Originally published December 1989 by the U.S. EPA Office of Policy, Planning, and Evaluation

CHAPTER 4
METHODOLOGY

by Joel B. Smith

NEED FOR CLIMATE CHANGE SCENARIOS

As discussed in Chapter 2: Climate Change, there is a scientific consensus that increased atmospheric concentrations of greenhouse gases will likely increase global temperatures, and that such a global temperature increase will likely increase global precipitation and sea levels. There is no consensus on how regional climates may change. We do not know whether temperatures will rise in all regions; we do not know whether precipitation in any particular region will rise or fall or whether we will have seasonal changes, and we are uncertain about the rate and magnitude of change. As discussed in Chapter 3: Climate Variability, scientists do not know how variability -- that is, the frequency of droughts, storms, heat waves, and similar phenomena -- may change. Without knowing how regional climate may change, we cannot predict impacts.

Despite these uncertainties, we can get a sense of what the future may look like through the use of scenarios. Scenarios are plausible combinations of conditions that may be used to illustrate future events. They may be used to identify possible effects of climate change and to evaluate responses to those effects. To incorporate uncertainties surrounding regional climate change, regional scenarios should include a variety of potential climate changes consistent with the state of knowledge regarding global warming. By analyzing many scenarios, we may be able to identify the direction and relative magnitude of impacts. Yet, unless scenarios have probabilities assigned to them, predictions of future impacts cannot be made. In this report, probabilities are not assigned and results do not represent predictions. Only the direction of change and relative magnitude are identified. The scenarios used in this report do not represent the entire range of possible climate change. Thus, the range of effects identified does not represent the entire range of potential effects.

SCENARIO COMPONENTS

To assess the potential effects of global climate change, regional scenarios of such change should have the following characteristics:

1. The scenarios should be internally consistent with global warming caused by increases in greenhouse gas emissions. A doubling of the CO_2 concentration in the atmosphere is thought to increase global temperatures by approximately 1.5 to 4.5°C (3 to 8°F). The regional temperature changes and seasonal distributions may be higher or lower, as long as they are internally consistent with the global range.

2. The scenarios must include a sufficient number of meteorological variables to meet the requirements for using effects models. These effect models include models of crop growth, forest succession, runoff, and other systems. Some models of the relationship between climate and a system use only temperature and precipitation as climate variables, while others also need solar radiation, humidity, winds, and other variables.

3. The meteorological variables should be internally consistent. While a scenario is not a prediction, it should at least be plausible. The laws of physics limit how meteorological variables may change in relationship to each other. For example, if global temperatures increase, global precipitation must also rise. Regional changes should be internally consistent with these large-scale changes.

4. The scenarios should provide meteorological variables on a daily basis. Many of the effects models used in this study, such as crop yield and hydrology models, need daily meteorological inputs.

5. Finally, the scenarios should illustrate what climate would look like on a spatial scale fine enough for effects analysis. Many effects models consider changes in individual stands of trees or farm fields. To run them, scenarios must illustrate how climate may change locally.

TYPES OF SCENARIOS

Two questions should be answered in analyzing the potential impacts of the greenhouse effect: What would be the effects of a large climate change in the future? How quickly will the effects become apparent over time? The first question asks what the world will be like in the future; the second is about the speed of change and the sensitivity of the system.

One way of examining the first question is to use scenarios of an equilibrium future climate. Climate equilibrium is defined as climate in which average conditions are not changing (although year-to-year variations could still occur).

A drawback of an equilibrium scenario is that it occurs at an arbitrary point in the future and assumes that the climate has reached a stable level corresponding with the higher concentrations of greenhouse gases. It does not indicate how climate may change between now and the equilibrium condition or how soon effects may be seen. Furthermore, a "stable" climate has never happened, nor is it likely to occur.

To help identify sensitivities and give a sense of when effects may occur, this study uses transient scenarios of climate change. A transient scenario is a scenario of how climate may change over time.

The options for creating regional scenarios of global warming include the following:

1. arbitrary changes in climate;
2. analog warming; and
3. use of general circulation models.

Arbitrary Changes

A simple way of constructing a scenario is to assume that climate variables change by some arbitrary amount. For example, one could assume that temperatures increase by 2 or 4°C, or that rainfall rises or falls by 10% and all other variables are held constant. Such scenarios are relatively easy to use and can help to identify the sensitivities of systems to changes in different variables. To determine how sensitive a system is to temperature alone, one could hold other variables at current climate levels and change temperature by arbitrary amounts.

A major drawback to using scenarios with arbitrary changes is that they may not be realistic, since evaporation, precipitation, wind, and other variables will most likely change if global temperatures change. A combination of unrealistic meteorological changes may yield an unrealistic effect. We are not sure how other meteorological variables would change on a regional scale if temperature rose a certain amount. Thus, scenarios with arbitrary changes may be useful for determining sensitivities to particular variables but not for determining the possible magnitudes of effects.

Analog Warming

Many climatologists have advocated the use of historic warming periods as an analog of how a future warming may affect regional climates (Vinnikov and Lemeshko, 1987). The instrumental weather record can be used by comparing a cool decade on record, such as the 1880s, with a warm decade, such as the 1930s (Wigley, 1987), or by comparing a decade such as the 1930s with the present.

Paleoclimatic data may also be incorporated into an analog warming scenario. For example, 6,000 years ago the temperatures were about 1°C warmer. Paleoclimatologists have determined how rainfall and temperature patterns on a broad regional scale differed in the past. The changes associated with past climates that were warmer than now may be used as an analog warming scenario.

The advantage of using an analog is that it gives a realistic sense of how regional and local weather patterns change as global climate warms. For example, climate data from 1880 to 1930 show how daily and local weather changed during a warming period.

However, analogs have several drawbacks. First, they are not consistent with the range of global warming now thought likely under the greenhouse effect: 1.5 to 4.5°C. The warmest period of the last 125,000 years was 1°C warmer than the present temperature. (Although the Pliocene Epoch (2 to 5 million years ago) had global temperatures several degrees higher than now, there is virtually no information on the regional distribution of temperature and rainfall during that period.) In addition, the past warmings were not necessarily caused by changes in the concentration of greenhouse gases, but may have been due to such factors as shifts in the inclination of the Earth's axis. These factors caused different regional climate changes than would be associated with increases in radiative forcing. Second, paleoclimatic and historic records do not provide enough detail to conduct comprehensive analysis of the 1°C warming. Paleoclimatic records only indicate broad regional patterns of change for a few variables, such as temperature, rainfall, and solar radiation. We cannot discern local, daily, or interannual climate from these records. Even using the 1930s data presents some problems. Daily records are available only for temperature and rainfall. Some effects models need more variables, such as wind or radiation. Furthermore, the number of weather stations with 1930s data is limited, which could present problems for creating comprehensive regional scenarios.

General Circulation Models (GCMs)

GCMs are dynamic models that simulate the physical process of the atmosphere and oceans to estimate global climate. These models have been developed over two decades and require extensive computations to run. They can be run to estimate current climates and the sensitivity of climate to different conditions such as different compositions of greenhouse gases. The GCMs are often used to simulate climate caused by a doubling of carbon dioxide levels, also referred to as doubled CO_2. Estimates of climate change caused by this effective doubling of CO_2[1] are referred to as "doubled CO_2 scenarios." Output is given in regional grid boxes.

CCMs have several advantages over the other approaches for creating scenarios. First, the models are used to estimate how global climate may change in response to increased concentrations of greenhouse gases. Thus, regional outputs are internally consistent with a global warming associated with doubled CO_2. Second, the estimates of climate variables (for example, rainfall, temperature, and humidity levels) are physically consistent within the bounds of the model physics. Third, GCMs estimate outputs for many meteorological variables (including wind, radiation, cloud cover, and soil moisture) providing enough input for effects models. Fourth, GCMs simulate climate variability on at least a daily basis.

Among the most important limitations are the GCMs' simulations of the oceans. The oceans play a critical role in determining the rate of climate change, regional climate differences, and climate variability. The GCMs, however, are coupled to relatively simple models of ocean circulation, which either treat the oceans as a "swamp" or only model the upper layers of oceans. The models' assumptions oversimplify the transfer of heat to and from the oceans. In addition, the GCMs simplify other important factors that affect climate, including cloud cover and convection, sea ice, surface albedo (the amount of light reflected, rather than absorbed, from the surface) and land surface hydrology (i.e., soil moisture), which may also contribute to uncertainty about the estimates of climate change (Dickinson, 1986; Schlesinger and Mitchell, 1985; Gates, 1985). For example, some of the GCMs model soil moisture storage in a simple manner, assuming the soils act like a "bucket." (There have been recent improvements on this method.) This method of modeling raises uncertainties concerning estimates of runoff from the models. The way GCMs simulate such important climate factors as oceans, clouds, and other features casts some doubt on the validity of the magnitude of global warming estimated by the models. (For a further discussion of the role of oceans in climate change, see Chapter 2: Climate Change. For a discussion of the GCMs' ability to estimate climate variability, see Chapter 3: Climate Variability.)

One of the major disadvantages of using GCMs for effects analysis is their low spatial resolution. GCMs give outputs in grid boxes that vary in size from 4 by 5 degrees latitude to as much as 8 by 10 degrees longitude. Figure 4-1 shows the grid boxes from the Goddard Institute for Space Studies (GISS)

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[1] The "effective doubling of CO_2" means that the total radiative forcing of all greenhouse gases (CO_2, CH_4 N_20, CFCs, etc.) is the same as the radiative forcing caused by doubling carbon dioxide concentrations, over midcentury levels, alone. In other words, the combination of all greenhouse gases has the same radiative forcing as simply doubling CO_2.

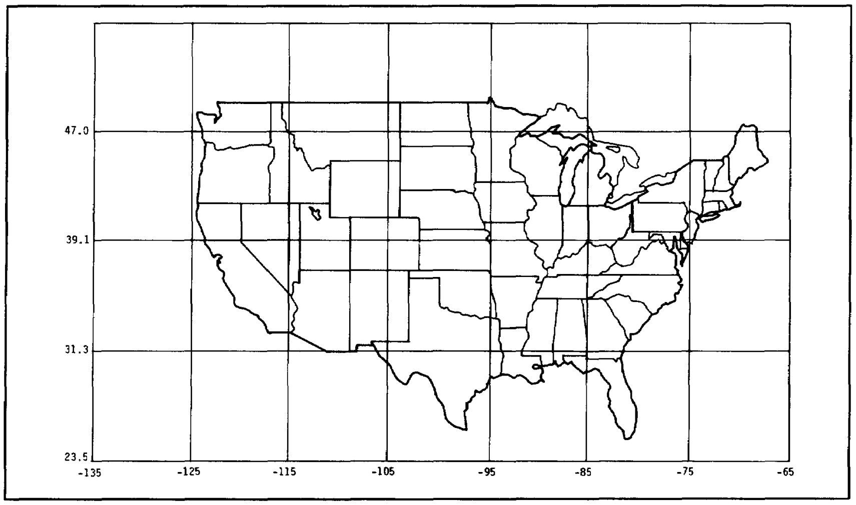

Figure 4-1. GISS model of the United States.

model overlaid on a map of the United States. Each grid box is 8 by 10 degrees and is an area larger than France (Mitchell, 1988). Within each grid box, the actual climate may be quite variable. For example, although both are in the same grid box, the weather in southern Washington State may be quite different from the weather in northern California. The models, however, do not account for variations within each grid box. For any simulated time, they provide a single value for temperature, for rainfall, and for other variables for the entire area of the box.

A second disadvantage for effects analysis, which may be more critical than the first, is that GCMs generally do not accurately simulate current regional climate conditions. In general, the accuracy of GCM climate estimates decreases with increasing resolution. The GCMs do a reasonable job of estimating observed global and zonal climates, but the estimates of regional climate are, in many cases, far from observed conditions. This is shown in Table 2-2 (see Chapter 2: Climate Change), adapted from Grotch (1988), which displays GCM temperature estimates and actual observations on different scales. GCM estimates of rainfall are less reliable on a regional scale. As Grotch points out, the disparities between GCM estimates of current regional climate and actual conditions calls into question the ability of GCMs to predict climate change on a regional scale.

The disparities among GCM estimates on a regional scale are due to a number of factors. One of the most important is the simplified assumptions concerning the oceans. The assumptions on other factors such as cloud cover, albedo, and land surface hydrology also affect regional estimates. The GCMs also simplify topographic features within grid boxes, such as the distribution of mountains or lakes. The large size of the grid boxes means that these features are oversimplified on a geographic scale. This contributes to uncertainty regarding estimates of regional climate change. In sum, as Grotch concluded, GCM estimates of regional climate change should not be taken as predictions of regional climate change. They should be interpreted as no more than illustrations of possible future regional climate conditions.

CHOICE OF DOUBLED CO_2 SCENARIO

GCM outputs were employed as a basis for constructing the scenarios to be used in our report because they produce the best estimate of climate change due to increased greenhouse gas concentrations and they produce regional climate estimates internally consistent with doubled CO_2 concentrations. Yet, GCMs are relatively new tools that need a great degree of refinement. Their results must be applied with caution. The regional GCM estimates of climate change are considered to be scenarios, not predictions. Given the uncertainties about GCM estimates of daily and interannual variability (see Chapter 3: Variability), a conservative approach involves using average monthly changes for each grid box.

The scenarios described in this chapter are a hybrid between GCM outputs and historic weather data. The estimates of average monthly change in temperature, precipitation, and other weather variables are used from GCM grid boxes. Model simulations of monthly doubled CO_2 conditions are divided by model simulations of average monthly current conditions in each grid. The ratios of $(2xCO_2)$:$(1xCO_2)$ are multiplied by historic weather conditions at weather stations in the respective grid boxes. Parry et al. (1987) used this approach in an analysis of impacts of climate change on agriculture. Thus, if a grid box is estimated to be 2°C warmer under the GCM doubled CO_2 run, all stations in that grid are assumed to be 2°C warmer in the doubled CO_2 scenario. The effect of this is to keep geographic variation from station to station within a grid the same as in the historic base period. Furthermore, interannual (year to year) and daily variability remain the same. If rainfall occurs 10 days in a month, in the scenario it also occurs 10 days in the month, and the amount of rainfall is adjusted by the GCM output. Since these scenarios are hybrids between GCM average monthly estimates and daily historic weather records, these scenarios are not strictly GCM scenarios. Each scenario is referred to by the GCM, whose monthly output serves as its base (e.g., the "GISS scenario").

The years 1951-80 were chosen as the base period to which average doubled CO_2 changes were applied. Several decades of data give a wide range of warm, cold, wet, and dry years. Since the data are from the most recent decades, they are the most complete historic data available. A complete daily record for a number of weather variables only began in 1948.

GCMs Used

To obtain a range of scenarios, output from three GCMs was used:

- Goddard Institute for Space Studies (GISS) (Hansen et al., 1988);
- Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and Wetherald, 1987); and
- Oregon State University (OSU) (Schlesinger and Zhao, 1988).

The average seasonal temperature and precipitation for the U.S. gridpoints for each model are displayed in Figure 4-2. All three models estimate that average temperatures over the United States would rise, but they disagree on the magnitude. OSU gives 3°C, GISS 4.3°C, and GFDL 5.1°C. The seasonal patterns are different, with GISS having a larger warming in winter and fall, GFDL having the highest temperature change in the spring, and OSU having little seasonal variability. All three models estimate that annual precipitation over the United States would increase. GISS and OSU estimate that annual precipitation would rise, respectively, by 73 millimeters (2.92 inches) and 62 millimeters (2.48 inches), while GFDL estimates a rainfall increase of only 33 millimeters (1.31 inches). The first two models have precipitation increases in all four seasons, while GFDL has a decline in summer rainfall. As can be seen in the regional chapters, the models show greater disagreement on the direction and pattern of regional rainfall changes than on regional temperature. Overall, OSU appears to be the "mildest" scenario, with the lowest temperature rise and largest increase in precipitation. GFDL appears to be the most "extreme," with the highest temperature rise, the smallest increase in precipitation, and a decrease in summer rainfall. Some of the important parameters in the three GCMs are displayed in Table 4-1.

