plants, for example, were set with reference to their effect on the quality of air Americans breathe.

That is no longer the case. Policy makers increasingly find that debates over environmental standards have become globalized, to borrow a word that has come into fashion in several contexts. Global warming is the most prominent of those issues: Americans now confront claims that the types of cars they choose to drive, the amount and mix of energy they consume in their homes and factories, and the organization of their basic industries all have a direct effect on the lives of citizens of other countries—and, in some formulations, may affect the future of the planet itself.

Other issues range from the management of forests, fisheries, and water resources to the preservation of species and the search for new energy sources. Not far in the background of all those new debates, however, are the oldest subjects of international politics—competition for resources and competing interests and ideas concerning economic growth, the distribution of wealth, and the terms of trade.

An important consequence of those developments is that the arenas in which environmental policy is determined are increasingly international—not just debates in the U.S. Congress, rulemaking proceedings at the Environmental Protection Agency, and implementation decisions by the states and municipalities, but opaque diplomatic "frameworks" and "protocols" hammered out in remote locales. To some, that constitutes a dangerous surrender of national sovereignty; to others, it heralds a new era of American cooperation with other nations that is propelled by the realities of an interdependent world. To policy makers themselves, it means that familiar questions of the benefits and costs of environmental rules are now enmeshed with questions of sovereignty and political legitimacy, of the possibility of large international income transfers, and of the relations of developed to developing countries.

In short, environmental issues are becoming as much a question of foreign policy as of domestic policy; indeed, the Clinton administration has made what it calls "environmental diplomacy" a centerpiece of this country's foreign policy.

AEI's project on global environmental policy includes contributions from scholars in many academic disciplines and features frequent lectures and seminars at the Institute's headquarters as well as this series of studies. We hope that the project will illuminate the many complex issues confronting those attempting to strike a balance between environmental quality and the other goals of industrialized and emerging economies.

Christopher DeMuth
Robert W. Hahn
American Enterprise Institute
for Public Policy Research

Acknowledgments

I want to thank Robert Hahn for his support, comments, and inspiration. I would also like to thank Christopher DeMuth, Christopher Green, James Neumann, Joel Smith, and Larry Williams for their helpful comments. I thank Larry as well for preparing the color map.

Robert Mendelsohn

The Greening of Global Warming

The world has yet to face a more important environmental policy decision than that to be made about controlling greenhouse-gas emissions. On the one hand, there is the potential threat that climate change will cause large ecological and human impacts; on the other, the trillions of dollars of abatement costs required to curb emissions. Striking a balance between the implied threat and those immense costs is an imposing challenge.

Introduction

This essay discusses the near revolution that has occurred over the past decade in our understanding of the impacts of climate change. Both the natural science and the economics underlying predictions of climate-change impacts have altered dramatically. We now have a perspective entirely different from that of a decade ago on what climate change is likely to do to the economy and to our quality of life.

The new research suggests that climate warming will not be as harmful as we once thought it might be. Climate scientists have reduced the magnitude of predicted warming, suggesting milder future climate scenarios. Ecologists have shifted from predicting ecosystem collapse to predicting that net primary productivity will likely increase over the long run. And economists are no longer predicting large damages, but rather a mixture of damages and benefits.

These changes are so dramatic that it is not clear whether the net economic effects from climate change over the next century will be harmful or helpful. The new research further suggests that effects are likely to vary across the planet. We now expect temperate and polar countries to enjoy small economic gains, whereas tropical countries are more likely to suffer economic losses.

Of course, we have not banished all uncertainty, which will always haunt future projections of outcomes. The dynamics of ecosystems are poorly understood; carbon cycles may change over time; polar ice may generate unwelcome surprises; and the effects of change on tropical regions have not yet had the thorough study they require. Nonetheless, the recent scientific and economic findings create a new perspective on the greenhouse-gas problem, and this new vision, in turn, calls for new strategies and new political outcomes.

The reduction in damage-estimates removes the urgency to engage in costly crash abatement programs. Our initial perspective on greenhouse gases suggested that we were rapidly approaching the edge of a cliff. Those fears now appear unfounded, for the impacts from climate warming seem to be relatively small for the next century. There will be damages to be sure, but they will be offset by benefits. The net expected effect now is closer to zero rather than to 2 percent of GDP. As a consequence, new abatement policies should be designed for the long run, and should be inexpensive and cost-effective.

In the absence of aggressive and expensive abatement, greenhouse gases will continue to accumulate in the atmosphere, and we will experience warming. We must learn to adapt to warming, and government policy must encourage efficient adaptation. Much of the adaptation will be private, as people and firms change their behavior to accommodate to the new environment. But some of it must be public, because actions such as building sea walls, controlling vector-borne diseases, or building new dams benefit many people.

Because the consequences of warming will vary across countries, the countries' interest in imposing controls will vary as well. Many countries will benefit from warming—the very countries, ironically, that have contributed the most to historic emissions. The industrialized nations of the earth happen to lie in boreal and temperate climates, where warming is likely to prove beneficial. Countries in subtropical and, especially, tropical climates—which to date have made no commitment to reduce their greenhouse-gas emissions—are likely to be damaged by warming. As each country becomes aware of national impacts, the impacts will become more important to the countries and affect future negotiations about abatement measures and costs. Each country will perceive different rewards for itself in taking action, and that will make it increasingly difficult to construct international agreements. Successful agreements will almost certainly have to include a compensation package to encourage at least some nations to cooperate.

In this essay I summarize what was understood about impacts a decade ago and show how much our understanding has changed since then. I then summarize (a) the changes in the natural sciences that have occurred over the past decade that provide the foundation for the economic projections of impacts, and (b) the changes in economic understanding of both market and quality-of-life impacts. In combination, the results from the new scientific and economic studies bring a new perspective, and in the final section of the essay I develop some of the consequent policy implications.

A Historical Perspective

In 1989, the U.S. Environmental Protection Agency issued the first comprehensive assessment of the impacts of greenhouse gases (Smith and Tirpak 1989). The study, which proved remarkably influential, provided a state-of-the-science review that linked emissions, greenhouse-gas accumulation, climate change, and economic and quality-of-life impacts. In effect, the report created the perspective that drives current policy—the view that climate change would cause great economic damage and great damage to our quality of life. Although the EPA study was limited to the United States, the conclusion that subsequent analysts reached, based on the study, was that the damages resulting from climate change would be universal and devastating (Pearce et al. 1996).

A review of what led the EPA to its conclusion will be helpful. Climate models from the period predicted that the doubling of greenhouse gases in the atmosphere would result in dramatic climate-change scenarios. The EPA report, for example, assumed that the doubling would cause sea levels to rise one meter. The climate models used in the report predicted temperature increases of from 3°C to 6°C, and the temperature increases were often accompanied by sharp reductions in precipitation during the growing season. Such predictions of climate change are relatively severe and suggest dramatic consequences.

The ecological models in the EPA report were also pessimistic. For example, the regional-gap models employed to study forest ecosystems suggested that many tree species would disappear. Maples would be driven from southern New England, and species in other regions would be damaged. Ecosystem balances would be destroyed, and the collapse of many terrestrial ecosystems would follow. The collapsing ecosystems would stress all species, but climate change was predicted to lead in particular to extensive loss of endangered species.

Pessimistic biological predictions extended to agriculture, and many crops were to suffer dramatic reductions in yields of from 30 to 40 percent. Although those effects were moderated when CO_2 was included in the calculations, the report did not make clear that one should include carbon-fertilization effects. Subsequent analysts placed equal weight on the scenarios with and without carbon fertilization (for example, Nordhaus 1991), and some chose to downplay carbon fertilization even further (Cline 1992). The life forms that were predicted to prosper in the new environment were pests and diseases: insects would pose a greater risk to crops and forests; vector-borne diseases from mosquitoes and other insects would spread as a result of the warmer climate and release third-world diseases across the United States.

