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CLIMATE CHANGE AND ECOSYSTEMS

By Lenny Bernstein

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Executive Summary

This report examines the basis for claims that projected human-induced climate change will have a severe impact on ecosystems. Past Marshall Institute Reports, most recently *Climate Science and Policy: Making the Connection*, have questioned the basis for projections that human activities will have a severe impact on the climate of the 21st century. This report does not repeat those arguments, but discusses the possible impact on ecosystems of different levels of climate change, as indicated by temperature increases, independent of time frame or cause.

Before considering specific claims of potential ecosystem damage, it is important to recognize that climate has always impacted ecosystems and that human activities have been impacting on ecosystems for tens of thousands of years.

- All of the plants and animals, including humans, that live on the Earth are sensitive to climate and will respond to climate change. Climate is a key determinant of what crops can be grown in a particular area. Paleontologists argue that past climate changes were a factor, perhaps the major factor, in the extinction of the dinosaurs and many other species.
- Human activities have had impacts on ecosystems since indigenous people, such as the Australian Aborigines, first used fire to clear underbrush to improve their hunting. Both primitive and modern people have caused the extinction of species, e.g., the moa in New Zealand and the passenger pigeon in North America.

Given the pervasive nature of human impacts, ecosystems can be divided into two categories:

- intensively-managed: farmland, managed forests and grasslands, and to a lesser extent, fisheries; and
- lightly-impacted: essentially unmanaged, natural wildlife areas and the oceans.

Concerns about intensely-managed ecosystems focus on the potential impact that climate change on the ability of these systems to produce the food and fiber they have traditionally supplied to the global economy. Concerns about lightly-impacted ecosystems focus on the potential for climate change to cause widespread species extinction.

Recent studies, which examined temperature rises of up to 5°C (9°F) and precipitation increases of 0–15%, indicate that climate change in the range projected by the Intergovernmental Panel on Climate Change (IPCC) for the 21st century would be beneficial for agriculture and forestry in the U.S. and other developed countries. Crops grow better at higher atmospheric concentrations of carbon dioxide (CO_2). The warmer, wetter world projected on average by climate models would mean longer growing seasons, less threat of frost damage, and in some areas, less threat of drought.

Crops grow better at higher atmospheric concentrations of carbon dioxide (CO_2). The warmer, wetter world projected on average by climate models would mean longer growing seasons, less threat of frost damage, and in some areas, less threat of drought.

While climate models project warming in all parts of the world, they are less uniform in their projection of increased precipitation; most areas are projected to have the same or more precipitation, but a few are projected to have less. This variability is discussed in the body of this report. Adaptation, either by growing crop varieties better matched to the changed climate or by switching crops, would be necessary to take full advantage of these potential benefits.

The IPCC Third Assessment Report (TAR) acknowledges the benefits of climate change for agriculture in developed nations, but expresses concern that these advantages would not be available in developing nations, most of which are in the tropics. The advantages of higher atmospheric concentrations of CO_2 are equally applicable in the tropics. Also, many tropical countries are arid, and would greatly benefit from increased precipitation. However, since their growing season is already year-round, these countries would not benefit from warmer conditions.

The IPCC TAR also expresses concern that developing countries would not have the capacity to adapt their agriculture and forestry to changing weather conditions. However, the ability of these countries to take advantage of technological developments in agriculture is demonstrated by their adoption in the 1950s and '60s of improved crop varieties and greater use of fertilizer and irrigation in what has been called the "Green Revolution."

Adaptive capacity is a function of wealth, and all projections indicate that the developing nations will become wealthier during the 21st century. IPCC baseline emissions scenarios, i.e., scenarios that assume no control of greenhouse gas emissions, show a wide range of possible futures, but even the lowest economic growth case shows a more than ten-fold (2.3%/year) increase in real per-capita income in the developing nations by 2100. This level of wealth should give the developing nations at least the same capability to adapt to climate change as developed nations have today. High economic growth cases show that by 2100 developing nations will have several times the per capita GDP enjoyed by the developed nations today. In these scenarios their adaptive capacity should be greater than that of the developed world today.

The plants and animal species that make up lightly-impacted ecosystems have been adapting to climate change for millions of years. However, not all plant and animal species will be successful in adapting. If biologists are correct that natural climate change has been a major factor in past species extinctions, any change in climate, whether natural or human-induced, will increase the risk that some marginal species will become extinct.

There are few studies of the comparative risks of species extinction posed by climate change and other human activities, but one recently published study concludes that habitat disruption by human activities will continue to be the largest threat posed by human activities to the survival of plant and animal species. Many innovative programs are being undertaken (e.g. reintroduction of wolves into Yellowstone National Park and kudzu control programs in the southeastern U.S.) to help plants and animals overcome the impacts of past disruption. These programs will make these species more resilient to climate change. However, we have a very low level of understanding of the way that the species that make up ecosystems interact, and of the potential impacts of climate change on those interactions.