The "extreme" values in the GFDL doubled CO_2 scenario are due, in part, to assumptions made in t9e model run used in this report. That run did not constrain sea surface temperature and sea ice, which yielded seasonal extremes in the northern hemisphere. A later run, produced too late for use in this study, constrained sea surface temperature and sea ice to observed values. Both runs yield the same average global warming of 4.0°C, while the later run has greater seasonal extremes in the southern hemisphere. Both runs show a large decrease in summer soil moisture (Wetherald, personal communication, 1988).

<u>Limitations</u>

A major limitation of the doubled CO_2 scenarios used for this study is the lack of temporal and spatial variability. By applying average monthly changes to the historic data set, it is assumed that the

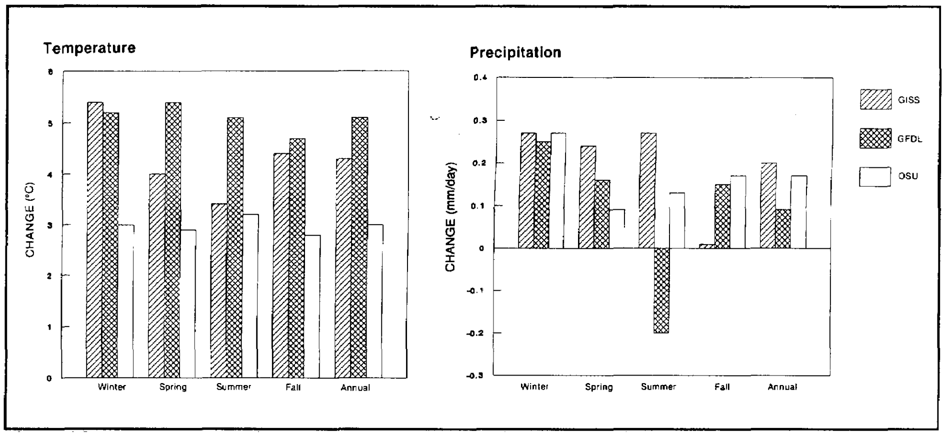

Figure 4-2. Average changes in temperature (°C) and precipitation (mm/day) over the grid boxes of the lower 48 states (2xCO_2 less 1xCO_2).

daily and interannual patterns of climate remain the same. This assumption is probably unrealistic, since a change in average conditions will probably lead to a change in variability. Furthermore, holding variability constant can have an impact on effects analysis.

Most climate-sensitive systems are sensitive to climate variability. For example, riverflow is very sensitive to the amount and intensity of rainstorms. Certain crops are sensitive to consecutive days with temperatures above a certain level. The studies do not identify how these and other systems could be affected by changes in temporal climate variability. Holding spatial variability within a grid box constant also affects the results of the analyses performed for this report. Climate change may also lead to changes in wind patterns, which could change storm patterns, cloud distribution, deposition of air pollutants, and other systems. In addition, the years 1951 to 1980 were a period of relatively low weather variability in the United States. Only adjusting average conditions from the base period in the scenarios may underestimate potential increases invariability. (For further discussion, see Chapter 3: Variability.)

The choice of the three doubled CO_2 scenarios does not necessarily bracket the range of possible climate change in the latter half of the next century. Due to the uncertainties about the rate and magnitude of global warming, it is possible that average global temperatures could be lower or higher than indicated by the models. Other climate variables could be different too. Thus, these scenarios should be interpreted as illustrations of possible future conditions, not as predictions. Furthermore, we did not assign probability to these scenarios. Currently, there is not enough information or a methodology for making such a determination.

If current emission trends continue, the effective doubling of CO_2 concentrations will occur around the year 2030. However, that estimate does not account for some recent developments that may slow the increase in greenhouse gas concentrations. If implemented, the Montreal Protocol would cut emissions of chlorofluorocarbons (CFCs) by 50%. If an international agreement is reached on reduction of nitrogen oxides (NO_X), the concentration of nitrogen dioxide (N_2O) may be slightly reduced. Pollution control measures in countries such as the United States may also reduce concentrations of low-level ozone, another greenhouse gas. Thus, the effective doubling of CO_2 may happen after 2030.

As discussed in Chapter 2: Climate Change, the change in climate potentially caused by CO_2 doubling would not occur at the same time as the increase in greenhouse gas concentrations. The oceans absorb greenhouse gases and heat from the atmosphere and serve to delay the warming. The full extent of climate change associated with CO_2 doubling could take several decades or more and may not occur until the latter half of the next century.

Table 4.1 Major Features for the Three GCMs[a]

GCM	When calculated	Model resolution (lat. x long.)	Model levels[b]	Diurnal cycle	Base 1 x CO_2 (ppm)	Temp for doubled CO_2 (°C)	Increase in global precipitation (%)
GISSc	1982	7.83 x 10[d]	9	yes	315	4.2	11
GFDLd	1984-85	4.44 x 7.5[d]	9	no	300	4.0	8.7
OSU	1984-85	4.00 x 5.0[d]	2	no	326	2.8	7.8
GISS Transient	1984-85	7.83 x 10[d]	9	yes	315 (in 1958)	--	--

[a] All models are global in extent and have an annual cycle. All models have a smoothed topography that varies between models. The later GFDL has been added for information. All models (except the transient) give data for the present climate ($1xCO_2$) and double CO_2 climate ($2xCO_2$).

[b] All models make calculations for surface conditions as well as for the listed upper-air levels.

[c] A gridpoint model with stated resolution

[d] This is a spectral model that has 15 waves.

Note: Oceans in Models:

GISS: This model has a slab ocean not over 65 meters deep; it has some variation of mixed depth over the seasonal cycle (for example, the depth is shallower in summer than winter in mid-latitudes). It has a specified pseudo ocean heat transport designed to reproduce the present day sea surface temperature (SST) in the simulation of the present climate. Ice thickness is predicted. For the GISS transient runs, the ocean depth was not limited in this way. In it, the average annual maximum mixed-layer depth was 127 inches.

GFDL: The slab ocean is 68 meters deep. There is no horizontal heat transport that would make the present day SST come out exactly right. Ice thickness is predicted.

OSU: This model has a slab ocean that is 60 meters deep (only 5 meters deep during spin-up period). It does not have heat transport that would force the model to reproduce the model to reproduce the present dat SST (this is being added in 1989).

In this report, results from doubled CO_2 scenarios are generally not associated with a particular year. When analysis is necessary, we have generally assumed that the CO_2 warming will occur in 2060. In some cases, researchers assumed a different time period for CO_2 warming, and those exceptions are noted as appropriate in the text.

The doubled CO_2 scenarios are often interpreted as estimates of future static (equilibrium) conditions. The assumption that the concentration of greenhouse gases becomes constant at doubled CO_2 levels is an arbitrary one. In fact, if emissions are not limited, concentrations could become greater and the global climate would continue to change. In many places in this report, responses are presented as if the climate stabilizes at doubled CO_2 conditions. Natural systems and society, however, may be responding and adapting to continuing and perhaps, accelerating changes in climate.

OPTIONS FOR CREATING TRANSIENT SCENARIOS

The options for developing transient scenarios are similar to the options for the doubled CO_2 scenarios:

1. arbitrary changes;
2. analog warming; and
3. GCM transient runs.

Arbitrary Changes

One could examine the manner in which a system responds to an arbitrary 1 or 2°C temperature warming and to small arbitrary changes in other variables. The problems of physically inconsistent assumptions about changes among variables and regions pertain here also. In addition, the arbitrary warming scenario gives no indication of when the warming may occur.

Analog Warming

Wigley (1987) has suggested using analogs as scenarios for climates that may occur within the next several decades. He noted that the warming from the late 19th century to 1940 was about 0.4°C, which may approximate the transient warming over the next two decades. The problem is that climate may change faster in the future than in the early 20th century. (The average decadal warming may be as much as 0.5°C, rather than the 0.1°C identified for earlier years.) Furthermore, the analog takes one only as far as a 0.5°C warming or, in the case of paleoelimatic records, a 1°C warming. It does not indicate what happens in the decades after the 0.5 to 1.0°C level is reached. In addition, the analog may not represent the regional distribution of climate associated with greenhouse forcing.

GCM Transient Runs

The Goddard Institute for Space Studies has modeled how global climate may change as concentrations of greenhouse gases gradually rise over the next century. This is called the transient run. GISS has modeled climate change under several assumptions of trace gas growth. The transient runs start in 1958 with the atmospheric concentrations of greenhouse gases that existed then. The concentrations of the gases and equivalent radiative forcing were estimated to increase from 1958 until an arbitrary point in the. future according to several different assumptions regarding trace gas growth. The GISS transient run yields daily climate estimates from 1958 until that arbitrary point.

For example, one of the transient scenarios, which is known as GISS A, assumes that trace gas concentrations continue to increase at historic rates and net greenhouse forcing increases exponentially. The scenario is run from 1958 to 2062. The end of the transient corresponds with a global warming equivalent to that of the equilibrium climate from the doubled CO_2 run. This scenario does not account for the potential reduction in CFC emissions due to the Montreal Protocol or for other activities that may reduce the growth in emissions. GISS B assumes a decreasing trace gas concentration growth rate such that climate forcing increases linearly (Hansen et al., 1988). It stops in 2029. GISS B includes volcanoes, while GISS A does not.

Since the GCMs are used to produce this transient run, the advantages and disadvantages of using this approach are the same as those described in the discussion of doubled CO_2 scenarios. In addition, the timing of the changes estimated by the GCMs is complicated by the uncertainties regarding the growth of greenhouse gas emissions and the roles of the oceans and clouds in delaying climate changes (Dickinson, 1986).

CHOICE OF TRANSIENT SCENARIO

This study used transient scenarios based on the GISS transient run because, of all the different approaches, only this one provides internally consistent estimates of climate change and allows examination of the entire range of climate change between current conditions and doubled CO_2 climate.

In creating the transient scenario, an approach similar to that used for the doubled CO_2 scenario was employed. Since relatively little confidence exists in the GCM's estimates of changes in interannual and daily variability, the monthly means were calculated for each decade of the transient. This process gives average decadal temperature, precipitation, and other changes. The average decadal temperature changes in GISS A and B for the United States are shown in Figure 4-3.

As in the doubled CO_2 scenario, the average meteorological changes from the transient are combined with a historic time series. What is different from the doubled CO_2 scenario is that a gradual change in temperature and other variables is mixed with a historic time series with its own variability. This can produce a regular oscillation.

In this study, the historic time series 1951-80 is used, and the transient monthly statistics are applied to the time series. The procedure for creating the transient scenario was to first linearly interpolate between decadal means. This smooths out the sharp decadal changes from the actual transient GISS results and is shown in Figure 4-4(a). The baseline 1951-80 weather data were repeated for 80 years, with the last 20 years consisting of a repetition of the 1951-70 data. Figure 4-4(b) shows the average U.S. temperatures for 1951-80 repeated for 80 years. The data transformations displayed in Figures 4-4(a) and (b) were done for data for each month for each grid box, site, and climate variable. The smoothed month-by-month transient data were added to the repeated 1951-80 data for each site and variable. Figure 4-4(c) displays the addition of the smoothed average U.S. transient temperatures with actual U.S. 1951-80 temperatures, repeated. Although there is a cooling from the 19505 to the 1960s, followed by a warming in the 19705, the underlying warming of the transient, which is 3.7°C by the middle of the 20505 in GISS A, is much greater than the variability in the base period.

Limitations

Since the transient scenarios were also derived from GCMs, the same limitations concerning temporal and spatial variability pertain as in the doubled CO_2 scenario. An additional limitation in the transient scenario is the rate of change. The GISS transient runs assume a gradual rate of change in temperature. The simplistic treatment of ocean circulation in the GCM affects the rate of warming estimated by the model. Broecker (1987) has shown that past climate changes may have been abrupt. Broecker, however, analyzed a global cooling, and the changes occurred over a much longer period than greenhouse warming. A sudden warming could mean that significant effects happen sooner and more suddenly than the results of the transient analysis used in this study indicate. The inclusion of the 1951-80 base period in the scenario yields short-term oscillations.

OTHER SCENARIOS

In a few cases, researchers used meteorologic data from the 19303 as an analog scenario. This scenario was used to provide additional information on the sensitivity of systems to climate change. In a few other cases, researchers only examined paleoclimatic records. In these cases, the goal was to determine how a system responded to past climate change.

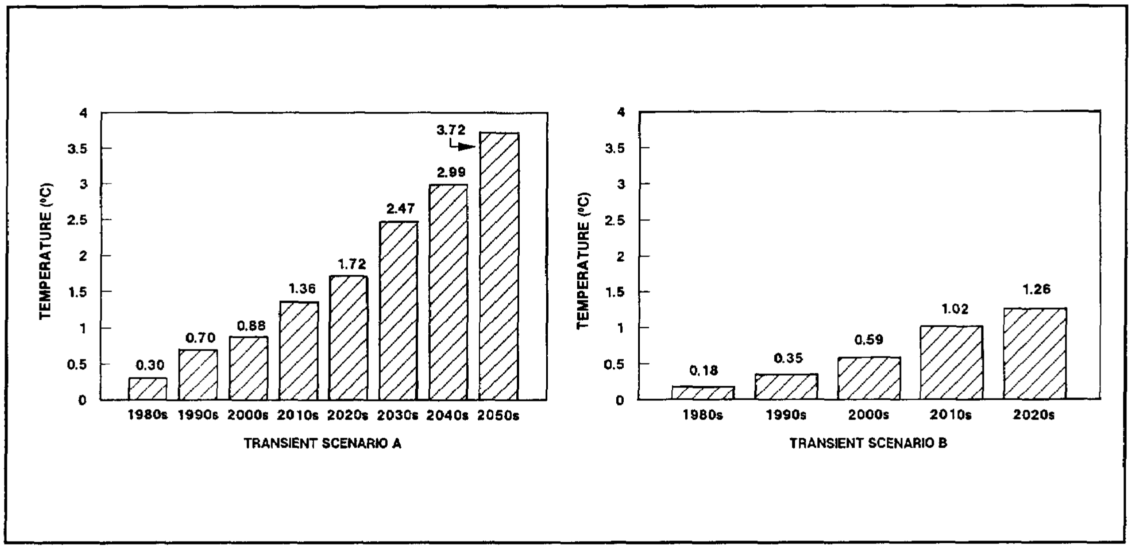

Figure 4-3. GISS transients "A" and "B" average decadal temperature change for lower 48 states gridpoints.

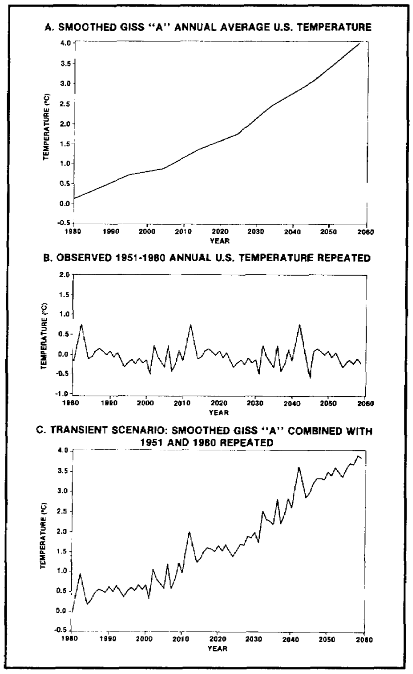

Figure 4-4. Transient scenarios (temperature change).

EPA specified that researchers were to use three doubled CO_2 scenarios, two transient scenarios, and an analog scenario in this study. Many researchers, however, did not have sufficient time or resources to allow for the use of all scenarios. EPA asked the researchers to run the scenarios in the following order, going as far through the list as time and resources allowed:

1. GISS doubled CO_2;

2. GFDL doubled CO_2;

3. GISS transient A;

4. OSU doubled CO_2;

5. Analog (1930 to 1939); and

6. GISS transient B;

Most researchers were able to use at least the GISS and GFDL doubled CO_2 scenarios. Comparison of results across studies may be limited because of inconsistent use of scenarios.