The impact on human systems was to be severe. Energy systems would require extensive new capacity to cope with the demand for cooling. Agriculture would suffer dramatic yield reductions, and prices would rise. Runoff would diminish, and water systems and irrigation would reflect the reduction. Water-pollution levels would rise in the absence of sufficient runoff for dilution. Forests would die back and leave timber supplies scarce. Heat waves would strike the elderly and cause deaths to soar. Coastal structures would have to be protected by costly sea walls. Air-pollution levels would rise as secondary pollutants, such as ozone, formed more rapidly in the heat. Virtually all economic and quality-of-life phenomena associated with ecosystems would generate damages. In fact, there were to be damages in almost every sensitive sector.

Building on this scientific foundation, economists developed quantitative estimates of the size of climate-change damages. Nordhaus (1991, 1994) predicted that the doubling of greenhouse gases would cause the United States damages amounting to about 1 percent of GDP. Subsequent analysts confirmed the aggregate predictions for the United States, although the estimates by sector, as seen in tables 1 and 2 (page 15), varied widely (Pearce et al. 1996). Extrapolations to other countries led to similar predictions for other members of the Organization for Economic Cooperation and Development (OECD) and damages ranging from 2 to 8 percent of GDP in many developing countries (Fankhauser 1995; Tol 1995). Global damages from the doubling of greenhouse gases were predicted to range from

1 to 2 percent of global GDP (Pearce et al. 1996). That is an enormous impact. Given a predicted global GDP of about $170 trillion by the year 2100, the Pearce et al. forecast leads to damages of $1.7 trillion to $3.4 trillion annually by 2100.

New Scientific Studies

Though many dramatic advances in the science of climate change over the last decade have altered our understanding of the phenomenon, three factors in particular have contributed to the emergence of a new perspective. First, modelers have developed transient ocean-atmosphere models that do a better job of capturing the dynamic relationship between oceans and the atmosphere. Second, scientists have discovered that sulfates cool the atmosphere. Third, continued climate measurements have confirmed the presence of a warming trend, but the trend is smaller than what earlier models predicted.

The transient ocean-atmosphere models, which capture the interaction between the warming of the ocean and climate, provide a more realistic tool for modeling the dynamics of greenhouse gas–climate interactions. The models predict much slower warming than the earlier equilibrium climate models. The discovery that sulfates are coolants explains an important geographic anomaly: that the cooler temperatures around the northern industrial countries are a consequence of the high quantities of sulfates found in those regions. Careful measurements of climate around the globe yield another important insight. The climate has been warming, but at a rate closer to the coupled-model predictions than to the predictions of earlier models. The net result of all these changes is that climate scientists are more confident in their prediction that greenhouse gases will cause warming, though they have also revised downward their estimate of the range and the expected amount of warming that will occur.

Whereas the EPA report worked with changes of from 3°C to 6°C by the middle of the next century, the International Panel on Climate Change (IPCC) now predicts changes of from 1°C to 3.5°C by 2100 (Houghton et al. 1996). The average amount of global warming expected for the next century without any abatement program is 2°C. Given that the most dramatic warming is predicted for the poles, most places where people currently live would endure changes of less than 2°C spread over the next century. The rate of predicted warming has fallen from about 0.5°C per decade to about 0.2°C per decade. Conjoined with these small temperature changes are an average increase in precipitation, more than a doubling of carbon dioxide, a reduction in the diurnal cycle (from warming at night), and a sea-level rise of about 50 centimeters. The reductions in predicted magnitudes are very significant.

Ecosystem modeling has developed rapidly, and ecogeography models have improved their ability to generate the potential distribution of natural vegetation across the earth (Neilson and Marks 1994; Neilson et al. 1992; Prentice et al. 1992; Haxeltine and Prentice 1996; Woodward et al. 1995). The models can predict the areas where forests of different types will grow and the areas that will become grasslands. The models can also predict how ecosystems will shift in a new climate. Not surprisingly, the models predict that warming will cause ecosystems to shift generally to higher latitudes.

The predictions of the ecogeological models are in sharp contrast to the predictions of ecosystem collapse generated by the gap models (Smith and Tirpak 1989). Rather than portraying the destruction of ecosystems around the world, the models simply display an alternative geographic pattern of ecosystems across the earth's surface. Even if many of the expanding ecosystems are considered desirable, the process of change will inevitably produce unwanted effects as well. The effects on endangered species remain largely unstudied, but they are likely to be harmful. Some shifts will be more harmful than helpful: deserts might expand, for example, or forest systems become grasslands. In presenting this complex set of changes, analysts must be careful not to focus only on harmful consequences but to give a balanced and representative view of all the myriad effects.

A second set of ecosystem models has begun to explore the effect of climate change on the metabolism or productivity of ecosystems. These ecophysiology models measure such key phenomena as photosynthetic rates and net primary productivity (Melillo et al. 1993; Running and Coughland 1988; Running and Gower 1991; Parton et al. 1988). Their assessment of carbon fertilization has been especially important. Experiments in laboratory conditions have indicated that certain plants grow much more readily in a CO_2-enhanced world. Although the magnitude of the benefits may be somewhat mitigated in a natural ecosystem context, the carbon-fertilization results point to more optimistic outcomes. They were largely supported by the ecophysiology models, which suggest that net primary productivity is likely to increase with warming. That is, a warmer, wetter world, with enhanced CO_2, is likely to be a greener world as well.

The insights of the ecophysiology and ecogeographic models together yield a new perspective on the ecosystem consequences of greenhouse gases. Tropical and temperate systems move to higher latitudes and push boreal forests into current tundra. Potential forest vegetation appears overall to increase. As ecosystems shift to new locations, animal populations will also shift. Overall productivity rises, but not uniformly.

There will be many changes associated with warming, then, and they do not readily translate into any single index. That is to say, a worldwide shift in ecosystems is likely to lead both to myriad benefits and to myriad damages. In general, the new results suggest an expansion in bioproductivity, which is a far more optimistic result than past predictions. It is important to note, however, that the available models focus on equilibrium effects. We still know little of the dynamics of ecosystem change and of how ecosystems will shift from one equilibrium to another. Thus, it is likely that the pace of change will be important to ecosystems and may introduce transient effects that the equilibrium models cannot foresee.

More optimistic scientific results also affect agronomy. The direct effect of increases in temperature on crop yields is mildly harmful in temperate climates and more severe in tropical climates (Reilly et al. 1996). But that effect is counterbalanced by a strong, positive carbon-fertilization effect. The average crop is 30 percent more productive in a CO_2-enhanced world (Reilly et al. 1996). Aggregate world production will likely be robust; production increases in temperate climates (Reilly et al. 1996) will offset small reductions in tropical output.

Even estimates of heat stress have changed over time. Daily mortality studies show that large increases in death among the elderly follow early summer heat waves (Watson et al. 1996). The studies were used to argue that warming would increase heat-stress deaths by from 6,600 to 9,800 per year in the United States alone (Pearce et al. 1996). Analyses of annual mortality rates, however, show that the elderly live longer in warmer climates (Mendelsohn and Shaw 1998; Moore 1998). A closer examination of heat-stress deaths reveals that they are higher in cold parts of the United States with high seasonal temperature variability. The death rates are relatively low in stable warm climates. Thus, heat-stress deaths appear to be caused not by warming but by temperature variability. They will grow in number not as climates warm but as the variability in climate increases.