Protection of endangered species enjoys widespread support in the U.S. and elsewhere, but the understanding needed to implement realistic protection programs that are in balance with other priorities is inadequate. Many fundamental questions, e.g. How many species are becoming extinct?, remain unanswered. In addition to focusing specifically on the potential impacts of climate change on ecosystems, this report identifies two areas under the U.S. Global Change Research Program that need improvement:

(1) improved models which project the combined transient effect of multiple stresses, including climate change, on ecosystems (both the IPCC and National Academy of Sciences (NAS) agree that current models are inadequate); and

(2) better techniques to help endangered species migrate in response to climate change.

In summary:

- Ecosystems are sensitive to climate change.
- With continuing adaptation, intensively-managed ecosystems, such are farms and commercial forests, can benefit from the levels of climate change projected by the IPCC for the 21st century. Developed countries already have the necessary adaptive capacity, and developing countries will acquire the necessary adaptive capacity as their wealth increases.
- Ecosystems, such as wildlife areas, which are currently lightly impacted by human activities, would also benefit from adaptation, but the understanding necessary to plan that adaptation is currently inadequate.

Introduction

This report examines the basis for claims that projected human-induced climate change will have a severe impact on ecosystems. Past Marshall Institute Reports, most recently *Climate Science and Policy: Making the Connection*, have questioned the basis for projections that human activities will have a severe impact on the climate of the 21st century. This report does not repeat those arguments, but discusses the possible impact on ecosystems of different levels of climate change, as indicated by temperature rise, independent of time frame or cause.

There are many definitions of ecosystem. This report will use one developed by the Intergovernmental Panel on Climate Change (IPCC):

> A distinct system of interacting living organisms, together with their physical environment. The boundaries of what could be called an ecosystem are somewhat arbitrary, depending on the focus of interest or study. Thus the extent of an ecosystem may range from very small spatial scales to, ultimately, the entire Earth.[1]

The ecosystems we discuss typically cover many thousand square miles, for example, the habitat of a bird species or a river's watershed.

Before considering specific claims of potential ecosystem damage, it is important to recognize that climate has always impacted on ecosystems and that human activities have been impacting on ecosystems for tens of thousands of years.

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Human activities have had impacts on ecosystems since indigenous people, such as the Australian Aborigines, first used fire to clear underbrush to improve their hunting. Both primitive and modern people have caused the extinction of species, e.g. the moa in New Zealand and the passenger pigeon in North America.

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The overwhelming majority of the Earth's ecosystems have been affected by human activities. Some of these activities have been planned, e.g., the conversion of forest to farmland. Others activities have been unplanned. For example, as documented in a recent issue of *Audubon*, the removal of wolves and other predators, and bans on hunting, have led to a dramatic increase in the U.S. deer population. This, in turn, has reduced the population of the plants deer like to eat, while increasing in the population of plants deer do not like to eat, thus changing the ecosystem.[2]

Given the pervasive nature of human impacts, ecosystems can be divided into two categories:

- intensively-managed; farmland, managed forests and grasslands, and to a lesser extent, fisheries; and
- lightly-impacted; essentially unmanaged, natural wildlife areas and the oceans.

Concerns about intensely-managed ecosystems focus on the potential impact that climate change will have on the ability of these systems to produce the food and fiber they have traditionally supplied to the global economy. Concerns about lightly-impacted ecosystems focus on the potential for climate change to cause widespread species extinction.

This report examines the question: How sensitive are intensively-managed and lightly-impacted ecosystems to different levels of climate change? In the course of answering this question, it is necessary to consider the relative importance of climate change compared with other human impacts, such as habitat disruption and local or regional pollution, in determining the rate of species extinction.

Three climate changes are discussed in this report: higher atmospheric concentrations of CO_2, warmer temperatures, and increased precipitation. All IPCC projections are for higher CO_2. Based on projection of higher CO_2, climate models project increases in temperature for all parts of the world. They also project increases in average precipitation, but are less consistent in the projections of the regional distribution of precipitation. Most areas of the world are projected to get more precipitation than they now do, a few are projected to get less.

The IPCC Third Assessment Report includes projections of precipitation based on nine climate models using two emissions scenarios: high emissions and low emissions. The results were evaluated for 23 regions of the world, and for two seasons: winter and summer. This resulted in 92 comparisons (23 regions x 2 emissions scenarios x 2 seasons). IPCC reported that in a third (32) of the comparisons, the models gave inconsistent results. In 9 other comparisons they showed no significant change in precipitation. In 40 comparisons, they showed increases in precipitation, and in 11 comparisons they showed decreases.[3] While these comparisons represent the best available modeling results, they hide large differences in the predictions of individual models. As the IPCC reports:

> The magnitude of regional precipitation changes varies considerably amongst models, with the typical range being around 0 to 50% where the direction of change is strongly indicated and around -30 to +30% where it is not.[4]

Given the physical basis for assuming a wetter world, and the preponderance of modeling results, we will assume that most ecosystems will experience wetter conditions in the future.