Sea Level Rise Scenarios

Unlike the climate scenarios, the alternative sea level rise scenarios were not based solely on the differences between various general circulation models. Instead, they were based on the range of estimates that previous studies have projected for the year 2100 (Hoffman et al., 1983, 1986; Meier et al., 1985; Revelle, 1983; Thomas, 1986), which have generally considered alternative rates of greenhouse gas emissions, climate sensitivity ranging from 1.5 to 4.5°C for a CO_2 doubling, and uncertainties regarding ocean expansion and glacial melting. Estimates for the year 2100 generally range from 50 to 200 centimeters.

This report uses three scenarios for the year 2100 -- 50, 100, and 200 centimeters -- and compares them to the current trend of 12 centimeters per century. Because most studies have not reported estimates for the intermediate years, we followed the convention of a 1987 National Research Council report (Dean et al., 1987) and interpolated sea level rise using a parabola. The rates of sea level rise assumed in this report are displayed in Figure 7-8 in Chapter 7: Sea Level Rise. Because various coastal areas are also sinking (and in a few cases rising), relative sea level rise at specific locations was estimated by adding current local subsidence trends. Note that sea level rise scenarios are presented for the year 2100, while doubled CO_2 scenarios are presented for the latter half of the It century.

EFFECTS ANALYSES

In this study, the preferred approach for analyzing potential impacts of climate change was to develop quantitative estimates. Most researchers estimated impacts by running models that simulate the relationship between weather and the relevant system. The climate scenarios were used as inputs into the models. Since the researchers had only several months to do the analysis, they used either "off-the-shelf" models or analytic techniques. In many cases, existing models were calibrated to new sites. This lack of time also limited the gathering of new data to a few studies.

A drawback of using empirical models of systems to estimate sensitivities is that the models are applied to climates for which they were not developed. The models estimate relationships with observed climate. This relationship is then extrapolated to an unprecedented climate. It is possible that in the new climate situation, the statistical relationship may be different owing to the crossing of a threshold or for some other reason. With the drawbacks of empirical models, the current statistical relationships are the best basis for quantitatively estimating sensitivities.

For the most part, researchers analyzed the potential effects of climate change on systems as they currently exist. Although these changes may be quite substantial, potential changes in populations, the economy, technology, and other factors were not considered. In some cases, researchers ran additional scenarios with assumptions about technological and other changes. In addition, potential responses to climate change were considered in some, but not all, cases. For these and many other reasons, the results should be interpreted only as an indication of the sensitivity of current systems to global warming, not as a prediction of what the effects will be.

In some situations, quantitative models of the relationship between climate and a particular system did not exist. In those cases, other approaches were used to try to identify sensitivities. Some researchers examined how systems responded to analog warmings. In other cases, expert judgment was used. This consisted of literature reviews to assemble information on sensitivities as they appear in the literature, and workshops and interviews to poll experts on how they thought systems would respond to global warming.

RESEARCH NEEDS

The scenarios used in this report help identify the sensitivities of systems to climate change. Because of the lack of confidence concerning regional estimates of climate change from GCMs, we cannot predict impacts. In order to predict the effects of climate change, major improvements need to be made in GCMs. These could take many years. In the meantime, we will continue to use scenarios to identify sensitivities. As with GCMs, scenarios can also be improved.

GCMs

To produce better estimates of regional climate change, both the resolution of GCMs and the modeling of physical processes need to be improved. The GCMs used for this report had large grid boxes, in which major geographic features, such as the Great Lakes or the Sierra Nevada Mountains, which have large impacts on local climate, were not well represented. Ideally, the higher the resolution, the better the representation of geographic features. But each increase in resolution means a large increase in computations and computing power needed to run the model. Furthermore, at high resolutions, the GCMs may require new parameterizations. The resolution should be increased at least to the point at which major geographic features are well represented in the models.

It is also important that the estimates of physical processes in the models be improved to increase the confidence about estimates of the magnitude and timing of changes. Three areas need the most attention: oceans, clouds, and hydrology. The oceans play an important role in delaying climate change and have a large influence on regional climates. However, the ocean models currently used in GCMs are relatively simple. Ocean models that better simulate the absorption and transport of heat and gases would give improved estimates of transient and regional climate change. Clouds are a major feedback to global warming and influence regional climate. More realistic modeling of clouds by GCMs would improve the estimates of the magnitude of global warming and regional change. Finally, more sophisticated hydrology in GCMs will yield better estimates of soil moisture and runoff, which will also improve estimates of regional climate changes.

Scenarios

The scenarios in this report were based on changes in average conditions, either at equilibrium (doubled CO_2) or due to a gradual change in average underlying conditions (transient). As pointed out in Chapter 3: Variability, many systems are quite sensitive to changes in the frequency and intensity of extreme events. In the future, scenarios should incorporate change in variability to help identify sensitivities to variability. Transient scenarios can also be improved. Such scenarios should be useful for testing sensitivities to changes in long-term climate trends as well as year-to-year variations. At the same time, it is important to keep scenarios simple. More detailed scenarios, involving a lot of data (such as daily data from GCMs) may be difficult to use. The more detailed the scenario, the more likely it will be applied incorrectly, which limits the ability to compare results by different researchers. In addition, scenarios should be simple, so the assumptions used in creating them can be easily understood. Designers of scenarios will have to wrestle with the competing desires of being more detailed and maintaining simplicity.

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CHAPTER 5
FORESTS

by Jack K. Winjum
and Ronald P. Neilson

FINDINGS

Global warming could significantly affect the forests of the United States. Changes could be apparent in 30 to 80 years, depending upon the region, the quality of a site, and the rate of climate change. There may be northward shifts in species ranges, dieback along the southern reaches of species ranges, and changes in forest productivity. Other stresses in combination with climate change may exacerbate these impacts. Different migration rates and climate sensitivities may result in changes in forest composition. Without large-scale reforestation, large reductions in the land area of healthy forests are possible during this century of adjustment to climate changes. Although climate fluctuations, timber harvests, disease outbreaks, wildfires, and other factors have affected forests during the last century, the magnitude of these changes is substantially less than those projected in response to climate changes considered in this report.

Range Shifts

- The southern ranges of many forest species in the eastern United States could die back as a result of higher temperatures and drier soils. The southern boundary could move several hundred to 1,000 kilometers (up to 600 miles) in a generally northward direction for the scenarios studied.

- The potential northern range of forest species in the eastern United States could shift northward as much as 600 to 700 kilometers (370 to 430 miles) over the next century. Actual northward migration could be limited to as little as 100 kilometers (60 miles) owing to the slow rates of migration of forest species. Without reforestation, full migration of eastern forests to potential northern distributions could take centuries. If climate change occurs too rapidly, some tree species may not be able to form healthy seeds, thus halting migration. Reforestation along northern portions of potential forest ranges could mitigate some of these impacts.

- If elevated CO_2 concentrations substantially increase the water-use efficiency of tree species, the southern declines would be alleviated.

- If climate stabilizes, forests might eventually regain a generally healthy status (over a period of several centuries). In the meantime, declining forests could be subject to increased fires, pest attacks, and replacement with low-value trees, grasslands, and shrubs. A continually changing climate could result in even greater dislocations among forests.

Productivity Changes

- Dieback along the southern limits of distribution of many species could result in productivity declines of 40 to 100%, depending on how dry soils become.

- Productivity could increase along the northern limits of some eastern tree species, particularly as slow-growing conifers are replaced by more rapidly growing hardwoods.

Combined Impacts With Other Stresses

- Large regions of severely stressed forests, combined with possible increases in fires, pests, disease outbreaks, wind damage, and air pollution, could produce major regional disturbances. These factors were not considered for this report.

- Additional impacts of changes in forests include reductions in biotic diversity, increased soil runoff and soil erosion, reduced aquifer recharge, changes in recreation, and changes in wildlife habitat.

Policy Implications

- Institutions such as the U.S. Forest Service, state forest agencies, and private companies should begin to consider how to factor climate change in their long-term planning. Global climate change may need to be a factor in the Forest Service's 50-year planning horizon.

- Where U.S. forests are clearly reduced by climate change, forest agencies will have to consider intensive strategies to maintain productivity. For example, they could undertake reforestation on a more massive scale than now practiced and possibly introduce subtropical species into the Southeast.

- A coordinated public and private reforestation effort, together with development of new and adapted silvicultural practices, would also be required. Forests are major carbon sinks, so a large reforestation program would also reduce atmospheric CO_2 concentrations, slowing the rate of global warming. This study did not evaluate the effectiveness of reforestation efforts.

EXTENT AND VALUE OF U.S. FORESTS

Forests occupy 33% of the U.S. land area and exist on some lands in all 50 states. In total, they occupy 298 million hectares (738 million acres) and are rich in such resources as water and wildlife.

Many biotic and abiotic factors influence the condition of forests, but climate is the dominant factor (Spurr and Barnes, 1980). This chapter summarizes the current knowledge and predictions concerning the effects of rapid climate change on U.S. forests.

Distribution and Ownership

Eight major forest regions of the conterminous 48 states contain 84% of the forested ecosystems of the United States (Figure 5-1). The forested areas of

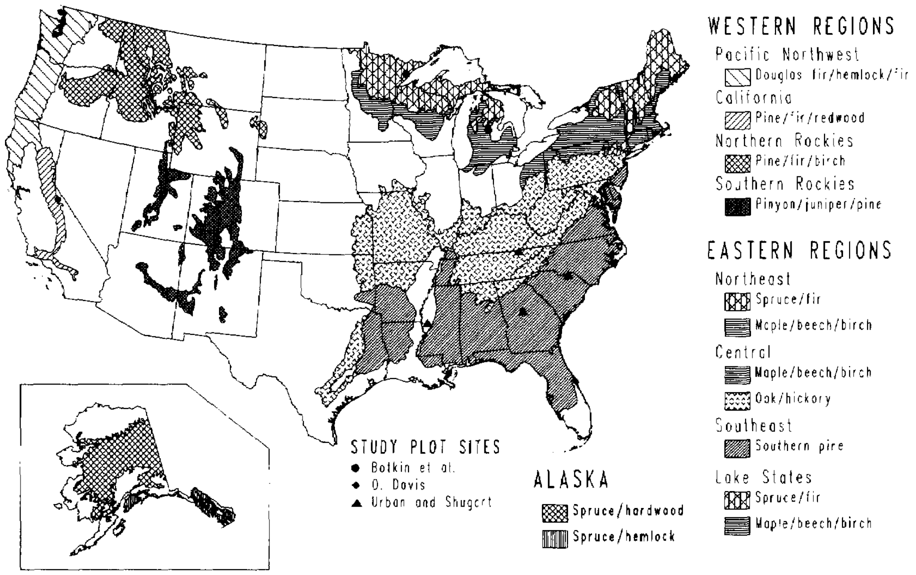

Figure 5-1. Major forest regions of the United States and their primary tree groups.

Table 5-1. Area of U.S. Forest Lands in 1977 by Federal, State, Private, and Other Ownerships (millions of hectares)[a]

			Commercial Forests[b]						
					Private				
	Regions/States	Primary Tree Species	Federal	State	Industry	Non-industry	Other[c]	Total	% Total
East	Northeast - CT, MA, ME, NH, RI, VT	spruce - fir - maple beech - birch	0.3	0.4	3.9	7.8	0.7	13.1	4.4
	Lake States - MI, MN, WI, ND, SE (E)	spruce - fir - maple beech - birch	2.3	2.8	1.7	9.9	4.2	20.9	7.0
	Central - DE, IA, IL, IN, KA, KY,	maple - beech - birch oak - hickory	1.8	2.0	8.6	22.9	2.6	37.9	12.7
	Southeast - AL, AR, FL, GA, LA, MS,	loblolly, shortleaf slash pine	5.8	1.0	14.7	54.3	8.0	83.8	28.1
West	Northern Rockies - ID, MT, SD(W), WY	pine - fir - birch	9.1	0.6	0.8	2.7	9.3	22.5	7.6
	Southern Rockies - AZ, CO, NM, NV, UT	pinyon - juniper - pine	6.4	0.3	0.0	2.4	24.1	33.2	11.1
	Pacific Northwest - OR, WA	D. fir - hemlock - fir	7.8	1.2	4.0	3.2	5.3	21.5	7.2
	California - CA	pine - fir - redwood	3.4	0.03	1.1	2.0	9.8	16.3	5.4
Separate States	Alaska - AK	spruce - hemlock - hardwood	3.3	1.0	0.0	0.1	43.9	48.3	16.2
	Hawaii - HI	ohia	0.01	0.2	0.0	0.2	0.4	0.8	0.3
		Total	40.2	9.5	34.8	105.5	108.3	298.3	
		% Total	13.5	3.1	11.7	35.4	36.3	100	100

[a] Hectare x 2.47 = acres.

[b] Commercial forests are those capable of growing at least 1.4 cubic meters per hectare per year (20 cubic feet per acre per year) of industrial wood materials.

[c] Other forests include county and municipal forests and those federal lands withdrawn from industrial and wood production for use as parks, preserves, and wilderness.

Source: USDA (1982).

16% (Table 5-1). Each forest region includes one or more forest types distinguished by the major tree species present. As a general rule, some types in each region have predominantly coniferous tree species (i.e., evergreen, needle-leaved, and softwoods); other forest types are composed mostly of deciduous trees (i.e., tree species that are broadleaved, have no winter foliage, and are hardwoods). Forest types with a mix of coniferous and deciduous trees, however, are not uncommon.

Superimposed over the natural distribution of trees, forests, and ecosystems in the United States is the human infrastructure. Ownerships include federal, state, and private lands (Table 5-1). Within the forests classified as "commercial" (64% of 298 million hectares), the federal government ownership of 40 million hectares (99 million acres) is primarily in the national forest system managed by the U.S. Department of Agriculture's Forest Service (36 million hectares or 91 million acres); most of the remainder is managed by the Department of Interior's Park Service, Fish and Wildlife Service, or Bureaus of Land Management and Indian Affairs. State ownerships total 9 million hectares (23 million acres). Private lands are divided between those of industrial forest companies (35 million hectares or 86 million acres) and those of small, private landowners, who collectively have 106 million hectares (262 million acres) (USDA, 1982).

Another significant segment of American forests consists of those maintained within urban and suburban areas. Examples are community parks, greenbelts, roadside forests, and wooded residential and industrial zones (USDA, 1981). These forest areas are important sources of outdoor recreation, wildlife habitat, and real estate values. In total, the urban/suburban forests of the United States occupy approximately 28 million hectares (69 million acres) (Grey and Deneke, 1978).

To the degree that all forest lands are owned by some individual or organization, all forest lands are under some form of management. A continuum of management policies exists, ranging from lands intended to have minimal human intervention except for protection from catastrophic wildfire (e.g., some parks and most wilderness areas) to lands where silvicultural practices are intensively applied (e.g., the most productive federal, state, and industrial forest lands dedicated to growing tree crops); (Table 5-2).

These forests under government and industrial management constitute roughly one-fourth of the total and might be the easiest to manage under climatic impacts simply because they are larger blocks of lands already under strong management commitments.

Value of U.S. Forests

Most populated regions in the United States are located close to or within a forested region. For instance, the Boston-Washington corridor is within the eastern hardwoods. The populations of Atlanta and the Southeast are interspersed among the southern pine forests. Chicago and nearby Great Lakes communities are surrounded by the mixed conifer-hardwood forests of that region, and the Los Angeles to San Francisco populations parallel the Sierra Nevadas to the east. In addition, urban/suburban forests exist in or near most of the nation's cities. Forests, therefore, are part of the environmental fabric and general habitability for the majority of U.S. citizens.

All forests shed water to some degree, and two thirds of the water runoff in the contiguous 48 states comes from forested ecosystems. Precipitation passes through forested ecosystems as canopy throughfall or flows along tree stems, and then flows along the ground surface or into the soil; eventually, some of the water flows into streams. Water yields from U.S. forests provide about 750 billion liters (200 billion gallons) of water each day for major uses such as irrigation, electricity production, manufacturing, and domestic consumption. These levels of demand are projected to continue to the year 2030 (USDA, 1981).

Table 5-2. Percentage of Forest Lands by Level of Management within Four U.S. Regions (estimates for 1977)

U.S. regions	Forest plantations[a]	Other commercial[b]	Reserved/deferred[c]
East			
North	9	80	11
South	21	69	10
West			
Rocky Mountains	2	38	60
Pacific Coast	16	44	40

[a] Intensively managed populations.

