# 1 Introduction

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In the absence of abatement measures, emissions of greenhouse gases are likely to grow over the next century largely from the burning of fossil fuels. As a result, atmospheric concentrations of carbon dioxide and other greenhouse gasses will continue to increase. The most recent IPCC (1996a) report links such increases to climate change. This poses a difficult choice for policy-makers. How much should society sacrifice to slow and possibly reverse the steady increase in greenhouse gas emissions?

Although not without controversy, there is a growing consensus among economists that near-term reductions in greenhouse gases could result in substantial costs. For example, many models suggest that the annual costs of stabilizing emissions could exceed 1–2 percent of GDP in OECD countries (IPCC, 1996a). Immediate reductions in emissions could add to costs if economies have little time to adjust to the change in policy. At the same time, global changes in climate could have undesirable impacts on both managed lands and unmanaged ecosystems. Examples of managed lands include agriculture, timber and water resources. Effects on unmanaged ecosystems could include effects on human health and biodiversity. As a result, choices made in the next few decades to either reduce emissions or continue the current pace of emissions growth have large and widespread ramifications.

The rational approach to greenhouse gas policy is to weigh the benefits of different control policies against their costs. But what are the benefits of reducing greenhouse gas emissions? What damages will be avoided if emissions are reduced and how do they compare with the costs of control? Unfortunately, the economic benefits of policies to reduce greenhouse gas emissions remain unclear. Some progress has been made, however, on the simpler question of estimating damages from a doubling of greenhouse gases. Existing national-level estimates of the economic impacts of climate change are largely expert judgments (Nordhaus, 1991; Cline, 1992; Fankhauser, 1995; Tol, 1995) based on a small set of comprehensive sectoral studies (Smith and Tirpak, 1989; Rosenberg, 1993). These early studies identified the sectors of the economy and the aspects of quality of life that are sensitive to climate change (IPCC, 1996b). They also provided an initial benchmark quantifying the impact of doubling greenhouse gases. These estimates of economic damage concluded that doubling would result in global damages equal to from 1.5 to 2 percent of GDP (IPCC, 1996c). Damages in the US were estimated to be between 1 and 2 percent of US GDP (IPCC, 1996c).

This book reexamines the link between climate change and damages by developing a new set of methods to measure the impacts on daily life from climate change. After engaging in several meetings to identify a set of needed studies, leading authors in each sector were recruited to conduct state-of-the-art studies. Based on results from climate research (IPCC, 1990; Houghton *et al.*, 1992), these authors were given an initial set of climate changes and future economic conditions. They were then asked to develop new methodologies and applications of existing approaches to improve estimates of impacts in their sectors. These strategies were implemented in a series of coordinated studies to quantify the damages from climate change. Beginning with a broad range of climate scenarios, the consequences to each sensitive sector of the economy were quantified. Effects on agriculture, coastal structures, energy, timber, water, and commercial fishing were all measured.

This book provides a detailed and comprehensive assessment of the effect of warming on the economy. In addition, several chapters quantify the effect of climate change on water quality and recreation. Although these latter two effects are illustrative of the kinds of changes in quality of life due to climate change, many important quality of life studies have not yet been completed and so are not included here. Specifically, health, aesthetics, and nonmarket environmental changes are not evaluated. The book consequently does not provide a comprehensive assessment of all impacts on the United States.

The studies presented in this book develop several improvements in the methodology of measuring global warming impacts. The research advances the state-of-the-art in impact assessment by:

- more fully including adaptation to climate change;
- developing "natural experiments", which compare economic activity across a cross-section of climate zones;
- employing dynamic modeling techniques to capture transitional responses by capital intensive sectors;
- generating more comprehensive welfare measures of affected sectors;
- using a consistent set of assumptions about future economic and population growth;
- estimating the response function of sectors to a broad range of climate outcomes.

In the next section, we critically assess the existing literature identifying its overall strengths and weaknesses. In Section 1.2, we highlight the major methodological innovations in this study. The chapter concludes with a brief review of each subsequent chapter.