Intensively-Managed Ecosystems

Society depends on ecosystems for a wide range of goods. Most of the food we eat, the wood we use for construction, and the natural fibers we use for clothing, are products of intensively-managed ecosystems. We also depend on both intensively-managed and lightly-impacted ecosystems for a wide variety of services including water purification and recreational opportunities. Since these ecosystems are sensitive to climate change, it is reasonable to ask whether changes in climate will diminish the ability of ecosystems to continue supplying these goods and services. The debate on the validity of this concern centers on the ability of human society to adapt intensively-managed ecosystems to climate change.

As climate changes, which it has and will in the future, human society will have to adapt to that change; adaptation is a necessity, not an option. But humanity's need to adapt to climate change is not a new phenomena, and both sides of the debate are succinctly captured by Brian Fagan, Professor of Archeology at the University of California, Santa Barbara, in his book, *The Little Ice Age*:

> Humanity has been at the mercy of climate change for its entire existence. Infinitely ingenious, we have lived through eight, perhaps nine, glacial episodes in the past 730,000 years. Our ancestors adapted to the universal but irregular global warming since the end of the Ice Age with dazzling opportunism. They developed strategies for surviving harsh drought cycles, decades of heavy rainfall or unaccustomed cold; adopted agriculture and stock-raising, which revolutionized human life; founded the world's first pre-industrial civilization in Egypt, Mesopotamia, and the Americas. The price of sudden climate change, in famine, disease, and suffering, was often high.[5]

Optimists point to the infinite ingenuity and dazzling opportunism Prof. Fagan refers to as evidence that humanity will be able to respond to any future climate change. Pessimists point to the high human costs of past climate changes. Which of these will shape the future?

The majority of studies of the impacts of climate change on intensively-managed ecosystems have the following characteristics:

- they assume today's technology with either no or limited adaptation;
- they use the impacts of severe weather events as predictors of the impacts of climate change; and
- they invariably show high negative impacts.

These studies are misleading. Severe weather events occur in the short-term, offering no opportunity for adaptation. But climate is the long-term average of weather, and climate change, whether natural or human-induced, will take decades to centuries to occur. During that time human society will continue to benefit from advances in knowledge and technology, and hence become more capable of adapting to different climate conditions.

The benefits of adaptation have been clearly demonstrated in the evolution of thinking about the potential impacts of climate change on agriculture. Early studies[6] did not consider adaptation. They assumed no change in the behavior of farmers in response to changing climate. This was known as the "dumb farmer" hypothesis, and was at odds with all of human experience, which indicates that farmers and others whose livelihood is sensitive to climate are very attuned to climate change and adapt to it on a continuous basis.

Later studies considered adaptation by the individual farmer, i.e., planting species that were better matched to climate conditions. For example, wheat farmers have a wide variety of species to chose from, some of which are better adapted than others to the warmer, wetter conditions that are projected by climate models. Choosing these better adapted species would minimize the potential adverse impacts of climate change, and in many cases provide a net benefit. Still more sophisticated studies consider both farmer adaptation and marketplace adaptation. If climate changed sufficiently, wheat farmers might become corn farmers, and corn farmers might grow fruit and vegetables. Using a "smart farmer" assumption led to very different results, often showing that climate change yielded net benefits.

Benefits of Adaptation

The limited number of studies which take growth in adaptive capacity into account often show benefits for climate change. One such study by Adams *et al.*[7] considers the impacts of climate change on U.S. agriculture in 2060, taking into account projected changes in the agricultural market to that time and allowing for the full range of adaptation. The authors considered the effects of changes in temperature, precipitation and atmospheric carbon dioxide (CO_2) content on agricultural yields. Photosynthesis, the process by which atmospheric CO_2 and water vapor are converted into plant matter, is enhanced by higher levels of atmospheric CO_2, though plants respond to increased CO_2 at different rates.

Adams, *et al.* looked at a series of cases in which atmospheric CO_2 concentration was increased from its 1999 level of about 365 ppm to 530 ppm, temperature increased by as much as 5°C, and precipitation increased by as much as 15%. These climate changes are larger than those typically projected by climate models for 2060. Farmers were allowed to adapt by either optimizing their current crops or by switching crops.

The authors found that for all cases studied, the U.S. benefited from improvements in the agricultural sector, with the benefits being split between consumers, who enjoyed lower food prices because of higher agricultural productivity, and the farmers who benefited from higher income. Not all cases resulted in benefits to both sides, nor were the benefits spread equally across all agricultural areas in the country, but the net effect for the U.S. economy was positive.

The physical basis for these benefits is fairly easy to understand. The benefits of higher CO_2 concentration have already been discussed. Warmer climates mean longer growing seasons and less chance of crop damage from frost. Much of the U.S.' agricultural area suffers from periodic droughts, so increased precipitation also provides benefits.