[b] Moderately managed forests.

[c] Recreational and protected forests

Source: USDA (1982).

A favorite use of forests is outdoor recreation. Activities include hiking, camping, hunting, sightseeing, boating, swimming, fishing, skiing, sledding, and snowmobiling. A 1977 survey of U.S. households indicated that a majority of people participated in outdoor recreation four or more times each year (USDA, 1981).

About 190 million hectares (470 million acres), or 64% of the total U.S. forested ecosystems, are highly productive commercial forest lands. These lands represent about 10% of the world's forest area, but they supplied nearly a quarter of the world's industrial forest products in the late 1970s (USDA, 1982). In 1980, 1.7 million people were employed in timber-based occupations across the United States. Such employment is basic to the economic well-being of many small towns and communities (Schallau, 1988). The total value of timber products harvested in 1972 was about $6.4 billion, and the total value after such processes as manufacturing, marketing, transport, and construction amounted to $48 billion, or 4% of the nation's gross national product. In 1979, timber product exports and imports were valued at $7 billion and $9 billion, respectively. Looking ahead, the consumption of wood products in the United States is projected to increase between current levels and the year 2030 (USDA, 1982).

RELATIONSHIP BETWEEN FORESTS AND CLIMATE

Scientific understanding of forest ecosystems has greatly advanced with each decade of this century. Yet the literature contains little information concerning the direct or indirect effects of climate change on the complex biological and physical processes in forest ecosystems. Some insights are gained from paleobotanical studies of past rates and magnitudes of ecological change during glacial-interglacial cycles, as well as changes in the species composition of forested ecosystems. Similarly, observations of forest responses to unusual drought or other weather extremes provide some knowledge. Estimates of rate, magnitude, and quality of change have also been derived using computer models developed by plant ecologists or forest management scientists for other objectives. Their validation for understanding how a forest can adapt to climate change is only in the initial stages.

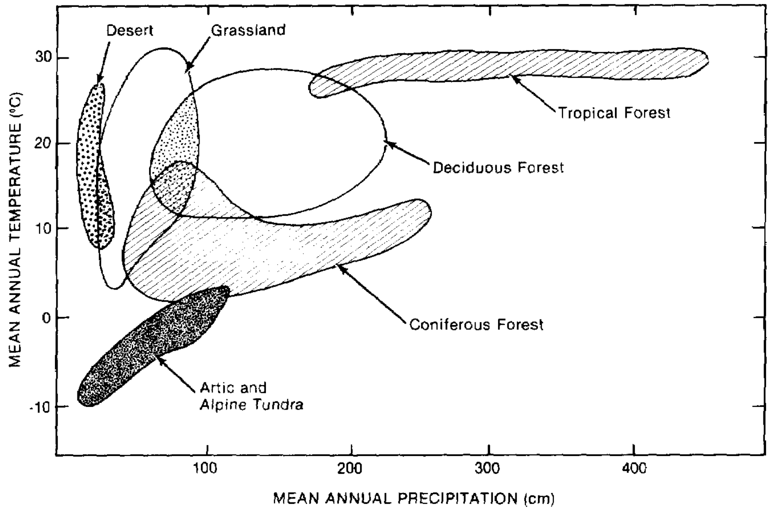

Figure 5-2. Approximate distributions of the major groups of world biomass based upon mean annual temperatures and precipitation (Hammond, 1972).

Climate is a primary determinant of existing forests. The ranges of annual average temperature and rainfall variation determine global forest distributions relative to different biotic regions (Figure 5-2). Substantial increases in temperature or decreases in rainfall could, for example, produce a shift from a forest to a grassland type. Thus, accelerated climate change resulting from human activities and related effects on U.S. forests is of high concern to citizens and policymakers alike.

Magnitude

Vegetation has been in an almost constant state of distributional change and adjustment due to an almost constantly changing climate over the past 10,000 years and even over the past several hundred years (Spurr and Barnes, 1980). Lines of evidence come from studies of fossils, tree rings, carbon-14 dating, plus peat and pollen analyses (Webb, 1987).

Historical climate changes appear to have been associated with such phenomena as fluctuations in solar radiation, earth orbit variations, and volcanic activity. Evidence of repeated continental glacial advances and contractions in the Northern Hemisphere dramatically illustrates the large-scale effects of global climate change.

In response to the glaciation, species shifted south. Evidence from fossil pollen, for example, indicates a southward shift of spruce into Georgia and east Texas during the last glacial advance and treeless tundra in the Great Lakes region (Spurr and Barnes, 1980). During the maximum interglacial warmth of 6,000 to 9,000 years ago, which was 1.5°C (2.7°F) warmer than the present temperature level, plant zones were one to several hundred kilometers (60 to 250 miles) north of present distributions.

Rates

All forested ecosystems experience change on both spatial and temporal scales; each biological and physical forest component may respond to climatic variation on different spatial and temporal scales. For example, microorganisms, insects, and birds come and go with relatively short-term climatic variation; shrub species' abundances vary within the timespan of decades; trees, once established, could persist for centuries. This understanding is important from the perspective of climate change, since it implies that forested ecosystems do not respond as a unit, but in terms of parts. Different parts respond differently; consequently, future forested ecosystems under a rapidly changing climate could be quite different from those existing today.

At the expected rapid rate of climate change, the potential rates of forest migration would become a major concern. Migration rates vary by species. Paleorecords of the Holocene (10,000 years ago to present) show that extension of ranges for tree species of eastern North American (in response to glacial retreat) varied from 10 to 20 kilometers (6 to 12 miles) per century for chestnut, beech, maple, and balsam fir (Zabinski and Davis, Volume D). Other species within the oak and pine groups extended at faster rates, i.e., 30 to 40 kilometers (19 to 25 miles) per century. It should be noted that there is some uncertainty as to whether these migration rates were in response to glacial retreat plus climate warming or primarily warming alone.

Mechanisms

Knowledge of causal links between weather patterns and forest response is fundamental to projecting growth and composition effects resulting from climate change. Another requirement is to understand the climatic influences on processes influencing populations of forest plants and animals. These include such phenomena as fires, windstorms, landslides, pest outbreaks, and other disturbances that affect survival and subsequent colonization by different species. Furthermore, the processes that control the dispersal of seeds through a mosaic of different ecosystem types (such as forest patches interspersed with agricultural lands, wetlands, grasslands, and other land-use groups) must be clearly defined.

Among the important factors now known to influence the growth and distribution of forests are the following.

Temperature

The optimum temperature for growth depends upon the tree species and other conditions. Warmer temperatures usually increase the growth of plants. However, high temperatures can decrease the growth of plants or cause mortality where temperatures greatly exceed optimum ranges for growth. Cold temperatures can limit plant distributions by simply limiting growth at critical stages or by directly killing plants.

Precipitation

Too much or too little precipitation can limit forest production and survival. Too much rainfall in some areas can cause flooding or raise the water table, thus drowning roots by reducing soil air that contains oxygen required for respiration or by promoting fungal attack. Too little rainfall can reduce growth, cause susceptibility to fire or pestilence, and possibly kill plants. The seasonal timing of rainfall is more important than total annual rainfall, although forests also require some minimum total annual rainfall (see Figure 5-2).

CO_2 Concentration

High CO_2 concentrations could increase tree growth through increases in photosynthesis rates and water-use efficiency (primarily hardwood species) when water and other nutrients are not limited (Strain and Cure, 1985). Plant responses to CO_2 have been investigated largely in growth chambers and are difficult to extrapolate to the real world. Responses are varied and do indicate some measure of adaptive capability most likely imparted from ancestral exposure to much higher and lower levels in the geologic past. However, in natural situations, water nutrients or temperature usually are limiting factors in forest growth, thus making the impacts of CO_2 enrichment uncertain. If water use efficiency increases, then tolerance to drought might increase, ameliorating declines in southern parts of ranges. Unfortunately, the current state of knowledge does not allow generalizations on this subject.

Another important relationship between forests and CO_2 is the role forests play as carbon sinks. Globally, forest vegetation and supporting soil contain about 60% of the organic carbon stored on world land surfaces. This organic carbon is largely cycled between forest ecosystems and the atmosphere by photosynthesis (uptake of CO_2) and respiration (CO_2 release) in the plants (Waring and Schlesinger, Ri5). Anthropogenically caused reductions of forests either directly (e.g., urbanization, mismanagement) or indirectly (as a response to CO_2 induced global warming) would tend to increase the "greenhouse effect."

The amount of sunlight bathing an ecosystem sets the upper limit on net primary productivity. Thus, the tropics exhibit higher productivity than do the boreal regions. This potential productivity would, of course, be limited by other climatic effects such as drought, cold, heat, and natural disturbances, and by the time required for forests to shift into new ranges. The length of day exerts considerable control on physiological processes such as release from and onset of dormancy. Significant northward shifts of forests would alter their day-length regime, producing uncertain results.

Nutrient Status

In addition to climate, most forest growth is strongly influenced by availability of soil nutrients. Disturbances over vast regions, such as drought followed by fire, can release large quantities of essential nutrients into the atmosphere or into surface waters. This leaves soils nutrient deficient. Lengthy periods of soil development are usually required to replenish the soil nutrients before a large, mature forest stand can be supported. In turn, soils reflect properties of the forests that they support. This results from decades of nutrient uptake, litterfall, decomposition, and other processes.

Atmospheric Chemistry

Much of the nutrient budget of forests involves deposition of chemicals from the atmosphere as gases, aerosols, or particles, or in solution with water as precipitation. Although most of these act as nutrients, some produce acid deposition that can leach important soil nutrients (e.g., $SO_4^=$), produce a fertilizing effect (e.g., NO_3), or damage leaf tissue (e.g., O_3). Climate change will alter transport paths of air pollutants, and increased temperature could increase the rates at which gases convert to deleterious forms.

Disturbances

Almost continually, forests experience natural disturbances or stresses from biotic or abiotic agents alone or in combination. Examples are insect and disease outbreaks, plant competition, wildfire, drought, cold extremes, and windstorms.

These disturbances, which are among the primary factors controlling the successional processes in forests (Pickett and White, 1985), may range from an opening of small gaps in the canopy as the result of single tree death or of windthrow occurring when trees are blown down by heavy winds (predominant successional mechanisms in eastern hardwoods) to large clearings from fire, windthrow, or pestilence (predominant successional mechanisms in western forests).

Landscape Processes

The horizontal movements of materials such as soil and biological organisms, together with human disturbances across the landscape, are critical to processes controlling tree migration, species diversity in forests, and the spread of fire, windthrow, and pestilence effects. These processes are very poorly understood; quantification in the emerging field of landscape ecology is just beginning.

Multiple Stresses

In general, trees or forests stressed by one factor, e.g., accelerated climate change, are more susceptible to natural stresses (secondary disturbances) such as insects, disease, or invading weed species. The concept of multiple stresses leading to forest declines is becoming more widely recognized (Manion, 1981). Regional climate changes, even if temporary, frequently predispose forests to damage by other natural or anthropogenic stresses.

PREVIOUS STUDIES ON THE NATIONAL EFFECTS OF CLIMATE CHANGE ON FORESTS

Concern regarding effects of climate change on U.S. forests has prompted several excellent reviews. One of the most comprehensive (Shands and Hoffman, 1987) was the result of a conference sponsored by EPA, the National Forest Products Association, and the Society of American Foresters. While pointing out the high uncertainty associated with current predictions of climate change, several authors suggested that if predictions are true, distributions of key forest species in the United States will change significantly.

Other recently produced compilations broadly consider forest effects along with other impacts (e.g., those on agriculture, prairie land, and the Great Lakes) (White, 1985; Titus, 1986; Meo, 1987; Tirpak, 1987). These reviews are largely pioneering efforts and some overlap occurs, but each presents some key points.

The methods used in the previous studies are quite similar to those used in this report. They include computer modeling of forest processes, literature surveys, studies of fossil evidence, and empirical relationships constructed by experts. The estimates of future change produced from these studies are generally based on the output of one or more of the general circulation models (GCMs) used for this report. Thus, the results of the previous studies are consistent with those reported here.

STUDIES IN THIS REPORT

Six studies on forest effects contributed to the regional case studies reported in this volume. The purpose was to use existing data bases analyzed in new ways to estimate effects on U.S. forests from climate change scenarios. The selection of the six studies was based upon three criteria: use of established statistical methods; hypotheses testing concerning causal mechanisms; and selection of a mix of studies that complemented each other, such that the strengths in one approach might overcome the weaknesses of another.

This report focuses primarily on forests within the contiguous 48 states. It is worth noting, however, that the largest magnitude of warming is expected in the northern latitudes encompassing the boreal forest and other forest types in Alaska and Canada. Thus, these large forests could also be under significant risk from climate warming.

RESULTS OF FOREST STUDIES

Design of the Studies

Characteristics of the six studies are briefly listed in Table 5-3. With the exceptions of the

Table 5.3. Principal Investigators, Regional Focus, and Method of Approach for the Regional Forested Ecosystem Studies

Principal investigator	Region	Method
Overpeck and Bartlein	Eastern North America	Correlation and fossil studies
Urban and Shugart	Southeast Uplands	Forest dynamic model
Botkin et al	Great Lakes	Forest dynamic model
Zabinski and M. Davis	California	Correlation
O. Davis	California	Fossil studies
Woodman et al	Southeast, California, and National	Literature review

Overpeck and Bartlein study and the Woodman study, the methods are discussed in the regional case study chapters and will be mentioned only briefly here. All of the forest studies are in Volume D.

Two studies used correlations between tree distributions and climate (Overpeck and Bartlein; Zabinski and Davis). Overpeck and Bartlein's approach consisted of correlating the modern pollen distributions of important tree species with January and July mean temperature and annual rainfall.

The correlation was then tested by reconstructing past pollen distributions from general circulation model simulations of past climates (during the most recent glacial-interglacial cycle) for each species and comparing them to observed pollen distributions from those periods. Future pollen distributions were then constructed from the expected doubled CO_2 climate projected from the different model climate scenarios. The correlations were constructed on modern pollen distributions, rather than tree distributions, to allow the direct comparison to fossil pollen data. Modern pollen distributions are similar to, but not exactly the same as, modern tree distributions. The verification studies indicated that the approach works reasonably well at a coarse spatial resolution. That is, northern trees are in the north and southern trees are in the south, with the regional patterns being reasonably well represented.

The approach of Zabinski and Davis was essentially the same as that of Overpeck and Bartlein, except that the correlations were constructed from the actual modern tree distributions rather than from the modern pollen distributions (see Chapter 15: Great Lakes).

Two of the studies used computer models of forest dynamics (Botkin et al.; Urban and Shugart). Growth characteristics of each tree species occurring in the study region are used by the models to determine the growth and development of individual trees on a site. These growth characteristics include such attributes as maximum age, maximum height, maximum diameter, and ranges in tolerance to stresses of temperature, moisture, and shade. Both studies explored forest response starting with bare ground on a range of soil types from well drained to poorly drained. Forest growth simulations from bare ground represent conditions after a fire, logging, or similar disturbance. Mature stand simulations are useful for investigating the potential response of present forests to gradual climate change in the immediate future.

For the California case study, Davis reconstructed vegetation patterns in the Sierra Nevadas from fossil pollen studies for the interglacial warm periods that occurred between about 6,000 and 9,000 years ago. These reconstructions represent possible analogs of a future warm period at the lower magnitude of the predicted future warming.

Woodman conducted a literature review for the Southeast and California forested regions and peripherally for the entire nation. The purpose was to ascertain the attributes of the forest resource in terms of extent, ownership, economic and recreational value, and policy considerations.

Limitations

Although predicted effects vary, these six analytical studies have results that are collectively consistent enough to advance our knowledge and justify concern regarding the future of U.S. forests under rapid climate change. The range of predicted effects is large; however, uncertainties exist regarding (1) the climate scenarios; (2) the kind and rates of responses of individual tree species; and (3) changes in forested ecosystems as a whole resulting from environmental change. All of these factors significantly influence the precision and accuracy of the results.