## 1.1 Literature review

There is an extensive literature that links economic activities to greenhouse gas emissions to their atmospheric concentration to climate change, but there are far fewer studies that link climate change to economic impacts (IPCC, 1996a,b,c). This young but growing literature on economic impacts provides the foundation upon which this book builds. The early literature made three important contributions. First, it identified the market and nonmarket sectors which might be sensitive to climate change. Climate change is expected to affect society by affecting parts of the economy: agriculture, coastal resources, energy, timber, and fisheries, and aspects of the quality of life: aesthetics, human health, and ecosystems (including recreation and species loss). By defining the problem and identifying these key effects, the literature allowed this study to focus scarce resources on the most important impacts. Second, the early literature developed some initial techniques to measure potential severity. These methods measured what would happen to the current economy and society if the climate suddenly changed. Third, these potential severity studies revealed that it was possible that climate change impacts in several key sectors, including coastal resources, human health, and ecosystems, could be serious.

The most comprehensive empirical effort to measure national climate change impacts in the literature was conducted by the USEPA (US Environmental Protection Agency) at the request of Congress (Smith and Tirpak, 1989). This study identified economic sectors and nonmarket services that are sensitive to climate change. In each sector, empirical studies of scientific effects and the resulting economic impacts were conducted. For example, the agriculture study began with an agronomic simulation model which predicted reductions in yield from climate change and then entered these predictions in a large scale agricultural model which predicted supply and price effects for the country (Adams *et al.*, 1990). The sea level rise study projected the total quantity of wetland and dryland which would be inundated and how much it would cost to protect all developed drylands (Titus *et al.*, 1991). The energy sector study examined how warming would affect the demand for electricity and what utilities would have to spend to meet this additional demand (Linder and Inglis, 1989). By studying a host of damages which were expected to be caused by climate change, the USEPA study pulled together a wide range of information about impacts for the first time.

Another important question facing impact analysis is whether studies of impacts can be carried out sector by sector or whether a systematic model of the entire economy is needed. If there are economy-wide impacts on prices, wages, and interest rates, a general equilibrium model may be needed to measure impacts accurately. Although Rosenberg (1993) does not employ a general equilibrium model, the study does construct an integrated analysis of impacts across sectors within a four state region (the "MINK" region, including the states of Missouri, Iowa, Nebraska, and Kansas). The MINK study concluded that climate impacts were too small to generate important interaction effects across sectors and thus require a general equilibrium approach. One must be cautious not to over-generalize from the MINK study, because sectors in some regions, though not MINK, may be closely linked (for example, agriculture and water in arid areas) and because MINK evaluated only a relatively mild climate scenario (less than a 2 °C increase). However, the MINK study does indicate that it is reasonable to conduct individual sector-specific impact studies as long as one controls for obvious interactions with other sectors.

Another issue addressed by the literature is how to measure climate sensitivity. Because climates have not noticeably changed over the last two centuries, it is difficult to measure the sensitivity of market and nonmarket sectors to climate change. Even with climate predictions becoming more moderate, the forecast rate and magnitude of climate change is unprecedented in human history (IPCC, 1996a). In order to understand what might happen to society if climate changes, it is necessary to look for other experiences or circumstances which are similar to climate change. The ideal impact "experiment" replicates what society will face if the climate changes and then measures what happens. Ultimately, this leads to a valuation, a measurement of the harm done. In the process of generating this estimate, the assessment postulates a plausible mechanism, linking cause and effect. Not only should an assessment provide a final estimate of damages for specific scenarios, but it should also provide sufficient detail about the process so that people can judge what confidence they should place in the damage estimate.

One important methodology to measure climate sensitivity is controlled experiments where individuals (crops, trees, buildings, etc.) are placed in artificial settings and their response to altered climate conditions and higher carbon dioxide concentrations are measured (Idso *et al.*, 1987; Kimball, 1982; Strain and Cure, 1985). These controlled experiments have been invaluable in identifying the mechanisms through which greenhouse gases and climate change will affect different sectors. Further, the empirical results have been incorporated in a number of simulation models to predict the impact of selected climate change scenarios (Rosenzweig and Parry, 1994; Rosenthal *et al.*, 1995).

Another important strategy is to compare the behavior of individuals (especially people) who currently live in different climates (see Mendelsohn *et al.*, 1994) or who face extreme climate events such as floods or droughts (Glantz, 1988). Because these experiments are not controlled, they can be marred by unwanted uncontrolled variation which can bias the results. Further, aspects of the environment which remain the same across space, such as carbon dioxide levels, are difficult to capture in cross-sectional experiments. However, in their favor, these natural experiments are conducted in field conditions where the real climate experiment will occur.