A similar study by Sohngen and Mendelsohn for the U.S. timber industry projects benefits under the same range of climate change conditions. The authors conclude:

> Overall, the timber market is likely to adapt to climate change, thereby ameliorating the potential problem associated with ecological change. This work shows how harvest schedules will adjust from region to region and from moment to moment so as to use timber stocks efficiently during the transition period (to equilibrium climate change). These adjustments occur regardless of the specific climate and ecological scenario. This chapter also shows how timberland owners will adjust their replanting behavior by responding to future ecological and economic conditions. Despite the apparent severity of some ecological effects, market behavior offsets the potential damages through adaptation.[8]

Overall, Mendelsohn and Neumann project that the benefits to managed ecosystems would result in a modest (+0.2%) benefit to the U.S. economy in 2060 for their moderate climate change case (+2.5°C, +7% precipitation).[9] This result was generalized by the IPCC, which In assessing these results, the IPCC concluded that there was medium confidence that small increases in temperature would have a net positive effect on the economies of developed nations.[10]

In assessing these results, the IPCC concluded that there was medium confidence that small increases in temperature would have a net positive effect on the economies of developed nations.

The IPCC defines “small increases in temperature,” as 0-2°C.[11] This literature also indicates that most, if not all, of the benefit comes from gains in intensively-managed ecosystems.

While the IPCC agrees that moderate climate change would be beneficial to managed ecosystems in the developed world, it raises two concerns: first, that more than 2°C warming would have adverse effects, even in the developed world, and second, that even small amounts of climate change would have adverse effects in the developing world.[12] Again, much of the basis for these concerns is the projected impact of climate change on intensely-managed ecosystems. The next few paragraphs examine the validity of these concerns.

The basis for the IPCC’s concerns about the inability of intensively-managed eco-systems to adapt to large amounts of climate change appears to lie in the fact that the studies collected by Mendelsohn and Neumann, and other similar exercises, show declining benefits at large amounts of climate change. The extent to which these results are a function of model limitation or represent real limitations in the ability of intensively-managed ecosystems to adapt is unknown. As Mendelsohn and Neumann state:

> … it is important to recognize the significant limitations involved in projecting climate, biophysical, and economic conditions over the next century. Although this book seeks to improve the arsenal of methodologies to measure the eco-nomic impact of climate change, none of the existing methods are perfect replicas of the experience that society will face if climate gradually warms over the next century.[13]

The physical basis for forecasting benefits to intensively-managed ecosystems, (i.e., higher CO_2 concentration promoting faster plant growth, warmer temperature leading to longer growing seasons and less potential for frost damage, and more precipitation leading to less risk of drought) is strong enough to provide confidence in the benefits of 2–3°C of warming, but uncertainty grows as the level of warming increases. For the US, which has been subjected to more analysis than any other part of the world, the benefits extend out to double the temperature level considered by the IPCC (5°C vs. 2.5°C). More scientific study and modeling will be needed to determine the extent to which this result can be generalized to other countries and regions. However, there is clearly room for more optimism than exhibited by the IPCC.

Adaptation in the Developing World

The question of whether adaptation can provide benefits for intensively-managed ecosystems in the developing world is more complex. The benefits of higher CO_2 concentration are equally applicable in developed and developing countries. However, most developing countries are in the tropics, and would see no benefit, but potential adverse effects, from rising temperature. The IPCC points out many cases in which extremely high temperatures will inhibit critical stages of plant growth for existing crop species.[14] These studies often do not consider the potential for developing more heat resistant crops or opportunities for adaptation through crop switching. Also, it should be noted that climate models typically project less than global average warming in the tropics.

In many developing countries, the growing season is 365 days of the year and frost does not exist. Thus longer growing season and less potential frost damage are not considerations. Some of these countries also have generous rainfall, so additional rainfall will provide little additional benefit. Others are either arid or desert countries, in which case, additional rainfall is a major benefit. No single description fits all cases.

The IPCC recognizes that there is considerable opportunity for the agriculture and forestry sectors to adapt to climate change, and that there is evidence that they have done so in the past. But it then raises concerns that the poorest and most vulnerable countries will not have the ability to adapt. This conclusion overlooks two factors.

First, there is little reason to believe that developing nations cannot take advantage of improvements in agricultural technology and use them to adapt to any changes in climate. Some of the poorest countries in the world were the one that benefited most in the 1950s and '60s from adopting the suite of agricultural technologies (improved plant varieties, increased used of fertilizer and irrigation) known as the "Green Revolution," which dramatically raised food production in much of the developing world. Countries with relatively stable governments benefited most. Democratic countries, such as India, were able to take quick advantage of these developments,[15] but even dictatorships, such as Syria, which became self-sufficient in grain in 1991, saw improvements in food production.[16] In today's world, despite a growing population, famine is a problem only in those countries which are at war or have unstable governments.

The trend in improved food production is projected to continue. In 2000, the FAO (the Food and Agriculture Organization of the UN) projected increasing food supplies for the developing world at least until 2030, as far into the future as their projections are made.[17] The projected improvements in developing nations food supply is based on their adoption of improved agricultural technology, which also should make them less vulnerable to climate variability and change.

Second, CO_2 emissions are the result of economic activity, which generates wealth, which in turn results in adaptive capacity. Since projected climate change and the ability to adapt to it are both the result of economic activity, we need to consider the future level of economic activity in developing nations.