A major uncertainty in the simulation model approach involves the rates of species dispersal into a region. The current generation of models has no dispersal mechanisms. A species is simply present or it is not present. For example, Botkin et al. excluded most southern tree species so that their dispersal was unrealistically nonexistent, and these southern species could never enter the Great Lakes region. But if they had been included in the simulations, these species would have entered the northern forests at the same rate as the climate change. This would have assumed dispersal rates far in excess of reality. This limitation can, in part, be overcome by studies, such as those of Zabinski and Davis, that provide some insight into actual dispersal rates and species migration. The simulations did not consider the impact of transplanting southern species in these areas.

The timing of forest declines as estimated by the models should be interpreted with caution. Declines are triggered by periods of high environmental stress. Forest models are usually not operated far beyond current conditions, such as for extremely dry soils. Therefore, the extreme climate simulated by these models may not estimate the timing and behavior of forest declines as accurately as desired. It should also be remembered that there is much uncertainty concerning the rate and timing of the climate change itself.

A further cautionary point is that although the models considered temperature limitations, nutrient deficiencies, and soil moisture stress, other important factors might affect the timing and magnitude of tree responses. Examples of factors in need of consideration include disturbance effects (e.g., impacts from wildfires, pests, and pathogens), age-dependent differences in tree sensitivities to stress (e.g., older trees are often more susceptible), and potential CO_2 induced increases in water-use efficiency.

The models also carry assumptions about the environmental controls of species limits. In most cases these assumptions are reasonable, given that indices of environmental stress, such as July temperature or annual rainfall, are usually related to factors that more directly affect plant growth, such as accumulated warmth or summer drought. However, large uncertainties exist in some instances. This is particularly true with regard to the climatic controls of the southern limits of southeastern forests, simply because of their association with the continental margin. Does the climate at that latitude represent the actual climatic limitation to the distributions, or are the species simply stopped by a geographic barrier? No one really knows. These uncertainties were partially addressed by Overpeck and Bartlein, who compared their fossil pollen approach to the modeling approach. The two approaches use similar relations to climate, and both can be used reasonably well to simulate forest distributions in the geologic past.

Several uncertainties with the pollen-climate correlation approach limit its precision and accuracy. First, many of the plant taxa used in the study are plant genera (e.g., pine, oak) rather than species, and thus the simulated results are not taxonomically precise. Second, the results are applicable only on a regional scale; local scale predictions are not made. Third, and very significant, the simulated results assume that all the plants are in equilibrium with the new climate. Rates of dispersal vary between species, and several hundred years may pass before plant communities are again in equilibrium with climate. How this lag would affect plant community dynamics is not addressed in this study and is an important research question.

The paleoecological analysis of the past vegetation in the Sierra Nevadas (O. Davis) presents several uncertainties. First, differences with respect to weather variations (i.e., season to season and year to year) could produce strikingly different types of vegetation. Also, there is much uncertainty about what the most appropriate analog period might be -- or if one even exists. Furthermore, the rate of climate change in the future is predicted to be much faster than the rate of climate change during the past 20,000 years. Lags in the response of species to the future climate could strongly affect the type of forest at any one location, whereas in the past, with a more slowly varying climate, lags in species response were not as important in determining forest composition.

All of the studies are deficient in some very important processes controlling forest responses to climate, particularly disturbance regimes such as fires, windstorms, hurricanes, landslides, and pest outbreaks. Over some forest areas, periods of cloud cover could change. This is an important uncertainty, for if the annual total is significantly increased, reductions in solar radiation could mean reduced photosynthesis and thus less forest growth.

In addition, the responses of mature trees to elevated CO_2 under conditions of moisture, temperature, or other nutrient limitations remain largely unexplored. Most research on elevated CO_2 on trees has been performed in controlled chambers using seedlings, and results show an increase in photosynthesis and improved water-use efficiency in some cases (Strain and Cure, 1985). However, the seedlings were not previously grown in or acclimatized to high CO_2 environments. Evidence has shown that plants grown under high CO_2 will respond differently to changes in temperature, light, and moisture conditions (Strain and Cure, 1985).

Another shortcoming is that methods to extrapolate CO_2 fertilization results from laboratory experiments to the natural world are limited, and an understanding of regional changes in water-use efficiency is even more limited. Furthermore, complex interactions between fertilization effects and changes in water-use efficiency can produce unexpected problems such as increased heat loads due to effects on evaporation cooling. These interactions are not well understood but could produce major regional changes in forest responses. Therefore, it is not yet possible to quantitatively incorporate the direct effects of CO_2 on forests into studies such as these. Further, if water or nutrients are limiting to forest growth, they would likely exceed the fertilization effects of elevated CO_2. Also, forest canopies at optimum development have multilayered leaf areas so that light limitations exist for the lower portion of the foliage in addition to frequent water and nutrient limitations. This adds further weight to the belief that CO_2 enrichment may not significantly affect forest prod3uctivity.

Results

The six studies conducted for EPA consistently indicate that climate changes would significantly affect the natural forests of the United States. The distribution of healthy forests in the eastern United States appears to become greatly reduced from their present areas during the next century (Figures 5-3 and 5-4). This results from a very slow northward migration coupled with a fairly rapid decline in the southern and western parts of species ranges. Drier forest conditions in the United States, induced as much by increased temperature as by changes in rainfall, would mean less tree growth and therefore reduced forest productivity in general.

The forest simulation models provide an indication of the importance of uncertainties imparted by the climate scenarios. The climate scenarios differ primarily in their representation of regional rainfall patterns. The model results indicate that temperature has a large effect on forest health, either directly through cold and heat stress or indirectly through exaggerated drought effects. Thus, the overall characteristics of forest responses are remarkably similar among the three climate scenarios. However, this generalization is uncertain because models usually do not incorporate all possible mechanisms of impact.

Magnitude

Eastern Forests - Northern Limits

All of the study results suggest a northward expansion of most eastern tree species (Figure 5-3 displays results from Overpeck and Bartlein). That is, spruce, northern pine, and northern hardwood species would move north by about 600-700 kilometers (375-440 miles) into the Hudson Bay region of the Canadian boreal forest (Overpeck and Bartlein; Zabinski and Davis). New England coniferous forests would be replaced by more hardwood forests and especially by the oak species from the eastern mid-United States (Botkin et al.; Overpeck and Bartlein; Zabinski and Davis). As the northern mixed forests shift from spruce-fir to sugar maple, some sites could actually triple their present productivity (Botkin et al.).

Additionally, southern pine species could shift about 500 kilometers (310 miles) into the present hardwood forest lands of eastern Pennsylvania and New Jersey (Overpeck and Bartlein; Urban and Shugart; Solomon and West, 1986; Miller et al., 1987). Depending upon the severity of climate change, Urban and Shugart estimated that near the northern limits of slash pine in East Tennessee, aboveground woody biomass in 100 years could range from little change to an extremely low biomass with almost no trees (i.e., a grassland, savanna, or scrub). However, even with little decrease in productivity, species shifts would alter the forest composition from shortleaf to loblolly pine, a more commercially valuable tree species.

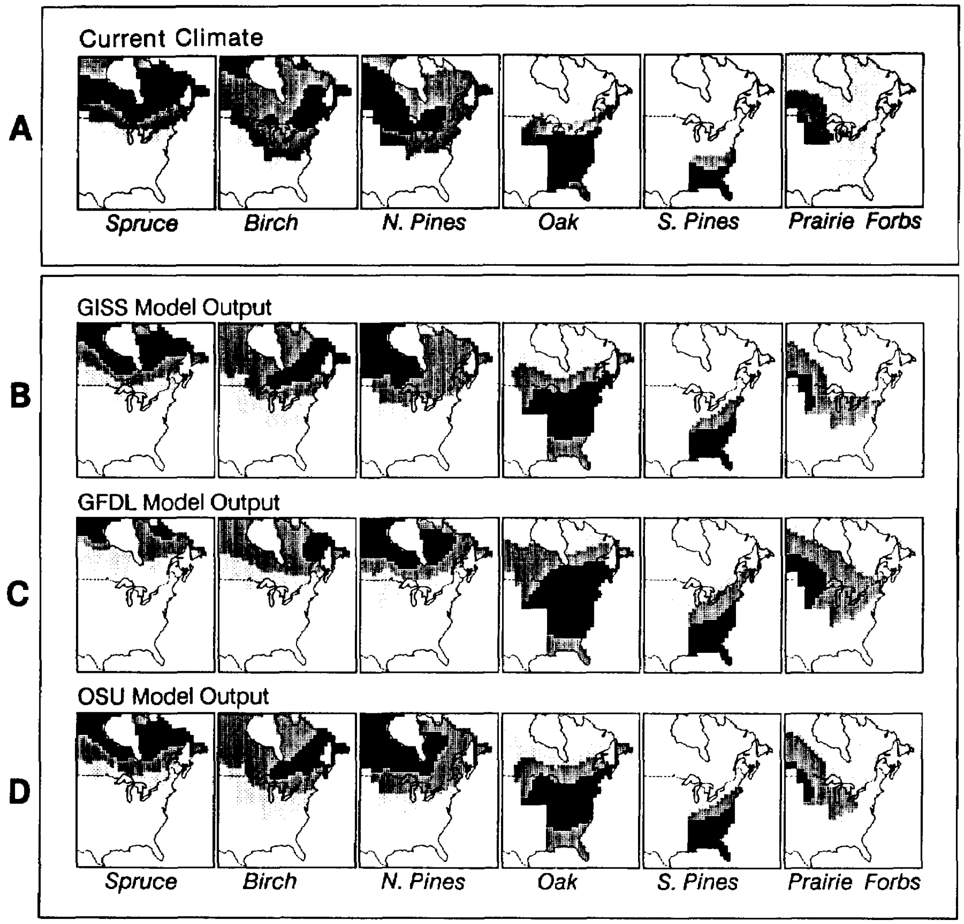

Figure 5-3. Maps of eastern North America depicting present distributions of major forest genera and herbacious vegetation compared with potential future distributions after reaching equilibrium with the climate predicted for doubled CO_2. The comparison is based upon (A) simulations using modern pollen data and simulated future pollen abundances for each of the three doubled CO_2 scenarios: (B) GISS; (C) GFDL; and (D) OSU. The three levels of shading in each scenario map indicate estimated future pollen abundances ranging from 20% (darkest or strongest chance of future distributions) to 5% and 1% (lightest or least chance of future distributions) (Overpeck and Bartlein, Volume D).

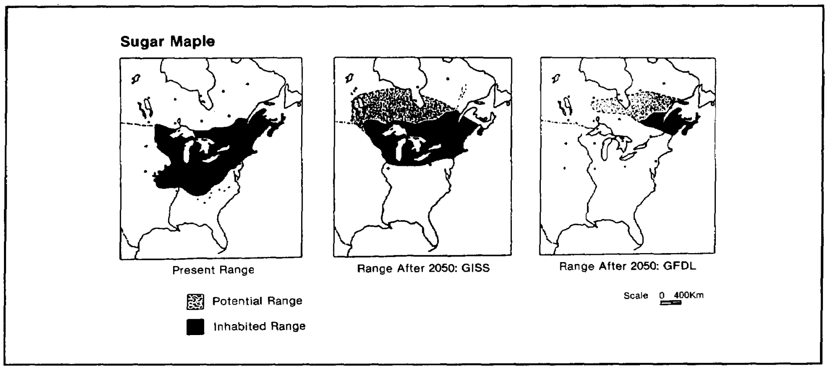

Figure 5-4. Present and future geographical range for sugar maple (Zabinski and Davis, Volume D).

Eastern Forests - Southern Limits

Ultimately, forest decline and mortality could truncate southern distributions of tree species by as much as 1,000 kilometers (625 miles) in many northern hardwood species (Zabinski and Davis; Overpeck and Bartlein) or by as little as a few hundred kilometers (about 120 miles) in southern pines and hardwoods (Urban and Shugart; Solomon and West, 1986). Under the driest scenario (GFDL), Zabinski and Davis estimate local extinction in the Great Lakes region of many eastern tree species such as eastern hemlock and sugar maple (Figures 5-3 and 5-4). These estimates bear considerable uncertainty for all species.

These uncertainties are particularly true for the southern limits of southeastern species that border the continental margin. The actual southern climatic limitations of these species are not well known (Urban and Shugart). Nevertheless, under the most severe climate scenario in the Southeast with increased temperatures and decreased growingseason precipitation, Urban and Shugart's results suggest that the 18 tree species they considered would no longer grow in the southern half of the region. Present forest lands in the region would be replaced by scrub, savanna, or sparse forest conditions. This estimation results from scenario conditions of heat that would exceed the tolerance limits for most tree species. Under the mildest scenario (OSU), even forest areas in South Carolina and southward would be marginal, supporting about half their current biomass.

Biomass accumulations in 100 years for mature natural forests in productive sites in the Great Lakes region could be reduced to 23-54% of their present values (Botkin et al.; Solomon and West, 1986). On poor sites, forests could be converted to grassland or savanna with very low productivity, ranging from 0.4 to 28% of their present values.

Western Forests

Similar projections were made for six western coniferous species: ponderosa and lodgepole pine, Douglas-fir, western hemlock, western larch, and Englemann spruce (Leverenz and Lev, 1987). Estimations are mixed for the West. Because of the mountainous conditions in the West, upslope shifts are possible for Douglas-fir, ponderosa pine, and western hemlock in the northern Rocky Mountains. In the coastal mountains of California and Oregon, Douglas-fir could shrink in the lowlands and be replaced by western pine species (O. Davis; Leverenz and Lev, 1987). Overall, the western forest lands are estimated to favor more drought-tolerant tree species, such as the hard pine group, at the expense of fir, hemlock, larch, and spruce species.

If regional drought persisted, the frequency of fires could increase, significantly reducing total forested area. Also, with massive upslope movement, some species could be pushed off the tops of mountains into local extinction.

No quantitative estimates have been derived for productivity for the western forests under potential warming conditions. However, using the analog approach of Davis, under the most severe conditions projected for California, the species composition of the west-side Sierra Nevada forests would become more similar to that of the east-side forests. This could reduce the standing biomass to about 60% of current levels.

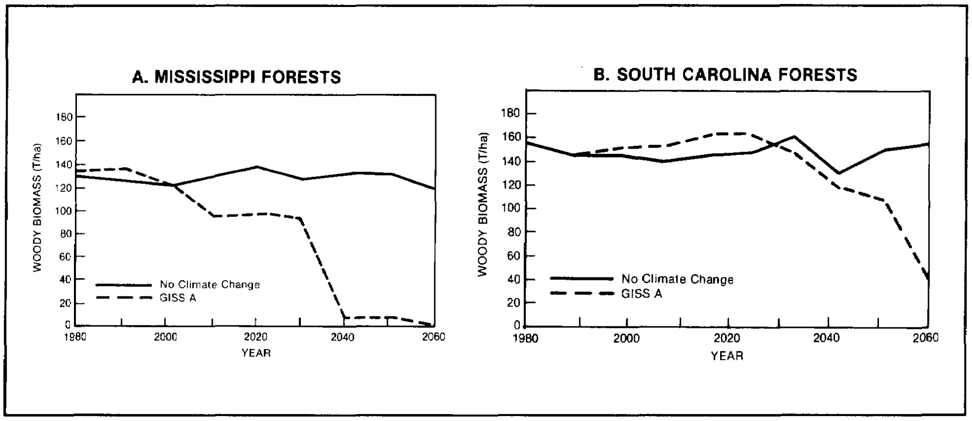

Figure 5-5. Estimated changes in biomass of mature forests in Mississippi (A) and South Carolina (B) under the GISS transient climate change scenario (Urban and Shugart, Volume B).

Rates of Decline and Migration

In the Great Lakes region, significant forest decline and forest compositional change could become evident within 30 to 60 years (Figure 5-5A; Botkin et al.). In the Southeast region, forest declines could become most evident in 60 to 80 years with declines in the drier western portions occurring even earlier, perhaps in about 30 years (Figure 5-5B and C); Urban and Shugart). As previously discussed in this chapter (see Limitations) there is considerable uncertainty about these numbers.

These rapid declines, coupled with the expected magnitude of climate change, raise the question of how fast forests can migrate. Based upon fossil records, Zabinski and Davis have estimated that the maximum dispersal rate of several tree species in response to the last glacial retreat was roughly 50 kilometers (30 miles) per century. Under the expected rapid warming, they estimated that a dispersal rate of about 1,000 kilometers (600 miles) per century would be required to maintain species distributions near their current extent. Such migration rates are doubtful, suggesting greater reductions in species ranges under rapid climate change, with declines in the drier western portions.