New Economic-Impact Studies

The revolution in economic studies of impacts has been as significant as that in the scientific studies. The new economic studies take a more representative view of sensitive sectors. Instead of studying only damages, they consider all changes, including many benefits. They carefully model adaptation and note how individuals and systems change in response to climate change. They treat capital-intensive sectors with dynamic models. They synchronize responses to match problems and reduce overall costs through gradual adjustments.

Measuring the impact of climate change is difficult because climates change slowly and the impacts are hidden by the numerous more dramatic changes that take place simultaneously. Analysts have developed two broad methods to help them learn about potential global warming impacts. One approach uses a combination of controlled scientific experiments and simulation models. The controlled experiments teach us how critical components of our economy and environment respond to alternative climates and carbon dioxide levels. The simulations then predict how systems will react given the experimental results. The alternative approach relies on cross-sectional evidence. Analysts compare what happens to farms, homes, and people in different climates. If warm places experience problems and cooler locations do not, the evidence provides a clue that warming would be harmful.

No method supplies a perfect picture of what will actually happen. The experimental approach does a good job of isolating the factors of concern, such as temperature, precipitation, and carbon dioxide. But only a limited number of experiments can be conducted, and they may not be representative of environmental conditions everywhere. Thus, scientists may study the impact of temperature on the performance of a crop. Crop research stations, however, are usually located near where that crop grows best. For example, the station could be at the optimum location for wheat, as depicted in figure 1 (page 17). Moving to warmer temperatures will harm wheat productivity at that research station. The simulation models might assume that warming reduces productivity across the landscape by that same amount. However, for farms that are cooler than the optimum, warming could actually increase productivity. So the farm in the optimal location is not likely to be representative of the effects across the landscape.

Controlled experiments also fail to account for adaptation adjustments that farmers might make to mitigate the damages from warming. The results with adaptation are likely to be much less harmful than such experiments suggest, as shown in both figures 1 and 2 (page 17). For example, if the wheat farmer makes no adjustment in how he grows wheat, he may experience dramatic losses, as shown in figure 1. By adjusting varieties, timing, and other subtle factors, the farmer may be able to mitigate some of those losses. The farmer may also choose to switch crops, as shown in figure 2. If he continues to grow wheat, he will experience small losses. But if he shifts from wheat to corn, he could experience a net gain. The adjustments can be built into the simulations, but analysts rarely understand, and include, all the reactions that complex changes might induce. The result is that the experimental approach tends to underestimate adaptation. In contrast, the cross-sectional approach is likely to take long-run adaptation into account, as people adjust to where they live. By comparing a farmer in Minnesota with a farmer in Iowa, one is already taking adaptation into account, because each farmer has adjusted his techniques for the climate he experiences. Of course, the cross-sectional results provide only long-run outcomes and do not reflect the dynamics of adjustment.

There are other problems with the cross-sectional approach. It has trouble isolating climate effects from other factors. Thus, the analyst may attribute a measured climate effect to some unseen (by the analyst) phenomenon that happens to be spatially associated with climate. For example, economic activity might prosper from a close proximity to ports; lands near ports tend to be coastal; and coastal lands, in turn, have moderate climates because they are tempered by large bodies of water. An unsuspecting analyst could confuse climate with access to ports. Other factors that the cross-sectional analysis does not foresee may suddenly turn out to be critical. A cross-sectional analysis might predict that a new ecosystem will replace an old one without considering that there may be no mechanism to introduce a new system. Further, the cross-sectional approach cannot measure the consequences of phenomena that do not vary across the sample, such as carbon dioxide concentrations and prices. Curiously, the strengths of the cross-sectional approach are the weaknesses of the experimental approach, and vice versa.

By studying both experimental results and cross-sectional results, analysts have been able to learn a great deal about the sensitivity of different ecological and human systems to climate (Mendelsohn and Neumann 1999). The net benefits from many systems exhibit a hill-shaped relationship to temperature (Mendelsohn and Schlesinger 1999). Starting from a cool climate, warming at first is beneficial. That effect gradually wanes, however, and a maximum is reached. Warming beyond that point is increasingly harmful. The exact shape of the climate-response function and the precise maximum point vary by sector. For energy, reductions in heating costs at first dominate. As temperatures warm, however, cooling costs rise and eventually dominate. The region with the lowest overall energy costs appears to be in a temperate climate. Crops also appear to reach a maximum net value in the temperate region. Timber, in contrast, appears to reach a maximum value in the subtropical region.

Determining whether warming is good or bad depends on where one starts, how much warming is involved, and what sector is being examined. There is an unstated myth in ecology that natural conditions must be optimal. That is, we must be at the top of the hill now. Of course, given the wide distribution of temperatures across the earth, that cannot be true for everyone. In general, countries in cold climates are likely to benefit from warming, temperate countries are likely to be only slightly affected, and countries in hot climates are likely to be adversely affected. This distribution of impacts differs sharply from the historic vision that warming would damage all countries. Further, mild climate scenarios, such as those predicted for the next century, are likely to contain many benefits, as well as damages.

The estimated climate-response functions suggest that net benefits are quadratic in temperature (Mendelsohn and Schlesinger 1999). As climate projections shift from large to small temperature changes, impacts will tend to shrink even more dramatically. For example, if the predicted temperature changes were to fall by one-half, the expected impacts would fall to a quarter of their previous size. It is not surprising that the new estimates of damages are so much lower than the old estimates (tables 1 and 2).

The more optimistic ecosystem predictions have also resulted in a dramatic revision of impacts. A comprehensive analysis of the United States (VEMAP 1995) examined the results of combining three ecophysiology models and three ecogeography models. The general increase in bioproductivity and the expansion of the more productive Southern pine region outweighed the reductions in more economically marginal forests, resulting in a general expansion of timber supply. Integrating these biological predictions into a dynamic forestry model suggests substantial benefits in the timber sector (Sohngen and Mendelsohn 1998). Even with dieback occurring as forests shift from one ecosystem to another, the U.S. timber sector is likely to benefit when timber harvesting moves forests quickly to more productive stands.

The U.S. studies show important effects, but are they representative of effects elsewhere in the world? To address that question, it is helpful to extend the U.S. analyses to other regions. Thus, to study global timber effects, MAPS3 was used to predict ecological effects for the entire world

(Haxeltine and Prentice 1996), and a dynamic global economic model of timber was constructed (Sohngen et al. 1999a). Integrating the ecological predictions of MAPS3 into the economic model predicts a worldwide expansion of timber supply from greenhouse gases and climate change (Sohngen et al. 1999b). The timber expansion would lower prices and generate substantial benefits. Such predictions of benefits stand in dramatic contrast to the predicted damages to timber made by earlier analysts (see table 1).

Another sector that has undergone a dramatic revision of its prospects under climate change is agriculture. As noted in the discussion of science studies, agronomists have revised some of their estimates of yield effects because of carbon fertilization benefits. Agro-economic models have also done a much better job of incorporating adaptation (Easterling et al. 1993; Kaiser et al. 1993; Adams et al. 1999) and of carefully modeling efficient adaptation changes that leave farmers better off. The studies reveal that farmers can make adjustments in their tilling, irrigation, planting, and harvesting decisions that significantly reduce the damages from warming. Further, cross-sectional studies of agriculture suggest very similar estimates (Mendelsohn et al. 1994, 1996, 1999a; Segerson and Dixon 1999). Combining the effects of adaptation and carbon fertilization suggests that agriculture in the United States will benefit from warming (table 1). Again, these results stand in sharp contrast to predictions of large agricultural damages (Pearce et al., 1996).