**Adaptation**

A controversial issue throughout the impact literature is the amount of adaptation to include in impact studies. The early studies, by focusing upon what sudden climate change would do to the current economy, placed a low weight on including adaptation. There are two types of adaptation to consider, private and public. Private adaptation is an action by an individual (firm) for the benefit of that individual (firm). Public adaptation is an action by a group or government whereby the group acts to protect the group's interest. Economists argue that victims will purchase private adaptation if the benefits to them (the damages removed or gains made) exceed the costs.[1] Efficient private adaptation is likely to occur, even if there is no official (government) response to global warming. Impact assessments need to capture private adaptation in order to represent this likely social response. It is less clear whether public adaptation will be efficient. In some cases, groups may decide to do costly public adaptation even when the benefits are small. In other cases, groups may fail to purchase public adaptation even when the benefits exceed the costs because the members of the group are not sufficiently cohesive to act in the group's best interest. Thus, although it is likely that efficient private adaptation will occur, it is not clear whether efficient public adaptation will be forthcoming.

Early impact studies included some adaptation but made limited attempts to include an efficient response. Specifically, many studies may have omitted important private mitigation efforts. For example, Adams *et al.* (1990) allowed farmers to adjust the existing mix of crops grown in their region and markets to adjust prices but did not allow new crops to be introduced from other regions nor did it consider many of the adaptations that can be made by farmers to offset adverse climate change effects. Crosson and Katz (1991) and Kaiser and Drennen (1993) demonstrate that efficient farm level adaptation can mitigate a sizable fraction of the potential damages caused

[1] Private actions may not account for damages to third parties. For example, an individual may make the rational decision to build a seawall to protect his property from sea level rise, but the seawall could destroy migrating wetlands which the individual might ignore. We classify cases, such as this, which involve externalities, as part of public adaptation.

by global warming. Some studies consider more adaptation than may actually be implemented. Rosenzweig and Parry (1994) examine two levels of adaptation in their world food supply study. In their higher level of adaptation, they assumed all farmers irrigated when necessary, regardless of cost or availability. It is likely that farmers, especially in third world countries, would not actually irrigate if it was not profitable.

With sea level rise, Titus *et al.* (1991) assumed all developed land would be protected against sea level rise. In many cases, however, developed land may not be worth protecting from sea level rise because the costs of protection exceed the value of the protected property. Further, the costs of protection can be lowered dramatically if one delays protection decisions until they are necessary. In a study of Long Beach Island, New Jersey, Yohe (1991) demonstrates that efficient protection decisions can lower the cost of sea level rise dramatically compared to complete and immediate protection. Although it is only a case study, the Yohe example indicates that efficient adaptation is important. However, with sea level rise, protection is often a group decision since a set of landowners must often agree before effective barriers can be erected. Further, protecting one area can have adverse effects on neighboring locations and these decisions need to be coordinated. With sea level rise a wide range of constraints and motivations affect public expenditures on coastal lands – these factors may influence the pace and nature of adaptation, and so it is reasonable to debate whether efficient options will be undertaken.

**Dynamic versus static**

Another debate which runs through the literature concerns whether or not impact models should be dynamic. Climate change is continuous but relatively slow. It is estimated that the climate change associated with the doubling of greenhouse gases will take 70 years to be realized (IPCC, 1996a). Whether or not impact models must be dynamic depends upon how rapidly the affected sector adjusts relative to this underlying rate of climate change. Some sectors are slow to adjust because they involve large inventories or stocks of resources which take many years to alter. Both forestry and coastal resources are slow to adjust relative to climate change because the timber inventory and housing stock take several decades to adjust. Dynamic forces are likely to be important in these sectors. Whether dynamic analysis is important in other sectors, such as agriculture and energy, is less clear.

Early impact studies relied heavily upon comparative static equilibrium analyses. In some cases, researchers explore a series of equilibrium analyses along a path of climate change, but the models contain limited dynamic properties. For sectors that adapt quickly, equilibrium models are reasonable. For example, equilibrium analyses may be perfectly adequate for modeling agriculture, because farmers appear to adjust to changing conditions within a few years. Most agricultural climate studies are equilibrium analyses (Kaiser and Drennen, 1993, is a notable exception).