Mechanisms of Migration

Distribution changes (i.e., migrations) suggested by these studies must be considered carefully. Reproductive processes are essential for the migration of tree species across the landscape. For many tree species, climate change could reduce natural regeneration in an existing location and introduce the species at different latitudes or altitudes. Reproductive processes in trees, such as flowering, pollination, seed set, seed germination, and seedling competitive success, are particularly sensitive to climate.

Specific regional climate scenarios vary as a function of the GCM. All scenarios estimate increases in temperature; however, some include increases in rainfall, and others have decreases. The northward shifts of species appear to result from a release from cold temperature stress, which normally freezes flowers, seedlings, and even adult trees. However, the western and southern limits of eastern tree species appear to result from insufficient moisture and excessive heat stress, which primarily affect sensitive life history stages but can also affect mortality rates of adult trees. Though difficult to detect in the early phases of rapid climate change, tree mortality is sensitive to chronic moisture stress and mortality rates would likely increase among the major forest regions of the United States.

Two points are important about regional uncertainties of future rainfall distribution. First, changes in the seasonal distribution of rainfall are as or more important than relatively small changes in the annual total. If summer rainfall decreases while winter rainfall increases, the trees may still experience summer drought stress. Second, evapotranspiration is a log function of temperature. Therefore, as temperature goes up, water loss from trees and soils can increase tremendously. If minor increases in rainfall are not sufficient to override the evapotranspirational losses of water, drought impacts will pervade. Both of these mechanisms appear to dominate the forest impacts in this study.

All of the study approaches used under all of the climatic scenarios estimate major forest declines in the southern parts of species ranges and expansions to the north. These declines, resulting primarily from drought stress, would occur despite the differing rainfall predictions among the climate scenarios used in this study. Global precipitation is generally projected to increase slightly with global warming (see Chapter 4: Methodology), but it is not known whether this increase would be sufficient to compensate for potential increases in plant moisture stress caused by higher temperatures. Precipitation in some regions may decline. Droughts would become more common. The western limits of eastern forests could similarly retract as the climate warms.

Existing forests probably would not shift intact, but would change in composition. Variations in migration rates and sensitivities to weather variables produce individual responses to climate change. These changes are consistent with the well-known dynamic nature of ecosystems and were projected for the forests of all regions. In the Great Lakes region, for example, beech could decrease in abundance (Zabinski and Davis), and birch and maple could increase (Botkin et al.). On some lands, forest productivity could remain about the same as today, but changes to less economically important species could be significant.

Not considered quantitatively in any of the studies are changes in forest disturbance regimes. These changes should not be considered lightly. Extreme and more frequent climatic variations (see Chapter 3: Variability) could cause much higher mortality in U.S. forests than the current experience. Although little is known as yet, some locations may experience an increase in the frequency of extreme weather events, for example, wind, ice, or snow storms, droughts, and flooding. Besides the direct damage these events can cause, they can predispose forests to damage from secondary stresses such as insects, disease, and wildfires.

ECOLOGICAL AND SOCIOECONOMIC IMPLICATIONS

The effects of doubled CO_2 climate changes may be considered from two perspectives: ecological and socioeconomic. Evidence for significant national implications is strong from both viewpoints.

Ecological Implications

Ecological implications for forests commonly start with tree response. But strong implications also exist for other ecosystem components, e.g., animals, soils, water, secondary impacts, and as noted, the atmosphere through which climate change is mediated. Forest effects are described in terms of tree distribution changes and biomass production changes, but many other processes interact among the other major components. Thus, significant changes in tree response would be accompanied by ecological reverberations throughout all the forested areas of major U.S. regions.

Tree Distributions and Biomass Productivity

As discussed, migrations of forest tree species to the North in response to rapid warming in North America during the next century will be likely.

However, significant lag is possible. Even under the maximum rates of species dispersal estimated by Zabinski and Davis, healthy forest areas may not redevelop for several centuries. Furthermore, if climate continues to change beyond the next century, then healthy forests may never redevelop. Meanwhile, distribution ranges may not be under such constraints, so the extent of healthy forested regions in the United States probably would be greatly reduced. Though some locations may have increased productive potential from a biomass per hectare standpoint, the large reductions in areas with healthy forests would likely create a net reduction in forest productivity for the United States for several centuries or longer.

Even if a massive reforestation effort were undertaken, the new forests resulting from species shifts might or might not be as productive as existing forests. More northern latitudes or higher elevations raise other considerations. Farther north, days are longer in the summer and shorter in the winter. At higher elevations, damaging ultraviolet light intensity is greater. All of these conditions could lower forest productivity below present levels. Furthermore, it is not clear that reforestation would be successful. A major intent of reforestation would be to artificially speed up northward migration of tree species. However, seedlings that would appear to be favored on some northern sites several decades in the future may not survive there now because of constraints imposed by temperature, day length, or soil conditions. Similarly, seedlings that could not survive on those sites now might not be the best adapted species for those same sites several decades in the future.

Animals

A change in the size and relative homogeneity of forests could influence whether some animals can continue to live in their present locations. Often, animals are finely adapted to habitats specific to a certain location. For some animals, migration can be hindered by boundaries between forests and other land types or facilitated as animals move along edges. Furthermore, some animals (e.g., many game species) prefer young forests, and others (e.g., many rare and endangered species) prefer old forests. In turn, animals can exert a profound influence on forest structure and composition through selective browsing of seedlings, insect attack of different tree species, seed dispersal, and other effects. All of these factors illustrate that climate change could influence the regional patterns of biotic diversity in both plants and animals (see Chapter 8: Biodiversity).

Soils

Soils under warmer climates also would change, although at a much slower rate than shifts in species distribution. Increased soil temperatures, however, would affect the entire range of physical, chemical, and biological soil processes and interactions. For example, populations of bacteria, fungi, and animals could increase in a way that would accelerate decomposition of litter and thereby reduce the availability of nutrients essential for forest growth (Spurr and Barnes, 1980).

Considerable time may be required to develop optimum soil conditions for high forest productivity supporting species at more northern latitudes or higher elevations. Furthermore, it is not at all clear how well some northern soils could support more southern species. The soils of the boreal forest differ from those under the deciduous forests to the south.

Water

Where forests give way to drier conditions (e.g., in the Great Lakes region and California), many lands now serving as watersheds might be used for different purposes. Furthermore, regional-scale disturbances (such as fire) and applications of chemicals (such as fertilizers and pesticides) could degrade regional water quality and increase airborne toxic chemicals (see Chapter 9: Water Resources).

Sea level rise may impact some coastal forests. Many forest lands of high value for timber production (e.g., in the Southeast) or recreation (in the Northeast, Northwest, and California) are close to ocean coasts. Inundations, decreases in depth to the water tables, and saltwater intrusions could trigger rapid forest declines near these areas.

Secondary Impacts

As the southern bounds of forests tend to shift north, forest decline (sick and dying trees) could become extreme over large areas that would become highly susceptible to weed competition, pest outbreaks, or wildfire. As forests decline, species of lower economic value, as well as weedy shrubs and herbs, could invade via wind dispersion. Under stressful environments, such species are severe competitors with most commercial tree species.

Trees experiencing less favorable growth conditions are more stressed and will be vulnerable to insect and disease attack. These secondary pest impacts could last "until the most vulnerable forest stands or tree species are eliminated" (Redden, 1987). In addition, it is estimated that the incidence of catastrophic wildfires will increase in U.S. forests with higher temperatures. Simand and Main (1987) estimated that fire occurrence and fire-suppression costs would increase 8 and 20%, respectively.

Socioeconomic Implications

The United States enjoys substantial economic and cultural benefits from its forests. Until recently, the nation's forest managers assumed that these benefits could be sustained by maintaining forests in a healthy condition (Fosberg, 1988). This was achieved, for example, by preventing fires or pest invasions, avoiding careless use, and enhancing productivity through good silviculture.

Beginning with the possibility of regional air pollution damage to forests, suspected in the 1980s, alterations of the environment external to forests presented a new concern. Research and policy discussions to deal with this issue are ongoing.

If climate changes as rapidly as predicted, this additional external influence with its more global dimensions looms as a possible hazard to forests and their use. As can be imagined, a list of potential socioeconomic concerns would be large. To provide a brief perspective, three issues are considered.

Quality of the Human Environment

The forest amenities enjoyed by most U.S. citizens will be affected according to different forest responses. In the Boston-Washington corridor, a composition change from predominantly hardwood to predominantly pine forests, though ecologically significant, may not be noticed by most people if it occurs gradually. However, a delay of years or decades between the decline of existing forests and replacement by migrating tree species would likely elicit a strong concern. In the Atlanta-Southeast region, the southern pine forests, while undergoing a gradual expansion of their northern boundaries, would have less vigor in the remaining stands. This could raise their vulnerability to damage from insects and disease, reducing esthetic values -atleast an intermediate impact for most of the local citizens. In contrast, within some portions of the Southeast, the Great Lake region, and California, drier climates may cause the loss of some forest lands to prairie or desert conditions -- a severe change for the people there, not only in their living environment but also in the whole spectrum of forest land use.

Recreation

Forests must be in a relatively healthy condition to support quality recreational use (Clawson, 1975). Forests undergoing gradual composition changes might remain healthy, but rapid changes would most likely cause stressed or declining forests. Such forest conditions would have less recreational appeal because of such factors as less pleasing appearance, greater threat of wildfire, and reduced hunting quality when game populations change or are diminished. Furthermore, drier conditions in U.S. forests would harm recreational opportunities that depend on abundant water or snow.

Wood Products

Altered U.S. forest productivity resulting from climate change would have obvious major economic impacts. Significant yield reductions could lead to unemployment, community instability, industrial dislocation, and increased net imports of wood products.

Reforestation projects could make up for some losses in forest productivity and artificially advance migrations forced by climate change. Reforestation technology has greatly improved in recent decades so that success rates also have increased greatly. Examples are high-vigor seedlings developed through improved nursery practices, genetic selection, and vegetative propagation. Improvements in the field include machine planting, fertilization, and weed control on selected sites. Results are evident from the large acreages of plantations established in the United States in recent decades, particularly with loblolly pine in the Southeast and Douglas-fir in the Pacific Northwest (Table 5-2). Large-scale reforestation in the United States and elsewhere could significantly add to the total carbon sink provided by world forests, thereby offsetting some of the buildup of atmospheric CO_2. Although this was not studied, attempts to reforest some very dry sites may be unsuccessful.

Innovative manufacturing trends should prove to be timely during times of rapid forest change. High-strength and durable products from reconstituted wood (e.g., new particle board concepts, warp-proof hardwood lumber, paper products of fiber from multispecies) are now in use or well along in development. These new methods will lessen the present overdependency on a few commercial conifer species from stands above minimum size and quantity (Ince, 1987). The result will be an ability to use the timber resources of the future, however they change in composition.

FOREST POLICY AND CLIMATE CHANGE

Historically, U.S. forest policies have undergone continued development to meet national change (Young, 1982). The earliest policies were adapted by the New England colonies in the 1600s to regulate overcutting near settlements. Wood was needed for fuel and buildings, but existing methods were not capable of long distance log transportation. Development of U.S. forest policies has continued and has been particularly intense this century, as the national forests, national parks, and wilderness areas have been established.

At present, forest managers are dealing with many additional policy issues. Five of these (Clawson, 1975) are important to climate change/forest response:

- How much U.S. land should be devoted to forests?
- How much forest land should be withdrawn from timber production and harvest?
- How should the federal forest lands be managed? (That is, the lands under the USDA Forest Service, USDI Park Service, Bureaus of Land Management and Indian Affairs, and other federal agencies that manage forest lands.)
- What constraints (e.g., mandatory forest practices) should be placed on forest managers to ensure national environmental goals?
- Who should pay the additional costs incurred in implementing new policies?

The large array of forest ownerships in the United States, public and private, makes development and implementation of forest policy more complicated than in most countries. Around the world, about 77% of all forests are in some form of public ownership (Hummel, 1984). The diversity of owners and managers results in widely divergent goals and objectives.

How Much Land Should Be Forested?

Changes in forest composition or regional boundaries induced by rapid climate change would magnify the complexity of national forest policy even further. Lands in forests now would require review relative to such competing needs as agriculture and residential use, which would also be adjusting to climate change.

How Much Should Be Withdrawn From Timber Production?

Where the productivity of wood is significantly reduced, increased, or shifted, a policy question that would surely arise concerns whether forest lands should be reallocated to maintain timber production. If so, how should competing forest uses, such as watersheds, parks, and wilderness, be treated? How much of each can the United States afford under changed climatic conditions? Should the federal government purchase more forest lands to support all public needs?

In the short term, forest managers could compensate for some loss of productivity by improved technology, although at increased costs. An example would be establishment of more drought-tolerant plantations through genetic selections, improved nursery stock, and more intensive silvicultural practices (e.g., weed control and thinning). Introducing new species adapted to warmer climates might be possible in some locations, but this would call for development of new silvicultural regimes and utilization methods -- possible, but time consuming and costly. In the long term, if growing conditions become extremely difficult on some U.S. forest lands because of climate changes, establishing trees for wood production on such sites may not be economically justified.

How Should We Manage Federal Forests?

The national forests under the USDA Forest Service are managed according to a series of complex legal directives and administrative procedures, beginning with the Organic Act of 1897 (Woodman and Furiness, Volume D). Ultimately, the objective became to manage the national forests for multiple uses, with timber and other forest resources on a sustained-yield basis and certain lands set aside as wilderness areas. The National Forest Management Act of the mid-1970s requires management plans for each national forest subject to public review. The plans look ahead 50 years and are to be updated every 10 years.

Lands managed by the Department of Interior are under similar mandates. For example, a congressional act passed in 1976 charged the Bureau of Land Management to manage its 2.3 million hectares (5.1 million acres) of forest and range land according to multiple-use and sustained-yield principles. Similarly, the National Park Service is mandated to manage national parks, monuments, historic sites, and so forth, for the recreational enjoyment of people. Such activities as timber harvesting, hunting, mining, and grazing are not permitted. In addition to the federal government, most states, many counties, and some municipalities own forest lands.

The Forest and Rangeland Renewable Resources Planning Act of 1974 requires the Secretary of Agriculture to make periodic reviews of the nation's forest and rangeland resources. In the future, these assessments and planning efforts should include consideration of the possible effects of predicted climate changes.

A key issue is the level of priority given to maintaining forest health under changed climate conditions. For instance, under more adverse environments, should national forests be left to decline as a natural process, thereby losing esthetic values in parks, water yields from watersheds, and highly productive timber crops? Or should silvicultural forest techniques such as thinning, weed control, fertilization, and reforestation be employed in an attempt to preserve them? This question and others will challenge the fundamental concepts of the benefits of multiple use and sustained yield of U.S. forests.

How Can We Ensure National Goals?

At the minimum, federal agencies must plan and act in concert with the state and private forest organizations. In the first half of this century, the federal government attempted to regulate forest harvests on all federal, state, and private lands. Development of this policy did not survive strong public concern and intense political debate against such policy (Worrell, 1970); the same sentiment would likely exist today. However, under the influence of climate change, the nation may once again have to face the touchy issue of what restraints or forest practices must be regulated for all public and private lands.

Solomon and West (1985) point out that while climate change might disrupt forest ecosystems in the future, it is uncertain whether forest managers could or would be able to apply silvicultural practices on a scale large enough to maintain the net productivity of commercial forest lands in the United States. Some states (e.g., Washington, Oregon, and California) have laws specifying fire protection requirements, control burn practices, and reforestation minimums following timber harvests. Zoning, permits, licenses, and various taxation measures also have been attempted with mixed results. It is much easier to prevent owners from destroying forests than to compel them to implement silvicultural practices.