As with the studies of timber, it is helpful to extend the results of the agricultural studies beyond the United States. An interesting set of new studies has used a cross-sectional approach to explore the climate sensitivity of agriculture in Brazil (Sanghi and Mendelsohn 1999) and India (Dinar et al. 1998). The results suggest that both countries will suffer small damages from warming. Net agricultural revenue was expected to fall 8 percent in Brazil and 12 percent in India as a consequence of a 2°C warming

TABLE 1
ANNUAL IMPACT ON U.S. ECONOMY OF DOUBLING GREENHOUSE GASES
(in billions of 1990 dollars)

Sector	*Estimates* Old[a]	New[b]	New[b]
Agriculture	–1.1 to –17.5	11.3	41.4
Energy	–1.1 to –9.9	–2.5	–4.1
Sea level	–5.7 to –12.2	–0.1	–0.1
Timber	–0.0 to –43.6	3.4	3.4
Water	–7.0 to –15.6	–3.7	–3.7
Total	–14.4 to –67.5	8.4	36.9
% GDP	–0.3 to –1.2	0.2	0.2

a. Pearce et al. 1996
b. Mendelsohn and Neumann 1999
NOTE: Positive numbers imply benefits and negative numbers imply damages. The baseline year for the economy in the first two columns is 1990; for the last column it is 2060.

TABLE 2
ANNUAL IMPACT ON U.S. QUALITY OF LIFE
OF DOUBLING GREENHOUSE GASES
(in billions of 1990 dollars)

Sector	*Pearce et al. 1996*	*New Range*
Health and pollution	–5.8 to –59.8	NA
Recreation	–1.7 to –12.0	3.0 to 5.0
Ecological	–4.0 to –8.4	NA
Extreme events	–0.2 to –0.8	–2.0 to 2.0
Migration	–0.5 to –1.0	–0.1 to 0.0
Total	–16.0 to –72.0	–15.0 to 15.0
% GDP	–0.3 to –1.3	–0.3 to 0.3

NOTE: Positive numbers imply benefits and negative numbers imply damages. A 1990 baseline economy is assumed.

TABLE 3
ANNUAL GLOBAL IMPACTS OF WARMING IN 2100
(in billions of 1990 dollars)

	Impact Simulation Models	
Climate Models	Cross-sectional	Experimental
BMRC	150	54
CCC	152	28
GF30	185	210
GFDL	184	203
GFQF	165	134
GISS	131	45
HEND	97	–69
OSU	116	–33
POLS	173	147
POLD	175	163
UIUC	98	–139
UKMO	136	27
WANG	119	–29
WASH	143	25
Average	145	55

NOTE: Positive numbers imply benefits and negative numbers imply damages. Aggregate GDP in 2100 is assumed to be $170 trillion.
SOURCE: Climate estimates rely on fourteen climate models in Schlesinger and Williams 1997. See appendix for identification of the models. More detail about the economic models is available in Mendelsohn et al. 1999b.

FIGURE 1
The Importance of Adaptation

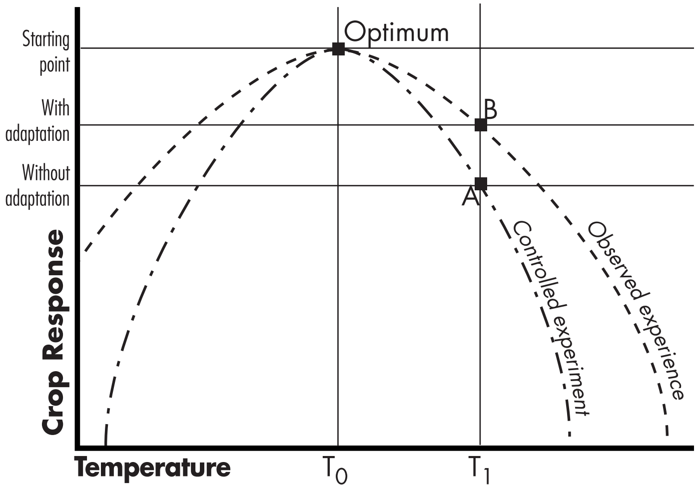


FIGURE 2
Crop Choice

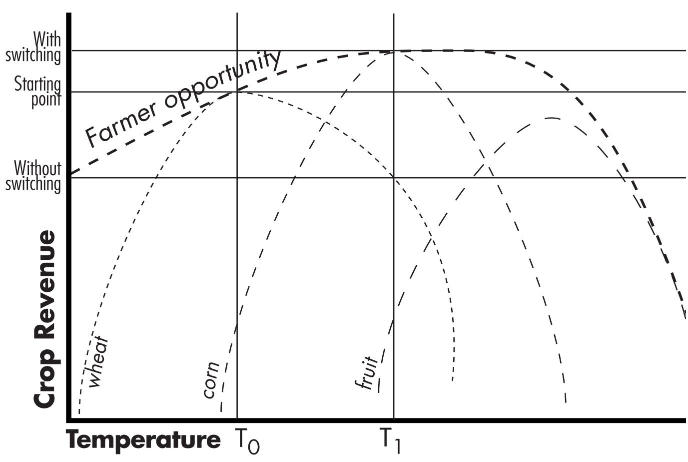
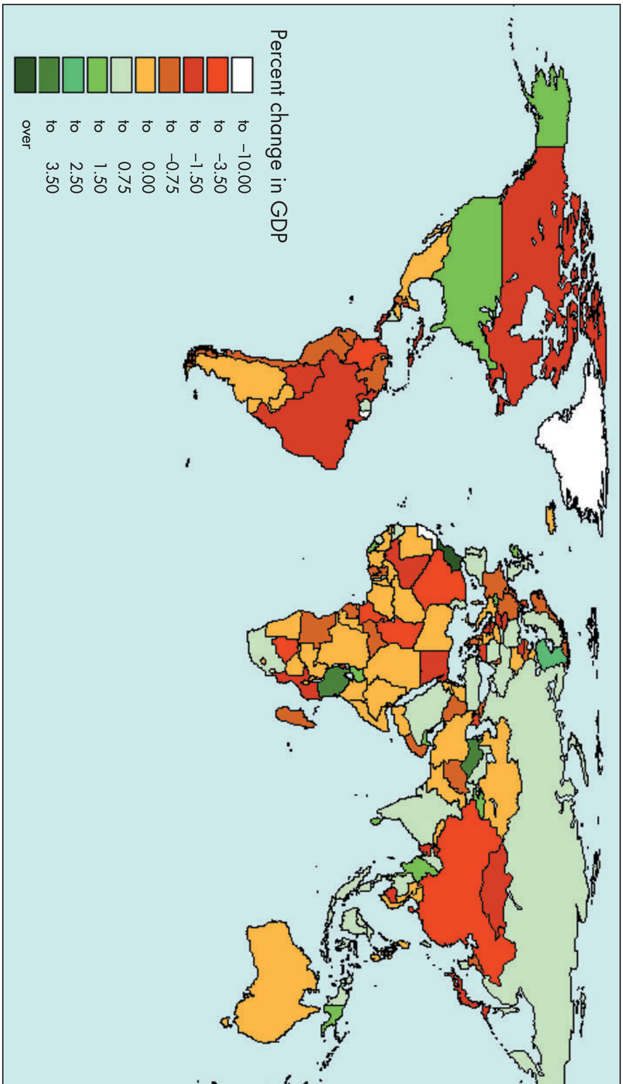


FIGURE 3

GLOBAL ECONOMIC IMPACTS USING GISS



with no carbon fertilization and no change in world prices. Similar but more severe results have been found using agronomic methods (Reilly et al. 1996). Adding carbon fertilization to the mix of factors should offset these aggregate damages from climate change in Brazil and India. With the expected increase in agricultural supply from developed countries, however, developing-country agriculture may be relatively worse off. Despite such regional shifts, the results from developed and developing countries together suggest that worldwide agricultural supplies will not be at risk from global warming (Reilly et al. 1996).