The IPCC Special Report on Emissions Scenarios (SRES),[18] published in 2000, provides a wide range of scenarios of the changes in CO_2 emissions and per capita income for both developed and developing nations from 1990 to 2100. As the IPCC is careful to point out, scenarios are not predictions, they are alternate images of how the future might unfold.[19] This report does not address the analytical basis for these scenarios or whether any of them are likely. They are used solely as a basis for assessing the potential growth in the adaptive capacity of developing nations.

The IPCC scenarios all show a faster rate of economic growth in developing nations than in developed nations, resulting in a narrowing of the economic gap between the developed and developing worlds. This higher rate of economic growth also results in developing nations emitting a higher fraction of the world's CO_2 emissions in 2100 than they currently do. The emissions scenarios that lead to the highest level of projected temperature rise to 2100 are the scenarios that have the highest level of economic growth in the developing world.

The SRES does not give country-by-county projections but divides the world into four regions:

1. The countries that were OECD members in 1990,
2. Russia and Eastern Europe,
3. Asia, and
4. Africa and Latin America.

The first two regions are developed nations, the last two, the developing nations.

The SRES authors developed 40 baseline scenarios; none of these scenarios include overt actions to control greenhouse gas emissions. The SRES scenarios differ in their assumptions about the rate and nature of economic development and about the importance placed on protection of local and regional environmental quality. These assumptions, in turn, lead to large differences in the projected use of fossil fuels and the level of greenhouse gas emissions. To make their results more manageable, the SRES authors suggest using six illustrative scenarios that capture the range of possible futures covered by the scenarios.

The following table summarizes the SRES projections for population, total CO_2 emissions, CO_2 emissions per capita, and GDP per capita for 1990 and 2100 for the illustrative scenarios with the highest (A1FI) and lowest (B1) global CO_2 emissions.

Table 1 – SRES Projections: CO_2 Emissions and GDP per Capita[20]

	1990	2100 Highest Emissions	2100 Lowest Emissions
Population, Billions			
Developed Nations	1.3	1.4	1.4
Developing Nations	4.0	5.7	5.7
Total CO_2 Emissions (GtC)*			
Developed Nations	4.1	10.0	1.1
Developing Nations	3.1	18.2	3.1
% Developing Nations	43	65	74
CO_2 per Capita (Tonnes C)			
Developed Nations	3.2	7.1	0.79
Developing Nations	0.78	3.2	0.54
Ratio	4.1	2.2	1.5
GDP per Capita (1990 US$)			
Developed Nations	13,800	109,500	71,700
Developing Nations	850	69,800	40,000
Ratio	16.1	1.6	1.8

* GtC = billion metric tonnes carbon

What the numbers in Table 1 show is a dramatic narrowing of current differences between developed and developing nation per capita CO_2 emissions and GDP during the 21st century. Even in the IPCC's lowest economic growth illustrative scenario, A2 (not shown), developing nation GDP per capita increases more than ten-fold (2.3%/yr.) during the 21st century, and the ratio of developed nation to developing nation GDP per capita decreases to 4.2.[21] It is reasonable to assume that this growth in the wealth of developing nations will be accompanied by a growth in their ability to adapt food production to climate variability and change. At a minimum, the adaptive capacity of developing nations should be roughly equivalent to that of developed nations today. In many cases it should exceed that level.

It is reasonable to assume that this growth in the wealth of developing nations will be accompanied by a growth in their ability to adapt food production to climate variability and change.

Pessimists argue that these broad averages hide pockets of poverty that will be resistant to economic growth. The evidence is overwhelming that poverty is caused by government corruption and the lack of rule of law, property rights and individual freedom. These problems dwarf the potential impacts of climate change and need to be addressed on an urgent basis, independent of concerns about potential climate change.

Lightly-Impacted Ecosystems

As noted in the introduction, concerns have been raised that human-induced climate change will lead to a significant increase in the rate of species extinction. The IPCC presents this concern in qualitative terms, and notes the presence of confounding factors. For example, in its synthesis of potential impacts of climate change, the IPCC states:

> Laboratory and field studies have demonstrated that climate plays a strong role in limiting the ranges of species and ecosystems. Species already are responding to changes in regional climate, with altered population sizes and breeding times or flowering dates that occur earlier in the season. These responses suggest that many unique species will undergo complex changes with a few degrees of warming, which could lead to extinctions in many locations. … However, projecting the responses of wild animals and plant species is extremely difficult for most species because there are many possible biological interactions and confounding factors, such as habitat destruction and invasive species.[22]

The IPCC literature repeats this concern many times, but contains no discussion of the absolute risk posed by climate change to endangered species, or of the relative risks of climate change and other human activities to these species.

Before discussing the potential impact of climate change on species extinction, we will consider the extent to which humans are and have been responsible for the extinction of other species. The most dramatic and well-known cases involve over-hunting, which led to the extinction of such species as the dodo, moa, and passenger pigeon, and almost led to the extinction of the American buffalo. But, habitat destruction has also been a major cause of species extinction. Conversion of natural habitats to intensive-managed farms and forests has caused the extinction of both plant and animal species.