Reforestation

To keep pace with the global climate changes estimated, the U.S. reforestation effort conceivably would need to be doubled or tripled in size. In recent years, about 800,000 hectares (2 million acres) per year (approximately 700+ million seedlings) have been reforested in the United States (USDA, 1982). Costs range from $200 to $700 per hectare ($80 to $280 per acre) depending upon species, site preparation, plantation density, and planting method. Using $500 per hectare ($200 per acre) as a mode, the total annual expenditure is near $400 million. About 0.4% of the commercial land base is reforested annually. At this rate, it would take 100 years to reforest 40% of the U.S. forest lands, assuming no repeat hectares to cover failures or harvests of the first plantations.

An expansion on the scale suggested above would require large investments in seed procurement, tissue culture capability, nursery capacity, and research to improve knowledge about the establishment and silviculture of droughtresistant plantations. Even if the dollar commitments were made, reforestation at this scale might be possible only if all forest lands were managed by one organization. The complex forest ownership pattern in the United States, therefore, would be an issue to overcome in a national reforestation program.

Who Should Pay?

Adjusting forest policies to address the issues arising from climate change will most likely raise the costs of using the nation's forests -- whether for water, recreation, esthetics, or timber. Additional research to answer many new questions will also require more funds. A major question will be who should pay for these costs. Land owners? Forest users? Consumers? All taxpayers? The answers will come when better information is available on resulting forest effects, followed by public debate establishing new priorities for forest use in a changed climate.

RESEARCH NEEDS

The forest effects resulting from rapid climate change are at present hypothetical. The change has not yet occurred, and many uncertainties are associated with the predictions. Effective policies to deal with new forest effects will require more information and fewer uncertainties that must come through forest ecosystem research. Four broad questions concerning U.S. forests frame the research needs for the 1990s: What will the effects be? How can they be measured reliably? How should they be managed? How can we ensure that research will be conducted in a timely fashion?

Effects of Climate Change

What will be the effect on the nation's forest ecosystems if climate changes occur as predicted by the middle of the 21st century? While subsets of this question must include extent, magnitude, and risk considerations, additional knowledge is needed concerning the following:

1. Forest migration processes and rates, including the landscape processes that control the horizontal movements of forests, animals, and disturbances;

2. Interactions among the different landscape components and land-use practices that affect biodiversity, and water quantity and quality;

3. The impact of climate change alone and in combination with other natural or anthropogenic influences, such as insects, pathogens, CO_2 enhancement, air pollutants, UV-13 radiation, and acid deposition on U.S. forests; and

4. The processes and mechanisms that play key roles in forest ecosystem effects -- both biologically as in photosynthesis and respiration, and physically as in flows of energy, carbon, water, and nutrients through ecosystems.

Methods

How can forest ecosystems be measured to reliably detect the effects of rapid climate change? Today, the response of ecosystems to environmental change is largely based upon extrapolating from field observations, from knowledge about seedlings or individual trees of a small number of commercially valuable species, and from computer models. The following must be accomplished:

1. A determination of the most useful integrating variables for forest ecosystems that indicate the effects of climate change -- particularly variables that are earlywarning indicators of ecosystem response;

2. Effective sampling designs developed for experiments and long-term monitoring at the forest ecosystem scale; and

3. Improved models capable of projecting regional effects on forests across multiple spatial and temporal scales.

Forest Management

What options are available to the public and private forest managers and owners in the United States to address the changes in the nation's forests that might occur in the next century? Research is needed to accomplish the following:

1. Understand the socioeconomic impacts of all forest ecosystem effects to clarify economic risks and alternatives; and

2. Develop technology to mitigate the adverse effects or to exploit the benefits of forest

change, such as breeding, bioengineering, transplanting, fertilization, irrigation, and other management approaches.

Timing of Research

The timing of the research is critical. The effects of climate change may be some decades away, but this should not lessen the urgency to begin research toward better information and methods. The complexities of the science are very large. Developing a base of knowledge to identify potential forest changes before they are upon the nation will require significant time and resources.

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CHAPTER 6
AGRICULTURE

by Cynthia Rosenzweig
and Margaret M. Daniel

FINDINGS

Climate change would affect crop yields and result in northward shifts in cultivated land, causing significant regional dislocations in agriculture with associated impacts on regional economies. It would expand crop irrigation requirements, stress livestock production, and increase infestations of agricultural pests and diseases. Preliminary results suggest that although U.S. crop production could decline, supplies would be adequate to meet domestic needs. The potential for reduction of the national agricultural capacity and the many uncertainties surrounding the interactive effects on the agricultural system create the necessity to respond to the climate change issue.

above temperature thresholds for particular crops in some locations. The exact magnitude of change will be sensitive to changes in climatic variability, particularly the frequency of droughts.

Crop Yields

- The effects of climate change alone may reduce average yields of corn , soybeans, and wheat, both rainfed and irrigated, except in the northernmost latitudes where warmer conditions provide a longer frost-free growing season. Decreases in modeled yields result primarily from higher temperatures, which shorten a crop's life cycle.

- When the direct effects of CO_2 on crop photosynthesis and transpiration are approximated along with the effects of climate change, average rainfed and irrigated corn, soybean, and wheat yields could overcome the negative effects of climate change in some locations. If climate changes are severe, yields could still decline. The extent to which the beneficial effects of CO_2 will be seen under field conditions with changed climate is uncertain.

- Even if the patterns of climate variability are unchanged, yield stability may decrease, particularly under rainfed conditions. This may occur because there would be more days above temperature thresholds for particular crops in some locations. The exact magnitude will be sensitive to changes in climatic variability, particularly the frequency of droughts.

Economic Impacts

- Under three out of four scenarios, a small to moderate aggregate reduction in the nation's agricultural output was estimated. The estimated production levels appeared to be adequate to meet domestic consumption needs. If droughts occur more frequently under changing climate, effects on agriculture may be more severe.

- Assuming no change in export demand, reduced outputs would decrease exports, which could negatively affect global food supplies and the U.S. trade balance. This report did not reduce average yields of corn, soybeans, and analyze global changes in agriculture, which could have a major effect on demand for U.S. products.

- Under the most severe climate change scenarios, continued technological improvements, similar to those in recent years, would have to be sustained to offset losses. Increasing food demand from higher U.S. and world population would aggravate the economic losses due to climate change.

- The economic response of agriculture to changes in regional productivity may be able to shift crop production and associated infrastructure in a northward direction. This is because yields in northern areas generally increase relative to yields in southern areas. Although availability of agricultural soils was included in the economic analysis, neither the sustainability of crop production in the northern areas nor the introduction of new crops into the southern area was studied.

Irrigation Demand

- The demand for irrigated acreage is likely to increase in all regions. This is due to the reliability of irrigated yields relative to dryland yields and to higher commodity prices that make expansion of irrigated production more economically feasible. Actual increases in irrigated production more economically feasible. Actual increases in irrigated acreage would depend on the adequacy of water supply and on whether the cost of water to farmers increases

- Demand for more irrigation would increase stress on and competition for regional water supplies. If irrigation does increase, it would increase surface and groundwater pollution and other forms of environmental degradation.

Agricultural Pests

- Climate warming could change the ranges and populations of agricultural pests. Temperature increases may enhance the survival of insect pests in the winter, extend their northward ranges, increase pest species with more than one generation per year, and allow pest establishment earlier in the growing season. These effects could result in a substantial rise in pesticide use, with accompanying environmental hazards. Changes in pests will also depend on regional shifts in crop production.

Farm-Level Adjustments

- Farmers may adjust to climate change by using full-season and heat-resistant crop species or varieties, by altering planting dates, by planting two crops during one growing season, by increasing or altering their scheduling of irrigation, by using more pesticides, and by harvesting earlier. If climate change is not severe, these adjustments may mitigate losses in crop yields; more severe climate change is likely to make major adaptation necessary.

Livestock Effects

- Higher temperatures may increase disease and heat stress on livestock in some regions. Existing livestock diseases may shift north, while tropical diseases may extend their ranges into southern regions of the United States. Cold stress conditions may be reduced in the winter, but heat stress is likely to increase in the summer. Reproductive capabilities may also decrease.

Policy Implications

- Global climate change has important implications for all parts of the agricultural system. The agricultural research structure, which is dedicated to maintaining U.S. farm productivity, should expand climate change research in activities ranging from the field level to the national policy level.

- Current U.S. Department of Agriculture (USDA) research on heat- and drought -tolerant crops and practices and maintenance of crop germ plasm should be sustained and enhanced to limit vulnerability to future climate change.

- The USDA should evaluate current legislation in regard to its ability to allow adaptation to global warming. Flexibility in shifting crop types and farm practices will speed adjustment. Such adaptation strategies should consider the impacts on soil erosion and water quality.

- The USDA, the Department of Commerce, the U.S. Trade Representative, and the State Department should consider the implications of potential long-term changes in the level of

U.S. crop exports for the U.S. balance of trade and strategic interests.

- A national drought policy is strongly needed to coordinate federal response to the possibility of increased droughts due to climate change. Even without climate change, such a policy is necessary not only for the agricultural sector but also for other sectors.

SENSITIVITY OF AGRICULTURE TO CHANGES IN CLIMATE

Agriculture is a critical American industry, providing food for the nation's population and as much as $42.6 billion in exports for the nation's trade balance (Figure 6-1). Agriculture employs 21 million people -- more than any other industry, when taking into account workers on farms and in meat, poultry, dairy, baking, and food-processing activities (Council for Agricultural Science and Technology, 1988). The U.S. agricultural production system includes farm equipment manufacture, fertilizer and seed supplies, rural banking, and shipping. Total farm assets were $771 billion in 1985; food and fiber were 17.5% of the total gross national product in the same year. Wheat, corn, soybeans, cotton, fruits and vegetables, and livestock are among the most important U.S. agricultural commodities.

Worldwide, agricultural products must provide sustenance for the world's growing population, now estimated at about 5 billion and projected to rise to 8.2 billion by 2025 (Zachariah and Vu, 1988). Global production and consumption of grain have grown steadily since 1960, although regional food shortages continue to occur owing to climate variability and socioeconomic factors. Technological advances, such as improved hybrids and irrigation systems, have reduced the dependence of crop yields on local environmental conditions, but weather is still an important factor in agricultural productivity.

For example, failure of the monsoon season caused shortfalls in crop production in India, Bangladesh, and Pakistan in 1987. The 1980s have also seen the continued deterioration of food production in Africa, despite adequate world food supplied elsewhere, because of persistent drought, internal wars, poor distribution, weak infrastructure, and a deteriorating environment. Climate extremes have had large effects on U.S. agriculture. During the Dust Bowl years of the 1930s, U.S. wheat and corn yields dropped by up to 50%. Midsummer 1983 saw an

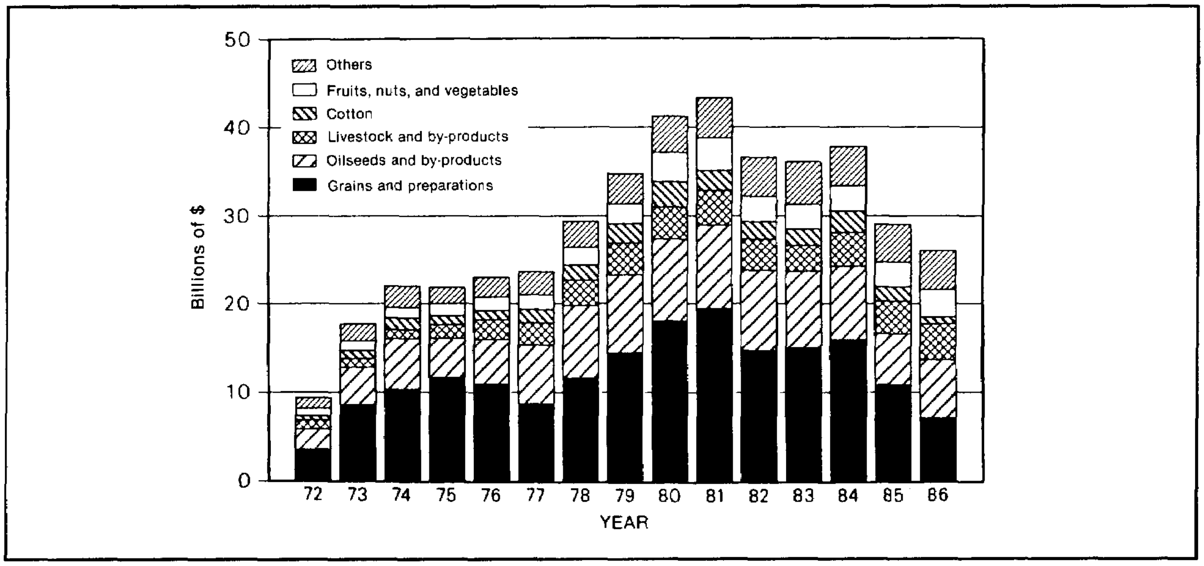

Figure 6-1. Value of U.S. agricultural exports by commodity, 1972-86 (not adjusted for inflation). Livestock excludes poultry and dairy products (The World Food Institute, 1987; U.S. Department of Agriculture, Economic Research Service, Foreign Agricultural Trade of the United States, Washington, DC, January-February 1987, and various other issues).

unpredicted drought in the U.S. Corn Belt and in the southeastern United States, causing U.S. corn yields to fall by about a third, from over 7,000 kilograms per hectare to about 5,000 kilograms per hectare (from about 110 to 80 bushels per acre).

The 1988 drought recently demonstrated the impact that climate variability can have on agricultural productivity. This drought decreased U.S. corn yields by almost 40%, and the cost of the 1988 Drought Relief Bill is estimated to be $3.9 billion (Schneider, 1988). The 1988 drought emphasizes anew the close link between agriculture and climate.

Light from the sun, frost-free growing seasons, and the hydrologic cycle largely govern the suitability of geographic areas for crop production and affect crop productivity. Livestock production is responsive to climate through differing levels of heat and cold stress and altered ranges of disease-carrying vectors such as mosquitoes and ticks.

Higher levels of CO_2 in the air would also affect crops. Increased CO_2 has enhanced crop photosynthesis and has improved crops' use of water in experimental settings. Because experimental research has rarely simultaneously investigated both the climatic and the direct effects of CO_2 on plants, it is difficult to assess the relative contributions of CO_2 and increased temperature to plant responses. This remains one of the most crucial questions in the analysis of impacts of climate change and increased CO_2 on agriculture.

The presence and abundance of pests affecting both crops and livestock are highly dependent on climate. The severity of the winter season, wind patterns, and moisture conditions determine in large part where pests will be prevalent. The geographical distribution of pests also depends on locations of crop types.

Much of U.S. agricultural production takes place under technologically advanced cropping systems that are primarily monocultural. Likewise, livestock production is highly specialized, both technically and geographically, and a high degree of integration exists between grain and livestock production. Any significant level of economic robustness associated with general, multipleenterprise farms has long since passed from the scene. The ability of our agricultural system to adapt to climate change may be more limited now in some ways than it was in the past.

Agriculture strongly affects the natural environment. It often increases soil erosion, intensifies demand for water, degrades water quality, reduces forested land, and destroys wildlife habitats. Many agricultural practices contribute to soil degradation, groundwater overdraft, loss of plant and aquatic communities, and generally reduced resilience in environmental and genetic resources. Therefore, climate-driven shifts in agricultural regions have implications for environmental quality.

Thus, climate plays a major role in determining crop and livestock productivity. Agricultural productivity determines profitability and decisionmaking at the farm level, which in turn define farming systems at the regional level and import-export supply and demand at the national and international levels. These complex interrelationships necessitate a broad consideration of the impacts of potential climate change on U.S. agriculture.

PREVIOUS STUDIES OF CLIMATE CHANGE AND AGRICULTURE

Relationships between climate and agriculture have been studied intensively for many years. However, relatively few studies have specifically addressed both the climatic and the direct effects that the growth in trace gases will have on agriculture. Even fewer studies have addressed these potential effects in an integrated approach that links both biophysical and economic spheres of analysis.

Most research attention in the United States, supported primarily by the U.S. Department of Energy, has focused on the direct effects of CO_2 on crops. These studies are reviewed by Acock and Allen (1985) and Cure (1985), who found an average increase in yields of about 30% and increases in water-use efficiency for crops growing in air with doubled CO_2 (660 ppm) and favorable, current climate conditions. Kimball (1985) and Decker et al. (1985) suggested that the potential effects of CO_2 and/or climate change on agricultural production systems may include shifts in production areas and changes in levels of livestock stresses, water availability, and pest control management.