Predictions of the damages to the coastal sector have also undergone dramatic revision. Although sea-level rise remains a harmful phenomenon, the predicted increases in sea level have fallen from 1 meter to 50 centimeters. Given that coastal damages appear to be related to the square of sea-level rise (Yohe et al. 1999), the reductions imply that damages should shrink sharply—by a factor of 4. New economic studies have further reduced the magnitude of damages by carefully studying the timing of sea-level rise. Previous studies examined the rise in sea level as though it happened all at once. In fact, it is predicted to occur gradually over a century. By carefully timing our responses to match the needs in each decade, the costs of coping with sea-level rise could be spread across a century, thereby reducing greatly the present value of the adjustment costs and damages (Yohe et al. 1999). Simply modeling the dynamics of the rise in sea level shrinks by almost one order of magnitude the overall damages attendant on the rise (see table 1).

The modeling of other sectors has also changed, but the changes have not always led to dramatic changes in results. More-representative models, developed for the energy sector, ensure that heating is taken into account as well as cooling (Morrison and Mendelsohn 1999). The earlier literature had focused on electricity. Although some electricity is used for heating, the primary spatial use of electricity is for cooling. With warming, the demand for electricity will increase. But it is important to examine what happens to other fuels, such as natural gas and oil, which are used primarily for heating. The Morrison and Mendelsohn study relied on cross-sectional comparisons of expenditures on all fuels, thereby including, appropriately, fuels for heating. By relying on cross-sectional evidence, the study also included the effects of adaptation. Those two changes counterbalanced each other. Warming reduced heating needs, especially for the colder regions of the United States, thereby suggesting large benefits. But one of the most important adaptations expected in the future is an increase in cooling, and that suggested larger damages. The new results, therefore, are not that different from the old estimates (table 1).

Water models, too, have become more sophisticated. To understand the effect of warming on water systems, one must start with a complex hydrological model that predicts runoff from precipitation and evapotranspiration. That model must then be integrated into an economic model of water allocation. We can deduce national water estimates by examining a series of representative watersheds (Hurd et al. 1999). Although previous studies examined selected watersheds, the sites were not representative, and the studies did not try to allocate water efficiently in the face of runoff reductions. As with earlier analyses, the national study predicted damages as a result of reductions in runoff. But the damages were largely limited to regions in the West with scarce water. Further, when scarce water was moved from low- to high-valued users, overall market damages were kept relatively small (table 1).

Although the importance of adaptation has been powerfully demonstrated in studies of market impacts (Mendelsohn and Neumann 1999), few studies of quality-of-life impacts have handled adaptation well. Most studies of ecosystems and health assume that there will be no management response to climate-change impacts. The problem is especially apparent in health studies that have systematically assumed no public-health response. For example, an otherwise sophisticated study of malaria, which includes both mosquito and pathogen ecology, presents only the potential, not the likely, health effects (Martens et al. 1995). Potential health risks reflect no public-health response whatsoever to thousands of possible new deaths. The health studies consequently give the misleading impression that the most serious health damage from warming is an increase of tropical diseases in temperate developed countries. But the potential risk is not a likely risk because developed countries have already demonstrated that they would control those diseases if they occurred within their boundaries, as, for example, the United States has controlled the malaria that used to affect travelers along the Ohio River. The inclusion of public-health responses is one of the most important priorities for health-impact research.

Another challenge facing health studies involves modeling the interaction between warming and pollution. Warmer temperatures will stimulate smog formation and cause an increase in secondary pollutants, such as ozone, which have known morbidity and mortality consequences. Warming may also affect runoff and change the concentrations of pollution in waterways. To model those effects, future studies must capture society's response: will it reduce emissions, or will it allow damages to increase? Pollution-control policies for those other pollutants will affect the magnitude of the health damages from warming.

An additional important problem with many quality-of-life studies is that they are not representative: analysts pick only exceptions and fail to select representative phenomena. For example, early studies on recreation examined only skiing. Warming leads to skiing damages because it shortens the skiing season and reduces the areas that remain suitable for skiing. But most outdoor recreation is based on warm weather. The increase in recreation opportunities that would result from the extension of warm weather overwhelms the reduction that would occur in winter-recreation opportunities (Mendelsohn and Neumann 1999). By engaging in more representative analyses, the studies demonstrate that warming should lead to large benefits in outdoor recreation, not damages (table 2).

Climate change presents new challenges for the field of valuation. The extensive geographic changes predicted in ecosystems have not been considered before, and we know very little about people's preferences for the complex outcomes of change. The changes will affect not only the types of trees and plant species able to live in an area but most animal species as well. Because endangered species may not be able to adapt, additional extinctions may occur. A great deal remains to be learned about the magnitude of these effects and their importance to people.

Although our perception of market impacts has perhaps changed the most over the past ten years, our perception of quality-of-life impacts is changing too. The results for recreation suggest that warming is almost certainly beneficial, and, indeed, two recent hedonic-wage studies suggest that quality-of-life effects in general could be beneficial (Moore 1998; Mendelsohn 1999). By comparing the wages of people in cool environments with those of people in warm environments, the hedonic-wage studies estimate marginal preferences for temperature. Because climate both generates weather and determines which ecosystems will be present, the quality-of-life consequences of climate involve both the direct aesthetic services of weather and the indirect ecological services of climate. The hedonic-wage method measures overall preferences for all the outcomes generated by climate.

The results indicate that Americans prefer warmer temperatures. That is, they are willing to accept lower average wages to live in warmer places. Although the results may derive from unmeasured consequences that are correlated with temperature, no analyst has yet been able to identify the hidden forces. The studies suggest that mild warming scenarios will have beneficial quality-of-life impacts—in sharp contrast to all the estimates of previous authors who could imagine nothing but large damages (Pearce et al.1996, and table 2). The studies also suggest that people prefer more precipitation, a result tied probably to the green ecosystems that precipitation supports.

Most of the economic studies tend to aggregate effects across a large area. Such aggregation can hide the sensitivity of selected places to climate change. It is highly likely that climate change will make some areas much less desirable to live in. Those losses are netted out in the aggregate analysis, but the people who live in the adversely affected areas will suffer net damages. If the changes occur quickly, people may find it necessary to abandon their homes and livelihoods and move. So migration can be a cost of warming. If climate scenarios include the likelihood of catastrophic events, migration costs could be substantial. In contrast, if the scenarios tend to be relatively mild and benign, migration costs are not likely to be significant.

Climate-change impacts, unlike most environmental problems, extend far beyond national borders. That creates a huge tension for research institutions accustomed to focusing strictly on matters within national borders. Scientists know a great deal about what will happen with climate change in the well-funded industrialized countries, but much less about what will occur in the rest of the world. We must extend the analyses to include developing countries, where market and quality-of-life effects are still highly uncertain.

New Impact Predictions

Combining the results of the new scientific studies with the results of the new economic studies yields a very different picture of the aggregate impacts of climate change. To illustrate the findings, we rely on a new climate tool that captures the forecasts of fourteen climate models for each country around the world (Schlesinger and Williams 1997). Attributes of each country, such as population, income, area, and length of coastline, have also been collected. The tool utilizes two American climate-response functions (Mendelsohn and Schlesinger 1999)—one based on experimental simulation studies, the other on cross-sectional studies—to provide a range of climate sensitivity. All these elements are integrated into a model that generates country-specific impacts for each climate prediction (Mendelsohn et al. 1999b).