Sectors that cannot adapt rapidly, however, may have dynamic dimensions which are important to capture in impact assessment. In assessing impacts on forests and developed coastal resources, it is important to model how capital stocks change over time in response to a path of climate change. Most of the forestry and sea level rise studies, however, simply compare current conditions to what would happen if the climate suddenly changed to a new equilibrium (Smith and Tirpak, 1989; Titus *et al.*, 1991; Callaway *et al.,* 1994). Because they are comparative static analyses, they cannot capture potentially important dynamic responses.

**Representative studies**

Impact studies are expensive to conduct and it is not always possible to analyze every aspect of a sector or every site of impacts. It is important when analyzing only a sample of impacts in a sector, that the sample be representative. For example, if one wanted an estimate of the impact of climate on outdoor leisure, one should not generalize from a study of snowskiing to the sector as a whole. Winter sports are a small fraction of outdoor leisure and the impact of climate on winter sports is not likely to be representative of impacts on summer sports. Similarly, one would have to be cautious in generalizing from an electricity study to the energy sector as a whole since electricity is utilized more in cooling than heating compared to other major fuels. The early literature on impacts tended to gravitate to effects which people anticipated would be deleterious. This focus on the harmful aspects of change can give a misleading impression of sector-wide impacts.

**National estimates**

Policy-makers want to know the magnitude of the benefits (damages avoided) from control programs they are considering today. Few studies, however, have measured effects across a sufficient geographic area to generate empirical measurements of national sector impacts. For example, in the Smith and Tirpak (1989) study, national empirical values were developed only for coastal resources, electricity, and agriculture. There were no national valuations or damage estimates for other sectors. In order to provide national damage estimates given limited empirical results, it was necessary to make expert judgments. The first such judgment was developed by Nordhaus (1991), who reviewed the Smith and Tirpak USEPA study and other available information and made informed guesses concerning the magnitude of sectoral impacts. Other experts (Cline, 1992; Titus, 1992; Fankhauser, 1995; Tol,

1995) reviewed this same material and made their own judgments. The results of these judgments are presented in Chapter 12.

Although these experts (Nordhaus, Cline, Titus, Fankhauser, and Tol) relied on the same background information, they came to very different sector level conclusions. For example, although all five analysts rely heavily on the same empirical study of electricity (Linder and Inglis, 1989) their estimates of energy sector damages range from $0.5 to $9.9 billion annually. In agriculture, they rely heavily on Adams *et al.* (1990) and yet predict damages from $1.1 to $17.9 billion. Given the same scientific evidence of forest decline, these authors estimate timber damages ranging from $0.7 to $43.6 billion annually. Even in market sectors which have received the most empirical research, "expert judgments" of the magnitude of sectoral impacts have a surprisingly large range. This reliance on expert judgment rather than empirical measurement in developing national-level estimates is one of the greatest weaknesses of this early literature (e.g. Chapter 6 in IPCC, 1996c).

**Nonmarket effects**

Nonmarket impacts are difficult to measure and hard to value. Nonetheless, changes in weather, natural ecosystems, health, recreation, and water quality all are potentially important. These impacts could have large consequences for the quality of life of many people. Unfortunately, there is significant uncertainty in the natural sciences concerning how climate change will affect natural ecosystems and human health. Further, even if the science were understood, it is difficult to assign an economic value to these nonmarket effects.

A number of mechanisms by which global warming may affect health have been identified. First, reductions in aggregate or local food supply can result in malnourishment. Global agricultural studies indicate that world food supplies will not be threatened by the level of climate change foreseen over the next century (Kane *et al.*, 1992; Rosenzweig and Parry, 1994; Darwin *et al.*, 1995). However, in places with extensive poverty and subsistence agriculture, failures of local food supply could result in increased rates of local malnutrition (Rosenzweig and Parry, 1994). Second, changes in ecosystems could alter disease vectors allowing some diseases to spread beyond their current boundaries. Martens *et al.* (1995) demonstrate that climate change could enlarge the potential geographic scope of malaria. Infectious vector-borne diseases such as dengue fever, tsetse fly morsitans, and arboviral encephalitis could all be affected by global warming (IPCC, 1996b). Third, warmer temperatures might induce heat stress resulting in heart attacks and pulmonary failure. Kalkstein (1989) found that populations (especially the elderly) in northern US cities have higher daily mortality rates during heat waves than southern cities. He concluded that climate change could increase heat stress mortality. Relying heavily on Kalkstein's heat stress results, Cline, Fankhauser, Titus, and Tol all predict that climate will generate sizable human health damages in the United States.