More recently, the introduction of invasive species, non-native plants or animals that have no natural enemies, has been another factor contributing to the stress on endangered species. Some of these species have been purposely introduced (e.g. kudzu, which was introduced in the southeastern U.S. for erosion control), while the introduction of others was inadvertent (e.g. zebra mussels, which entered the Great Lakes in the ballast water of ships).

While there is no debate that humans have been, and continue to be, responsible for the extinction of some species, there is an active debate as to how serious the problem is. We do not know how many species there are, nor what the background rate of species extinction is, nor how many species are becoming extinct as the result of human activities.

The current best estimate of the number of species on the Earth is between 10 and 80 million, of which only some 1.6 million have been identified.[23] Such a wide range indicates deficiencies in the current estimating methodologies. Systematic studies invariably discover new species, even in intensively studied areas. For example, in 1998, about 12,000 species were known to exist in the Great Smoky Mountains National Park. In that year, the All Taxa (Species) Biodiversity Inventory project was started with the goal of raising the total number of species identified in the park to 100,000. Thus far, 1,480 new species have been identified in the park, 144 of which are new to science.[24]

Background rates of extinction are similarly unknown. Fossil records indicate massive extinctions in the past, the most famous being the extinction of the dinosaurs 65,000,000 years ago. This extinction is now believed to have been caused when a massive asteroid hit the Earth creating a large, sudden change in climate. Fossil records also indicate that most of the species that existed over the Earth's history are now extinct. However, there is no accepted estimate for the number of species that would become extinct as the result of natural evolutionary processes during a "normal" year.

Estimates of the number of species becoming extinct because of human activities vary widely. One widely-quoted number is 40,000 per year, but as has been documented by Bjorn Lomborg in his book *The Skeptical Environmentalist*, this number can be traced to a speculation by Norman Myers, a well known environmentalist.[25] Even critics of Lomborg's approach, such as Thomas Lovejoy, Chief Biodiversity Advisor to the President of the World Bank and a former Director of the World Wildlife Fund – US, agree that Myers provided no basis for his estimate.[26] At the other extreme of the estimates for human-induced species extinction, documentary evidence exists for the extinction of only 1,033 species since 1600.[27] Even those who believe that humans are not causing large-scale species extinction agree that this number is highly likely to be low, since undocumented extinctions as the result of human activities are certain to have occurred.

The lack of agreed values for the number of species on the Earth, the background rate of extinction, and the number of species becoming extinct as a result of human activities makes discussion of this topic the potential impact of climate change on species extinction difficult. Better methodologies for arriving at these values are needed. Since larger animals are easier to identify and count than smaller animals, an attempt is being made to determine the ratio between various classes of animals, e.g. the ratio of birds to mammals to insects, etc. However, there is no certainty that these ratios would hold in different parts of the world, or that if they hold for existing species, that they would also hold for species that become extinct.

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Climate Change and Species Extinction

The starting point for concerns about the potential impacts of climate change on endangered species is indisputable: all plants and animals living on the Earth are sensitive to climate. All, with the possible exception of humans, have a preferred climate. These preferences are often shown as a plot of the type of ecosystem that will be prevalent as a function of average temperature and rainfall.[28] Any change in climate will put stress on some plant or animal species. However, translating these generalities into threats to specific species is far from easy. The IPCC summarizes the problems involved as follows:

> Modeling changes in biodiversity in response to climate change presents some significant challenges. It requires projections of climate change at high spatial and temporal resolution and often depends on the balance between variables that are poorly handled by climate models (e.g., local precipitation and evaporative demand). It also requires an understanding of how species interact with each other and how these interactions affect the communities and ecosystems of which they are a part. In addition, the focus of attention in the results is often particular species that may be rare or show unusual biological behavior.[29]

To address these knowledge gaps, the IPCC calls for:

> Improvement of regional scale models coupled with transient ecosystem models that deal with multiple pressures with appropriate spatial and temporal resolution and include spatial interactions between ecosystems within landscapes.[30]

The term "landscape" refers to "groups of ecosystems (e.g., forests, rivers, lakes, etc.) that form a visible entity to humans.[31]

Elsewhere the IPCC documents the huge difficulties involved in developing regional climate models.[32] The challenges in developing transient ecosystem models are just as large, and coupling the two would be still another difficult task. Yet, the IPCC is correct in its conclusion that this is what would be needed for a predictive model of the effect of climate change on plant and animal species. Faced with the difficulty of developing predictive models and quantitative assessment tools, any discussion of the impacts of climate change on species is limited to qualitative statements.