The range of market impacts predicted by the model, assuming a 2°C climate change for the year 2100, is shown in table 3 (page 16). The table shows two sets of results, and the results are the sum of the agriculture, timber, water, coastal properties, and energy impacts. One set of estimates was developed from the experimental literature; the other comes from the cross-sectional literature. The old vision of impacts suggested net damages ranging from 1 percent to 2 percent of GDP (Pearce et al. 1996). The new vision suggests global impacts between 0.1 percent of GDP in damages and 0.1 percent of GDP in benefits. In other words, net impacts have been reduced by one order of magnitude.

Just as important as the reduction in magnitude is the new uncertainty as to whether the net impacts by the end of the next century will be harmful or beneficial. Depending on the climate model employed, total market impacts for the globe could involve between $97 billion and $185 billion of benefits according to the cross-sectional model, and between $139 billion of damages and $210 billion of benefits according to the experimental model (in a future world with aggregate GDP of $170 trillion). The range of predicted effects has clearly shifted from being strictly harmful to being ambiguous.

The distribution of impacts across countries is also important. The old vision suggested that warming would damage almost everyone; the new reveals that impacts are likely to be heterogeneous. As shown in figure 3 (page 18), warming will have a wide range of national effects as a percent of GDP. Tropical countries are more likely to be damaged, whereas polar countries will benefit. North America, Europe, and the former Soviet-bloc countries are all likely to benefit from warming, while tropical and subtropical regions of Africa, South America, and Asia are more likely to suffer damages. Island countries are also expected to suffer damages, although the chance that catastrophe will befall them has lessened.

These country-specific results are uncertain, of course, and they are based on many assumptions that need to be tested. For example, the predictions assume that other countries have the same climate-response functions as the United States. The American response functions are likely to apply to other temperate developed countries, such as Japan and the nations of Western Europe, that have climate and economic conditions similar to those of the United States. But they may not apply to former Communist countries, whose economic behavior remains uncertain. The results are even less clearly relevant to developing countries in tropical zones, where neither the climate nor the economy is similar to that of temperate developed countries. Although continued development will help many tropical countries cope with climate change, the pace of development in many countries remains slow.

The analysis evaluates a gradual warming from now through 2100. It does not examine an increase in climate variability or extreme events. Impact studies reveal that both interannual variability and extreme events would lead to damages (Pearce et al. 1996; Mendelsohn et al. 1999a). Climate scientists are currently unable to predict, however, whether more greenhouse gases will lead to greater climate variability (Houghton et al. 1996). Nonetheless, climate change might still harbor an unexpected catastrophe. Large shifts in ocean currents such as the Gulf Stream could have significant consequences for regional climates; sudden changes in ice sheets could lead to dramatic changes in sea levels; increases in severe weather from hurricanes and storms could cause large damages. Climate research must examine these potential high consequence–low probability events more carefully and determine whether they warrant a policy response and, if so, what might be done.

We must also work to improve the estimates of nonmarket impacts. Estimates of health effects, for example, are still preliminary. They have yet to include public-health responses. Research on nonmarket ecological effects has just begun to understand the physical changes that may occur, and research on valuing those complex ecological changes has barely started. Research on the value people attach even to the weather they face in their lives is also at a preliminary stage. Studies of environmental values suggest, in general, that people do not like change, and so there is bound to be some expression of damages associated with the nonmarket effects of climate change. However, we have little experience valuing changes that take a century or more to unfold. There may yet be additional surprises regarding nonmarket impacts as we learn more about all these phenomena.

Finally, research must extend our understanding across the globe. Climate change will affect everyone in the world. Unfortunately, our current understanding is not global but is concentrated rather on impacts in the industrialized countries. Yet developing countries may well be the most vulnerable to climate change because their economies depend more heavily upon natural resources and they are already located largely in hot climates. We need to expand our vision to include a better understanding of impacts over the entire earth before we can hope to make the best possible choices in the future.

Policy Consequences

Research over the past decade suggests that the original EPA report (Smith and Tirpak 1989) should no longer be the basis of climate policy: the research does not support the predictions of the report. Climate impacts are likely to be quite mild over the next century, approximately an order of magnitude smaller than previously thought. Moreover, whether those impacts will be beneficial or harmful is now unclear. And the impacts will not be homogeneous. Some areas of the world—higher-latitude regions, for example—will clearly gain, while others—low-latitude regions—will be harmed.

This dramatic change in perspective begs for a dramatic change in policy. As damage estimates shrink, abatement costs should diminish as well. There is no emergency that requires ill-considered crash programs, and expensive short-term abatement programs should be abandoned. Short-run programs, such as switching from oil to natural gas, will have only small and temporary effects on emissions. In the long run, we will simply run out of natural gas more quickly and have to face a coal economy sooner. Indeed, the emissions associated with the future coal economy, which is expected to begin in the middle of the next century, loom large on the horizon. That coal economy is expected to increase ambient concentrations of carbon dioxide well beyond a mere doubling.

All concern for near-term abatement should shift to inexpensive, cost-effective efforts (Hahn 1998). Society can afford to plan near-term mitigation carefully, to exploit inexpensive options fully, and to encourage as much efficiency as possible. More expensive abatement programs do not guarantee more benefits, and spending trillions of dollars on abatement over the next few decades is simply wasting resources, given what we now understand about climate change. Current negotiation efforts should focus on designing efficient programs, not on committing resources to foolish initiatives. Long-term efforts should focus on reducing the carbon emissions from a future coal economy or on finding substantial alternative sources of energy. Since both activities look daunting at the moment, we may very well need to focus R&D on them for the next few decades.

If we entertain only modest mitigation strategies, we must be prepared to experience warming, and we must learn to adapt. A great deal of the adaptation will be private, undertaken by individual persons and firms as they deal with the many changes life will bring. Governments should assist private adaptation by providing information about how climate is changing, what the consequences of the changes might be, and how people can adjust to them.

Some adaptation is public, in that there are many beneficiaries of the adaptation decision. Because private initiatives for such activities are likely to be inefficient, governments must take an active role in managing public adaptations and making them efficient. For example, people who could be hurt from sea-level rise are likely to ask for public sea walls. But many coastal properties are not worth protecting, and governments must resist building sea walls that are expensive and that benefit only limited numbers of people. A dam, however, may control flooding that would hurt many people, and public-health initiatives could limit the number of mosquitoes in entire neighborhoods. All such actions have many beneficiaries, and it is not clear that people could coordinate them on their own. Hence, governments have an important role to play in adjusting public programs and infrastructure to help with adaptation. The question is whether governments can pursue reasonably efficient and effective policies while doing so.

Governments must continue to fund research on adaptation. If every individual firm or household has to engage in research, a vast amount of duplication and inefficiency will ensue. The government can improve on this outcome by conducting research for entire groups, such as farmers or homeowners, and then disseminating the results broadly. The new information will help citizens, firms, and the governments themselves alter their behavior to adjust to new climates. Further, only the government is likely to fund research on managing resources in the public trust. For example, few organizations would fund research into the effects of climate on air pollution, endangered species, or water management—the kinds of representative topics that arise naturally in areas of shared public interest where the government should take the lead. And the government should explore how land management can respond to the ecological effects of climate change, or how conservation biology can change to protect endangered species in a changing world. Public-health authorities should design management strategies to protect populations from the potential of climate-caused vector-borne diseases.