These judgments about sizable health effects from climate change may be premature. Uncertainties about the role of climate variability and human adaptation to heat stress make it difficult to predict the magnitude of the effect. For example, if daily temperature variation declines, use of air conditioning increases, or housing stock improves, vulnerability to heat stress could decline in the future. In addition, the value to assign to these premature deaths is problematic. It is uncertain whether those who die from heat stress mortality would have lived only a few days more (and therefore would place a relatively low value on this loss) or would have lived for decades (and would place a high value on this loss).

Ecological studies of natural systems suggest that these systems will be different if the climate changes. The gap models (Smith and Tirpak, 1989) and the biogeographical models (VEMAP, 1995) all suggest that tree species will retreat from their southern boundaries and expand beyond their current northern boundaries. It is likely that there will be some noticeable shifts between grasslands, deserts, and forests. Some studies conclude that grassland and open forests will expand (Smith and Shugart, 1993), others find that productive closed forests will expand (Prentice *et al.*, 1992), and others predict that overall ecosystem productivity will increase (Melillo *et al.*, 1993). In addition, it is likely there will be subtle shifts of species composition within existing systems. What is poorly understood is how quickly these systems will change and what will happen during the transition period. One possibility is that a large fraction of the forest will die back because of increased fires and pests, potentially leaving large tracts of dead trees as forests gradually adapt by migrating to new and more suitable locations. An alternative possibility is that standing trees will survive during the transition which will largely affect new stands. The composition of the forest will shift towards early succession species but the forests will remain intact during the transition. Each of these scenarios, in turn, would have significant effects on animal populations as their habitat increases or shrinks.

Even if all the physical changes which will occur in natural systems over time were understood, it is still difficult to determine what value to place on these effects. Each of the impacts discussed above is likely to be valued quite differently by society. However, there are no universal measures of ecosystem value. Complex changes in ecosystems across locations and time are difficult for even one individual to assess. Within society, there is a wide range of values held concerning ecosystems. Determining what aggregate value society should place on a complex set of ecological changes is a formidable task. Given that the issue has received scant attention to date, it is no surprise that there are no clear answers.

## 1.2 Key methodological improvements in this study

The economic approaches employed in this series of parallel sector studies reflect several improvements in measuring climate sensitivity. First, all of these studies attempt to capture the potential for adaptation to mitigate impacts. Throughout history, there is strong evidence that societies learn to adapt to harsh environments by adjusting their behavior. Each of the sector studies assesses the extent to which economic agents could adapt to climate change given current technology. For example, owners of coastal structures are assumed to make economically rational decisions about whether to protect coastal structures from rising sea level or gradually abandon them. Farmers and foresters are assumed to choose crops, planting, and harvest methods suitable for the new climates that they are experiencing. By moderating their behavior to fit the changing environment, people can and most likely will mitigate some of the possible harms and increase the potential benefits from change.

A second important innovation in this book is that several studies rely on natural climate experiments. Although there are few examples of climates changing over time that we can readily use to measure sector responses, nature is full of examples where agents adapt to different climates over the landscape. By comparing behavior in one location with one climate to another location with a different climate, we can learn a great deal about how people might adapt to climate change in the long run. As each locality adapts to the environment they experience, they customize their behavior to their climate. For example, by observing the energy expenditures, leisure activities, and farming values of town A (which experiences 25 °C temperatures) and comparing them to a similar town B (which experiences 30 °C temperatures), one can learn how a 5 °C temperature increase may affect town A. These cross-sectional comparisons reveal long run changes in which firms and people adapt to their new environment.

Third, some sectors, such as coastal structures and timber, are characterized by large capital stocks which are difficult to adjust over time. These sectors are quite vulnerable to the rate of change of climate because it is difficult to change large housing stocks or vast timber stocks quickly. In order to understand what would happen in these sectors, it is critical to build dynamic models that explicitly examine the rate of climate change and how quickly the sectors can respond. The timber and coastal property (sea level rise) studies are the first impact models in these sectors to