The U.S. Global Change Research Program (USGCRP) recognizes the need for research into the effects of multiple pressures on ecosystems. Much of USGCRP's ecosystem effort has been devoted to satellite observations of the changes occurring in these systems. While this effort has provided useful information on questions such as the rate of disappearance of the Amazonian rainforest, it has not been translated into a predictive capacity that answers questions about how future climate change might effect ecosystems and species extinction. In its 1999 critique of the USGCRP, a committee of the National Research Council of the National Academy of Sciences (NAS) characterized efforts in this area as "ad hoc,"[33] and agreed with the IPCC's recommendation by listing "How do multiple global changes interact to produce ecosystem responses (including species extinction)?" as a key unanswered question.[34] Clearly, the USGCRP's program should include well-coordinated research to develop the predictive capacity needed to answer the questions posed by both the NAS and the IPCC.

Any discussion of the role of climate change in future rates of species extinction must also consider the relative threats posed by climate change vs. habitat disruption and other human activities. Given the high level of uncertainty about both current and future rates of species extinction, we can only speculate about the relative importance of climate change vs. habitat disruption or other human activities.

One study has attempted such speculation and concluded that the dominant factors determining biodiversity decline will be climate change in polar regions and land-use change (habitat disruption) in the tropics. Temperate ecosystems were estimate to experience the least biodiversity change because major land-use changes have already occurred.[35] There are far more plant and animal species, and apparently a far higher number of species becoming extinct, in the tropics than in polar regions. Therefore on a global basis, habitat disruption will continue to be the major impact on animal and plant species.

Not all of the impacts on ecosystems of projected climate change will be negative. As in the case of agriculture, a warmer, wetter, higher CO_2 world will be beneficial for uncultivated plants. Global ecosystem models project higher net biomass production,[36] and observations of a variety of tree species indicate that they are already responding to higher atmospheric concentrations of CO_2 and higher temperatures[37] with increased

> *...on a global basis, habitat disruption will continue to be the major impact on animal and plant species.*

growth rates. Warmer, wetter conditions, and increased biomass production, also could be expected to benefit some animal species.

Animal and Plant Responses to Climate Change

There is agreement among experts that animals that are capable of moving will attempt to migrate in response to climate change. The movements of commercially important species, such as cod, in response to changes in ocean temperature, have been documented for centuries.[38] More recent studies show that a variety of animal species have moved in response to the warming of the 20th century.[39]

Individual plants cannot migrate, but plant species can and do migrate in response to changes in climate. All plants have seed dispersal mechanisms and therefore are constantly trying to establish seedlings in new areas. Seedlings thrive in a more desirable climate, but fail in a less desirable climate, moving the range of the plant as climate changes. The total change in range can be dramatic. Fossil evidence indicate that since the end of the last Ice Age, the balsam fir migrated from the southeastern U.S. to northern Canada, while the black spruce migrated from the central plains to Alaska.[40]

While it is agreed that plants and animals could migrate in response to climate change, at least four further concerns are raised about the likelihood that this will occur to a sufficient degree to prevent large scale species extinction:

1. human activities, particularly habitat disruption, will block potential migration routes;
2. even if they can migrate, the members of a given ecosystem will migrate at different rates leading to imbalances that will result in species extinctions;
3. plants may not be able to migrate fast enough to keep up with projected rates of climate change; and
4. plants and animals that live in restricted niches, e.g., near mountain tops, will have no place to migrate.

These concerns assume no human intervention to help wild species to adapt to climate change. In light of the growing and successful effort to reintroduce species such as beaver and wolf to their former habitats, to replant native plants, and to remove invasive plant species, this assumption is overly conservative.

Can Species Migrate Given Habitat Disruption and Other Human Activities?

Human activities have fragmented the areas in which many plants and animals can thrive. The remaining habitats are often pictured as "islands," which climate change could make unattractive to the species that live there. Migration to other "islands" could be difficult or impossible because the paths for that migration would be blocked by farms, cities, etc. However, recent studies raise questions about this conceptual model. Many species have been shown to either make use of fairly limited habitats or use multiple habitats to provide the area they need.

A recent *New York Times* article quoted Dr. John Wiens, a professor of ecology at Colorado State University, as follows:

> "We need to shift our thinking away from isolated areas in the midst of inhospitable human development," he said. "They're not oceanic islands." Only if biologists think of fragments in the context of an overall landscape, he went on, can they help manage, conserve and restore these habitats.[41]

The *New York Times* article went on to cite the work of Dr. Diane Debinski, a professor of animal ecology at Iowa State University. She found that even "habitat sensitive" species, which tend to stay in the interior of a particular "island," were present in greater number when those habitats were replicated in an attempt to provide a larger area of suitable habitat for these species. These results show that species are able to make use of all available suitable habitats, even if they are fragmented.

As noted above, habitat disruption is projected to be the largest contributor to human-induced species extinction in the 21st century. The steps that society will need to take to reverse this trend should also make it possible for plant and animal species to migrate in face of whatever climate change may occur in the future.

Can Ecosystems Migrate as a Unit?

An ecosystem is an interacting system of living organisms. Scientific understanding of the complexity of interactions between the species in an ecosystem is limited. Food chain relationships tend to be easy to observe, but there are many, more subtle, interactions. As a result, there is a concern that unless all, or a substantial fraction, of the species that make up the ecosystem migrate as a unit, the ecosystem, or at least some of its members, will fail to survive.