Countries are likely to be interested in the global impacts that particularly affect them. Although most countries take no interest in impacts at the moment, countries that expect the impacts on them to be more severe (such as the island nations) have encouraged more-severe policies. As the variation in impacts across countries becomes evident, specific national impacts are likely to become important. Abatement costs may still dominate the political landscape—because those costs are borne today, not in some distant time. But as the new studies make it possible to predict the impacts of warming, countries that will benefit are likely to be aware of their good fortune. And although efficient control of greenhouse gases requires that every country take a global perspective, it is easy to imagine that national impacts will be a strong factor in future negotiations. Each country will know the national abatement costs and impacts that will follow from a negotiation. Because effects will vary dramatically from country to country, they will make it more difficult to fashion international agreements, which must somehow appeal across the range of national interests. The design of such agreements will have to incorporate incentives to win the participation of countries that may benefit from, or be only mildly affected by, warming.

This essay argues that warming is likely to benefit wealthy, industrialized countries and harm poor, less-developed countries. That distribution of consequences will hamper international negotiations. Because major polluters currently perceive that they will benefit directly from curbing greenhouse gases, they are promoting an international agreement. Once the industrialized nations realize that there is no national gain in such an enterprise, they may lose interest. The less-industrialized countries, which are currently not willing to join the agreement, may soon find that they are the only parties still interested in having an agreement signed. If the countries that must pay for abatement are different from the countries that will benefit from it, concluding agreements in the future could become very difficult.

Countries may even find it difficult to arrive at consistent internal global-warming policies. Diverse countries will find that some regions will benefit and others will lose. For example, the southwestern states of the United States will suffer energy and agricultural damages from warming at the same time that northern states enjoy beneficial effects in those sectors. Further, the people who will be harmed by climate change are quite different from the people who will have to pay for abatement. Because substantial resources are at stake, these competing interest groups are likely to become involved, and they may block countries from developing effective policies.

Current global-warming negotiations have focused almost entirely on mitigation, but future negotiations may want to consider the alternative of international compensation. If net damages are small and abatement costs are high, mitigation is an unattractive strategy. In contrast, the process of compensation can be immediate and reasonably inexpensive. For example, the sum of the damages in the year 2100 of all the countries that are harmed in the 2°C scenario of table 3 is about $250 billion in the experimental projection and about $50 billion in the cross-sectional projection. The average of those two estimates suggests an expected annual damage of about $150 billion in a hundred years. Assuming that the damaged countries would prefer an immediate compensation package to a long-delayed and minor reduction in climate change, we need to calculate a payment today sufficient to compensate for damages in 2100. If we use a 4 percent interest rate, the value today of a payment of $150 billion in 2100 is about $3 billion (that is, $3 billion invested today at 4 percent interest would yield about $150 billion by 2100).

Three billion dollars is a relatively modest sum compared with the trillions of dollars required to support aggressive abatement, and compensation could be a bargain for the industrialized countries. But for compensation to occur, countries would have to agree on a mechanism to raise the funds. For example, donor nations might contribute to the Global Environmental Fund, which could administer the contributions. Or they could agree to a carbon tax that would raise the requisite sum. There are many alternative mechanisms. The essential point is that the amount needed for compensation to occur is relatively small when measured against the costs of mitigation—and the money could be used for problems of immediate concern to the recipient nations. Thus, compensation offers an opportunity that would be beneficial to both the carbon emitters and the potential victim countries. Given the long list of problems that currently press upon most of the nations likely to be damaged by warming, they might well choose the receipt of immediate income over a promise to slow climate change only slightly.

APPENDIX

Identification of Climate Models

Acronym	Institution
BMRC	Bureau of Meteorology Research Center
CCC	Canadian Climate Centre
GF30	Geophysical Fluid Dynamics Laboratory (R30 run)
GFDL	Geophysical Fluid Dynamics Laboratory (first run)
GFQF	Geophysical Fluid Dynamics Laboratory (Q-flux run)
GISS	Goddard Institute for Space Studies
HEND	Henderson-Sellers using CCM1 at National Center for Atmospheric Research
OSU	Schlesinger and Zhao at Oregon State University
POLD	Pollard and Thompson—GENESIS with dynamic sea-ice
POLS	Pollard and Thompson—GENESIS with static sea-ice
UIUC	Schlesinger at University of Illinois at Urbana-Champaign
UKMO	United Kingdom Meteorological Office
WANG	W.C. Wang et al. at State University of New York at Albany and National Center for Atmospheric Research
WASH	Washington and Meehl using CCM1 at National Center for Atmospheric Research

References

Adams, R., B. McCarl, K. Segerson, C. Rosenzweig, K. Bryant, B. Dixon, R. Conner, R. Evenson, and D. Ojima. 1999. "The Economic Effect of Climate Change on U.S. Agriculture." In *The Economic Impact of Climate Change on the United States Economy,* ed. R. Mendelsohn and J. Neumann. Cambridge: Cambridge University Press.

Cline, W. 1992. *The Economics of Global Warming.* Washington, D.C.: Institute of International Economics.

Dinar, A., R. Mendelsohn, R. Evenson, J. Parikh, A. Sanghi, K. Kumar, J. McKinsey, and S. Lonergon. 1998. *Measuring the Impact of Climatic Change on Indian Agriculture.* World Bank Technical Report No. 409. Washington, D.C.: World Bank.

Easterling, W. III, P. Crosson, N. Rosenberg, M. McKenney, L. Katz, and K. Lemon. 1993. "Agricultural Impacts of and Responses to Climate Change in the Missouri-Iowa-Nebraska-Kansas (MINK) Region." *Climatic Change* 24: 23–61.

Fankhauser, S. 1995. *Valuing Climate Change: The Economics of the Greenhouse.* London: Earthscan.

Hahn, R. 1998. *The Economics and Politics of Climate Change.* Washington, D.C.: AEI Press.

Haxeltine, A., and C. Prentice. 1996. "BIOME3: An Equilibrium Terrestrial Biosphere Model Based on Ecophysiological Constraints, Resource Availability, and Competition among Plant Functional Types." *Global Biogeochemical Cycles* 10(4): 693–709.

Houghton, J., L. Meira Filho, B. Callander, N. Harris, A. Kattenberg, and K. Maskell, eds. 1996. *Climate Change 1995: The Science of Climate Change*. Cambridge: Cambridge University Press.

Hurd, B., J. Callaway, J. Smith, and P. Kirshen. 1999. "Economic Effects of Climate Change on U.S. Water Resources." In *The Economic Impact of Climate Change on the United States Economy*, ed. R. Mendelsohn and J. Neumann. Cambridge: Cambridge University Press.

Kaiser, H., S. Riha, D. Wilkes, and R. Sampath. 1993. "Adaptation to Global Climate Change at the Farm Level." In *Agricultural Dimensions of Global Climate Change*, ed. H. Kaiser and T. Drennen. Delray Beach, Fla.: St. Lucie Press.

Martens, W., T. Niessen, J. Rotmans, T. Jetten, and A. McMichael. 1995. "Potential Impacts of Global Climate Change on Malaria Risk." *Environmental Health Perspectives* 103: 458–64.

Melillo, J., A. McGuire, D. Kicklighter, B. Moore III, C. Vorosmarty, and A. Schloss. 1993. "Global Climate Change and Terrestrial Net Primary Production." *Nature* 363: 234–40.

Mendelsohn, R. 1999. "The Non-Market Impacts of Global Warming: A Hedonic Wage Study." New Haven: Yale School of Forestry and Environmental Studies.

Mendelsohn, R., and J. Neumann, eds. 1999. *The Economic Impact of Climate Change on the United States Economy*. Cambridge: Cambridge University Press.

Mendelsohn, R., W. Nordhaus, and D. Shaw. 1994. "The Impact of Global Warming on Agriculture: A Ricardian Analysis." *American Economic Review* 84: 753–771.

———. 1996. "Climate Impacts on Aggregate Farm Values: Accounting for Adaptation." *Journal of Agricultural and Forest Meteorology* 80: 55–67.

———. 1999a. "The Impact of Climate Variation on U.S. Agriculture." In *The Economic Impact of Climate Change on the United States Economy*, ed. R. Mendelsohn and J. Neumann. Cambridge: Cambridge University Press.

Mendelsohn, R., and M. Schlesinger. 1999. "Climate Response Functions." *Ambio* (in press).

Mendelsohn, R., M. Schlesinger, and L. Williams. 1999b."Comparing Impacts Across Climate Models." New Haven: Yale School of Forestry and Environmental Studies.

Mendelsohn, R., and D. Shaw. 1998. "Will Global Warming Cause Heat Stress?" New Haven: Yale School of Forestry and Environmental Studies.

Moore, T. 1998. "Health and Amenity Effects of Global Warming." *Economic Inquiry* 36: 471–488.

Morrison, W., and R. Mendelsohn. 1999. "The Impact of Global Warming on Energy Expenditures." In *The Economic Impact of Climate Change on the United States Economy*, ed. R. Mendelsohn and J. Neumann. Cambridge: Cambridge University Press.

Neilson, R., G. King, and G. Koerper. 1992. "Toward a Rule-Based Biome Model." *Landscape Ecology* 7(1): 27–43.

Neilson, R., and D. Marks. 1994. "A Global Perspective of Regional Vegetation and Hydrologic Sensitivities from Climatic Change." *Journal of Vegetative Science* 27: 715–30.

Nordhaus, W. 1991. "To Slow or Not to Slow: The Economics of the Greenhouse Effect." *Economic Journal* 101: 920–37.

———. 1994. *Managing the Global Commons: The Economics of Climate Change.* Cambridge: MIT Press.

Parton, W., J. Stewart, and C. Cole. 1988. "Dynamics of C, N, P and S in Grassland Soils: A Model." *Biogeochemistry* 5: 109–131.

Pearce, D., W. Cline, A. Achanta, S. Fankhauser, R. Pachauri, R. Tol, and P. Vellinga. 1996. "The Social Cost of Climate Change: Greenhouse Damage and the Benefits of Control." In *Climate Change 1995: Economic and Social Dimensions of Climate Change*, ed. J. Bruce, H. Lee, and E. Haites. Cambridge: Cambridge University Press.

Prentice, C., W. Cramer, S. Harrison, R. Leemans, R. Monserud, and A. Solomon. 1992. "A Global Biome Model Based on Plant

Physiology and Dominance, Soil Properties and Climate." *Journal of Biogeography* 19: 117–34.

Reilly, J., et al. 1996. "Agriculture in a Changing Climate: Impacts and Adaptations." In *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analysis,* ed. R. Watson, M. Zinyowera, R. Moss, and D. Dokken. Cambridge: Cambridge University Press.

Rosenzweig, C., and M. Parry. 1994. "Potential Impact of Climate Change on World Food Supply." *Nature* 367: 133–38.

Running, S. W., and J. Coughland. 1988. "A General Model of Forest Ecosystem Processes for Regional Applications. I. Hydrologic Balance, Canopy Gas Exchange and Primary Productivity Processes." *Ecological Modeling* 42: 125–54.

Running, S. W., and S. Gower. 1991. "FOREST BGC. A General Model of Forest Ecosystem Processes for Regional Applications. II. Dynamic Carbon Allocation and Nitrogen Budgets." *Tree Physiology* 99: 147-60.

Sanghi, A., and R. Mendelsohn. 1999. "The Impact of Global Warming on Brazilian and Indian Agriculture." New Haven: Yale School of Forestry and Environmental Studies.

Schlesinger, M., and L. Williams. 1997. "COSMIC—Country Specific Model for Intertemporal Climate." Palo Alto, Calif.: Electric Power Research Institute.

Segerson, K., and B. Dixon. 1999. "Climate Change and Agriculture: The Role of Farmer Adaptation." In *The Economic Impact of Climate Change on the United States Economy,* ed. R. Mendelsohn and J. Neumann. Cambridge: Cambridge University Press.

Smith, J., and D. Tirpak. 1989. *The Potential Effects of Global Climate Change on the United States: Report to Congress.* Washington, D.C.: Environmental Protection Agency.

Sohngen, B., and R. Mendelsohn. 1998. "Valuing the Market Impact of Large-Scale Ecological Change: The Effect of Climate Change on U.S. Timber." *American Economic Review* 88: 686–710.

Sohngen, B., R. Mendelsohn, and R. Sedjo. 1999a. "Forest Conservation, Management, and Global Timber Markets." *American Journal of Agricultural Economics* (forthcoming).

Sohngen, B., R. Mendelsohn, and R. Sedjo. 1999b. "The Impact of Climate Change on Global Timber Markets." New Haven: Yale School of Forestry and Environmental Studies.

Tol, R. 1995. "The Damage Costs of Climate Change: Toward More-Comprehensive Calculations." *Environmental and Resource Economics* 5: 353–74.

VEMAP. 1995. "Vegetation/Ecosystem Modeling and Analysis Project: Comparing Biogeographic and Biogeochemistry Models in a Continental-Scale Study of Terrestrial Ecosystem Response to Climate Change and CO_2 Doubling." *Global Biogeochemical Cycles* 9: 407–437.

Watson, R., M. Zinyowera, R. Moss, and D. Dokken, eds. 1996. *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analysis.* Cambridge: Cambridge University Press.

Woodward, I., T. Smith, and W. Emanuel. 1995. "A Global Land Primary Productivity and Phytobiogeography Model." *Global Biogeochemical Cycles* 9: 471–490.

Yohe, G., J. Neumann, and P. Marshall. 1999. "The Economic Damage Induced by Sea Level Rise in the United States." In *The Economic Impact of Climate Change on the United States Economy*, ed. R. Mendelsohn and J. Neumann. Cambridge: Cambridge University Press.

About the Author

Robert Mendelsohn is the Edwin Weyerhaeuser Davis Professor in the School of Forestry and Environmental Studies at Yale University, where he teaches forest management, natural-resource and environmental economics, and the economics of global warming. Earlier, after receiving his Ph.D. in economics from Yale, he taught at the University of Washington and the University of Michigan. In addition to numerous articles and papers on environmental issues, he is the author of *Towards Efficient Regulation of Air Pollution from Coal-Fired Power Plants* and the coeditor of *The Economic Impact of Climate Change on the U.S. Economy* and *The Economics of Pollution Control in the Asia Pacific.*

The American Enterprise Institute for Public Policy Research

Founded in 1943, AEI is a nonpartisan, nonprofit research and educational organization based in Washington, D. C. The Institute sponsors research, conducts seminars and conferences, and publishes books and periodicals.

AEI's research is carried out under three major programs: Economic Policy Studies; Foreign Policy and Defense Studies; and Social and Political Studies. The resident scholars and fellows listed in these pages are part of a network that also includes ninety adjunct scholars at leading universities throughout the United States and in several foreign countries.

The views expressed in AEI publications are those of the authors and do not necessarily reflect the views of the staff, advisory panels, officers, or trustees.

AEI STUDIES ON GLOBAL ENVIRONMENTAL POLICY
Robert W. Hahn, Series Editor

Costs and Benefits of Greenhouse Gas Reduction
Thomas C. Schelling

The Economics and Politics of Climate Change
Robert W. Hahn

The Greening of Global Warming
Robert Mendelsohn

Making Environmental Policy: Two Views
Irwin M. Stelzer and Paul R. Portney

Why Sovereignty Matters
Jeremy Rabkin