As with many claims about the potential impact of climate change on ecosystems, there is not doubt that this concern is valid in some situations. But given the current low level of understanding of ecosystem interactions, it is difficult to judge the magnitude of this risk. Ecosystems will be subjected to a variety of pressures, some natural, others, the result of human activities. The evidence available suggest that since these ecosystems have had to adapt to climate change in the past, they may be more capable of adapting to this pressure than many of the others they face. And, as our knowledge grows, so will our ability to help ecosystems in the adaptation process.

Can Plants Migrate Fast Enough?

The IPCC summarizes the knowledge about the rate of plant species migration as follows:

> Many studies of past changes have estimated natural rates of migration of tree ranging from 40 to 500 meters per year. … Gear and Huntly calculated from several sites in Britain migration rates of Scots pine of only 40-80 meters per year. However, for other species, such as white spruce, much faster dispersal rates of 1 – 2 kilometers per year have also been reported. It is not always clear whether observed past rates were maximal rates of migration or whether they were limited by the rate at which the climate changed.[42]

The IPCC concludes that these rates of migration are slower than the 1.5 – 5.5 kilometers per year that trees would have to migrate to keep up with projected rates of warming. However, this analysis assumes that a tree's habitat is a fixed point. Viable trees have ranges that cover many kilometers. Climate change might reduce that range in the short-term, but climate change alone should not lead to significant rates of extinction. Adaptation, for example, by transplanting tree species, could be beneficial in speeding migration.

Can Species with Already Limited Habitats Survive?

If climate warms, the migration path for plants and animals that live on mountains will be upward. This option is limited, since the plant or animal will soon run out of mountain. Since soil conditions typically become poorer with increasing altitude, other factors may limit migration long before the top of the mountain is reached. For species that have very limited habitats, in the extreme, a single mountain, this could lead to extinction. No doubt some of the past climate-related extinctions occurred for this reason. However, most alpine species have broader habitats than a single mountain and would survive, albeit with a changed habitat.

Summary: Can Plants and Animals Adapt to Climate Change?

The answer to this question has to be yes, since plants and animals have been adapting to climate change for billions of years. However, not all plant and animal species will be successful in adapting. If biologists are correct that natural climate change has been a major factor in past species extinctions, any change in climate, whether natural or human-induced, will increase the risk that some marginal species will become extinct.

Despite the concern about climate change, habitat disruption will continue to be the largest threat posed by human activities to the survival of plant and animal species. Many innovative programs are being undertaken to help plants and animals survive counter the adverse effects of habitat disruption, and these programs will help make these species more resilient to climate change. However, understanding of ecosystem interactions and the potential impacts of climate change on those interactions is simply inadequate.

Many innovative programs are being undertaken to help plants and animals survive counter the adverse effects of habitat disruption, and these programs will help make these species more resilient to climate change.

Migration is the major response that plants and animals can make to climate change. Many concerns have been raised about the ability of plants and animals to migrate given habitat disruption, scenarios involving of high rates of climate change during the 21st century, etc. Societal efforts to counter adverse effects by relocating endangered plant and animal species to more favorable habitats could reduce the impact of these changes.

Protection of endangered species enjoys widespread support in the U.S. and elsewhere, but the understanding needed to implement realistic programs that are in balance with other priorities is inadequate. Many fundamental questions, e.g. How many species are becoming extinct? remain unanswered. In addition, in focusing specifically on the potential impacts of climate change on ecosystems, this report identifies two areas in which research under the U.S. Global Change Research Program needs improvement. Efforts are needed to develop:

1. improved models which project the combined transient effect of multiple stresses, including climate change, on ecosystems; both the IPCC and NAS agree that current models are inadequate; and

2. better techniques to help endangered species migrate in response to climate change.

Conclusions

The destruction of ecosystems and species extinction as a consequence of projected climate change have been reported widely by the media and drive much of the perception of the global warming debate. This study examined available scientific evidence to fairly evaluate the claim that anticipated changes in the Earth's climate will result in unacceptable ecosystem impacts.

There is no question that ecosystems are sensitive to climate change and that any significant change is likely to have detrimental consequences for some ecosystems and some species. However, the scope of these consequences is limited by the ability to adapt to an evolving climate.

With continued adaptation, intensively-managed ecosystems, such are farms and commercial forests, can benefit from the levels of climate change projected by the IPCC for the 21st century. Developed countries already have the necessary adaptive capacity, and developing countries will acquire the necessary adaptive capacity as their wealth increases.

Ecosystems, such as wildlife areas, which are currently lightly impacted by human activities, would also benefit from adaptation, but the understanding necessary to plan that adaptation is currently inadequate.

To address these questions in a manner that will provide information and analysis needed to evaluate risks and consequences, decision makers need better tools and better information. These include better models, more robust data collection, and better techniques for estimating species and effects on them.

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Biography

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