Integrated approaches to the impacts of climate change on agriculture involving both biophysical and economic processes have been considered in studies by Callaway et al. (1982), the Carbon Dioxide Assessment Committee (1983), Warrick et al. (1986), and the Land Evaluation Group (1987). A benchmark international study on both the agronomic and economic effects of climate change on agriculture was conducted by the International Institute for Applied Systems Analysis (Parry et al., 1988). No study has as yet comprehensively examined the combined effects of climate change and the direct effects of CO_2 on U.S. agriculture.

CLIMATE CHANGE STUDIES IN THIS REPORT

Structure of and Rationale for the Studies

The regions studied for this report are important agricultural production areas (see Table 6-1). The Great Lakes and Southeastern States are major corn and soybean producers, and the Great Plains States grow mainly wheat and corn. California annually produces about 10% of U.S . cash farm receipts from cotton, grapes, tomatoes, lettuce, and many other crops.

The agricultural studies involve the following research topics (see Table 6-2): (1) crop growth and yield, (2) regional and national agricultural economics, (3) demand for water for irrigation, (4) water quality, (5) pest-plant interactions, (6) direct effects of CO_2 on crop growth and yield, (7) impacts of extreme events, (8) potential farm-level adjustments, (9) livestock diseases, and (10) agricultural policy.

Production of corn, wheat, and soybeans is critical to the economic well-being of the nation's farmers and the national trade balance. These crops make up about two-thirds of the total U.S. agricultural acreage, and their economic value is equal to that of all other crops combined. These three crops were selected for the modeling studies on the effects of climate change on yields.

The results from the regional studies of crop production (not including California), hydrological predictions from the climate models, and an agricultural economics model were linked in an integrated approach to enable investigators to translate the estimated yield changes from the crop modeling studies and predicted changes in water availability into economic consequences (see Figure 6-2). Such a coordinated analytical framework is necessary to account for the effects of market forces on the total agricultural sector, including livestock, and to evaluate the adequacy of the nation's resource base for agricultural production under climate change. Economic forces may lead farmers to grow more crops in areas with relatively high productivity and fewer crops in areas with relatively low productivity.

The studies of demand for irrigation water, water quality, and farm-level adjustment were also linked with the integrated modeling studies by common assumptions, sites, or outputs. Because California grows a large and diverse number of crop commodities, a simple approach was used to estimate crop yield changes for the California case study based on heat, sunlight, and photosynthetic response to CO_2. These yield changes were then used in a model of agricultural land and water use in California. Adjustment experiments were included in several studies to test possible adaptation mechanisms, such as changes in planting dates and crop varieties.

Table 6-1. Crop Production by Region.

EPA study areas	Corn	Wheat (thousands of bushels)	Soybeans	Harvested acres (thousands)
Southeast	311	272	306	29
Great Lakes	4,644	297	822	92
Great Plains	921	755	136	71
California	38	63	--	6
Total (48 states)	8,209	2,507	1,990	337

Table 6-2. Agriculture Projects for EPA Report to Congress on the Effects of Climate Change

Regional Studies

- Effects of Projected CO_2 Induced Climate Changes on Irrigation Water Requirements in the Great Plains States - Allen and Gichuki, Utah State University (Volume C)
- Climate Change Impacts upon Agriculture and Resources: A Case Study of California - Dudek, Environmental Defense Fund (Volume C)
- Farm-Level Adjustments by Illinois Corn Producers to Climate Change - Easterling, Illinois State Water Survey (Volume C)
- Impacts of Climate Change on the Fate of Agricultural Chemicals Across the USA Great Plains and Central Prairie - Johnson, Cooter, and Sladewski, Oklahoma Climatological Survey (Volume C)
- Impact of Climate Change on Crop Yield in the Southeastern U.S.A.: A Simulation Study - Peart, Jones, Curry, Boote, and Allen, University of Florida (Volume C)
- Effects of Global Climate Chance on Agriculture: Great Lakes Reams - Ritchie, Baer, and Chou, Michigan State University (Volume C)
- Potential Effects of Climate Change on Agricultural Production in the Great Plains: A Simulation Study - Rosenzweig, Columbia University/NASA Goddard Institute for Space Studies (Volume C)

National Studies

- The Economic Effects of Climate Chanize on U.S. Agriculture: A Preliminary Assessment - Adams, Glyer, and McCarl, Oregon State University and Texas A&M University (Volume C)
- Analysis of Climate Variability in General Circulation Models - Mearns, Schneider, Thompson, and McDaniel, National Center for Atmospheric Research (Volume 1)
- Direct Effects of Increasing CO_2 on Plants and Their Interactions with Indirect (Climatic) Effects - Rose, Consultant (Volume C)
- Potential Effects of Climatic Change on Plant-Pest Interactions - Stinner, Rodenhouse, Taylor, Hammond, Purrington, McCartney, and Barrett, Ohio Agricultural Research and Development Center and Miami University (Volume C)
- Agricultural Policies for Climate Changes Induced by Greenhouse Gases - Schuh, University of Minnesota (Volume C)
- Changing Animal Disease Patterns Induced by the Greenhouse Effect - Stem, Mertz, Stryker, and Huppi, Tufts University (Volume C)
- Effect of Climatic Warming on Populations of the Horn Fly- Schmidtmann and Miller, USDA, Agricultural Research Service (Volume C)

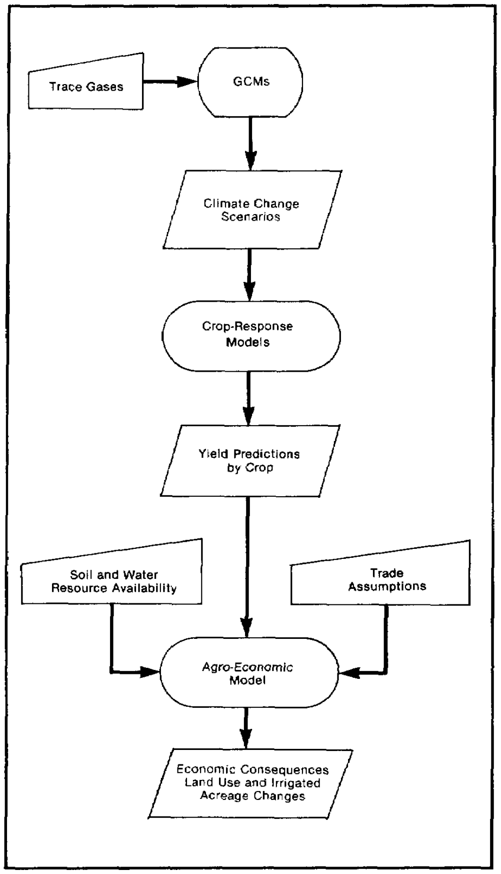

Figure 6-2. Flow chart of model interactions in EPA studies of the effects of global climate change on U.S. agriculture (Dudek, 1987).

The agricultural studies performed for this EPA report explore the sensitivities of the different parts of the agricultural system (shown in Table 62) to climate change scenarios. They are not meant to be predictions of what will happen; rather, they aim to define ranges and magnitudes of the potential responses as the system is currently understood. Regional results were extrapolated to other areas to give estimates of changes in national production.

Variability

All of the modeling studies used the doubled CO_2 climate change scenarios developed for the report (see Chapter 4: Methodology). These scenarios were developed from estimated changes in monthly mean climate variables from general circulation models (GCMs), without alterations in climate variability. For example, the number of days of precipitation remains the same in the baseline and climate change scenarios, and the amount of precipitation on each of those days is adjusted by the GCM ratio for climate change. Extreme events, such as maximum temperature, vary in the climate change scenarios according to the ratios, but the daily and interannual patterns of warm episodes are determined by the observed baseline climate.

The lack of changes in the daily and interannual patterns of extreme events may result in underestimation of impacts of climate change. This is because runs of extreme climate variables (for example, prolonged heat spells during grain filling and drought) can decrease crop productivity. For rainfed crops, yields may change considerably, depending on whether a change in precipitation is caused by more or fewer events or by higher or lower precipitation per event. The frequency, intensity, and/or duration of extreme climatic events can be much more consequential to crop yields than are simple changes in means.

Timing of Effects

The timing of climate change is uncertain - rates of future emissions of trace gases, as well as when the full magnitude of their effects will be realized, are unknown. CO_2 concentrations are estimated to be about 450 ppm in 2030 and 555 ppm in 2060 if current emission trends continue (Hansen et al., 1988). Other greenhouse gases besides CO_2 (e.g., methane (CH4), nitrous oxide (N_20), and chlorofluorocarbons (CFCs)) are also increasing. The effective doubling of CO_2 means that the combined radiative forcing of all greenhouse gases has the same radiative forcing as doubled CO_2 (usually defined as 600 ppm). The effective doubling of CO_2 concentrations will occur around the year 2030, if current emission trends continue. The climate change caused by an effective doubling of CO_2 may be delayed by 30 to 40 years or longer.

RESULTS OF AGRICULTURAL STUDIES

Regional Crop Modeling Studies

Design of the Studies

Widely validated crop growth models --

CERES-Wheat and CERES-Maize (Ritchie and Otter, 1985; Jones and Kiniry, 1986) and SOYGRO (Jones et al., 1988) -- were used to simulate wheat, corn, and soybean yields at selected geographically distributed locations within the Great Lakes, the Southeast, and the Great Plains. Representative agricultural soils were modeled at each site. California crop yield changes were predicted separately by using an agroclimatic index. (See the regional chapters, Chapters 14 through 17 of this report, for descriptions of individual studies.) Changes in temperature, precipitation, and solar radiation were included in the crop modeling studies. The crop models simulated both rainfed and irrigated production systems. The crop modeling approach allowed for analysis of latitudinal gradients in changes in crop yields and provided compatible results for each climate change scenario to be used as inputs in the agricultural economics study. (See Ritchie et al., Peart et al., and Rosenzweig, Volume C.)

The direct effects of CO_2 -- i.e., increased photosynthesis and improved water-use efficiency -- were also included with the climate change scenarios in some model runs to evaluate the combined effects. The direct effects were approximated by computing ratios of elevated CO_2 (660 ppm) to ambient CO_2 (330 ppm) values for daily photosynthesis (Table 6-3) and evapotranspiration rates (see Peart et al., Volume C, for detailed description of method).

Limitations

Uncertainties in the crop modeling studies reside in climate model predictions, locations of the climate stations (not always in production centers), crop growth models, and estimates of the direct effects of CO_2 . In particular, the climate change scenarios did not include changes in climate variability, even though changes in the frequencies of extreme events may considerably affect crop yields. Technology and cultivars were assumed not to change from present conditions.

Table 6-3. Increase in Daily Canopy Photosynthesis Rates Used in Crop Modeling Studies (%)

	Soybean	Wheat	Corn
Increase photosynthesis (%)	35	25	10

Source: Peart et al. (Volume C); Ritchie et al. (Volume C); Rosenzweig (Volume C).

The CERES and SOYGRO models describe relationships between plant processes and current climate. These relationships may or may not hold under differing climatic conditions, particularly the high temperatures estimated for the greenhouse warming. Lack of analysis of the nature and extent of agricultural soils at each modeling site adds uncertainty to the results.

The direct effects of CO_2 in the crop modeling results may be overestimated for two reasons. First, experimental results from controlled environments may show more positive effects of CO_2 than would actually occur in variable, windy, and pest-infested (weeds, insects, and diseases) field conditions. Second, since the study assumed higher CO_2 levels (660 ppm) in 2060 than will occur if current emission trends continue (555 ppm), the simulated beneficial effects of CO_2 may be greater than what will actually occur.

Results

Under climate change scenarios alone, without the direct effects of CO_2, yields of corn, soybeans, and wheat were generally estimated to decrease in the Great Lakes, Southeast, and Great Plains regions, except in the northernmost latitudes, where warmer conditions provided a longer frost-free growing season. Figures 6-3 and 6-4 show change in modeled rainfed corn and soybean yields for the GISS and GFDL scenarios. The northern locations where yields increased included sites in Minnesota.

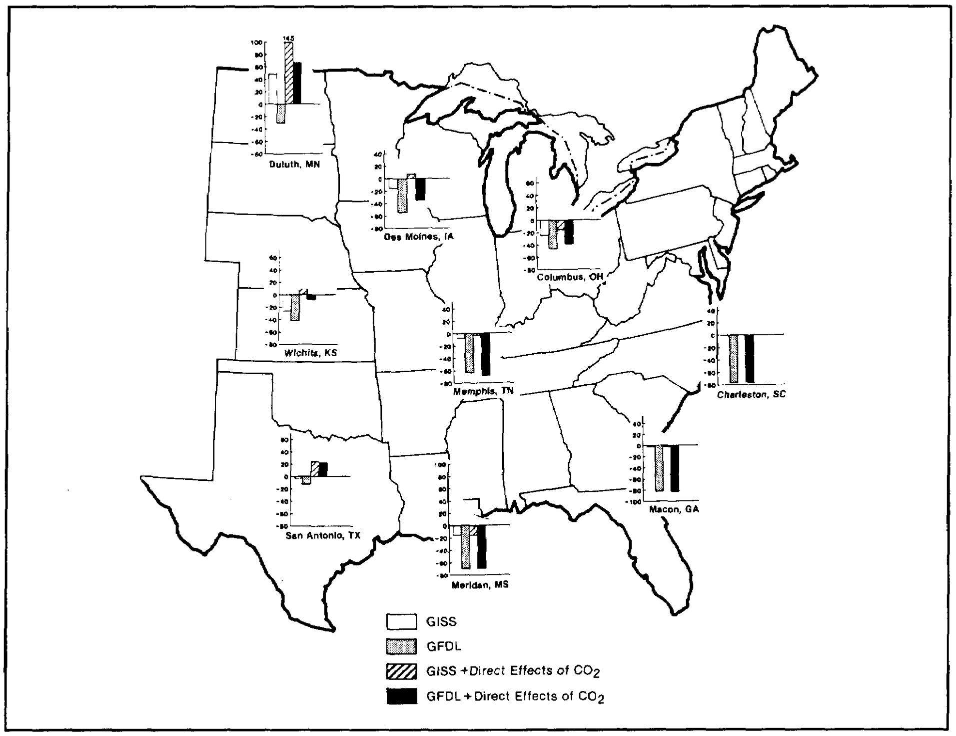

Figure 6-3. Percent change in rainfed corn yields simulated by the CERES-Maize model for baseline (195180) and GISS and GFDL climate change scenarios with and without the direct effects of CO_2 for selected locations (Peart et al., Volume C; Ritchie et al., Volume C; Rosenzweig, Volume C).

Decreases in modeled yields resulted primarily from higher temperatures, which would shorten the crop life cycle thus curtailing the production of usable biomass. In the Southeast, rainfall reductions were a major factor in the GFDL results. Modeled rainfed yields were estimated to decrease more than irrigated yields.

When increased photosynthesis and improved water-use efficiency were included in the crop models along with the climate change scenarios, yields increased over the baseline in some locations but not in others (see Figures 6-3 and 6-4). Particularly when combined with the hotter and drier GFDL climate change scenario in the Southeast, the direct effects of CO_2 would not fully compensate for changes in climate variables -- net yields were estimated to decrease significantly from the base case. Elsewhere, yields were generally estimated to increase, with relatively greater increases at the northern locations.

The crop models were also used to test several possible adaptations by farmers to the predicted climate changes. For example, a corn variety that is better adapted to longer growing seasons was tested in Indiana. Use of this later maturing variety would not compensate entirely for the yield decreases caused by the warmer climate change scenarios.

Implications

The potential for climate change-induced decreases in crop yields exists in many agricultural regions of the United States. In some northern areas, crop yields may increase. Farmers would need varieties of corn, soybeans, and wheat that are better acclimated to hotter and possibly drier conditions to substitute for present varieties.

If the major agricultural areas are to continue to provide a stable supply of food under the predicted changes in climate, supplemental irrigation may be required for many soils. Pressure for increased irrigation may grow in these regions. This could further tighten water supply problems in some areas and increase pollution from nonpoint sources (i.e., pollution that is not traceable to any one distinct source, such as

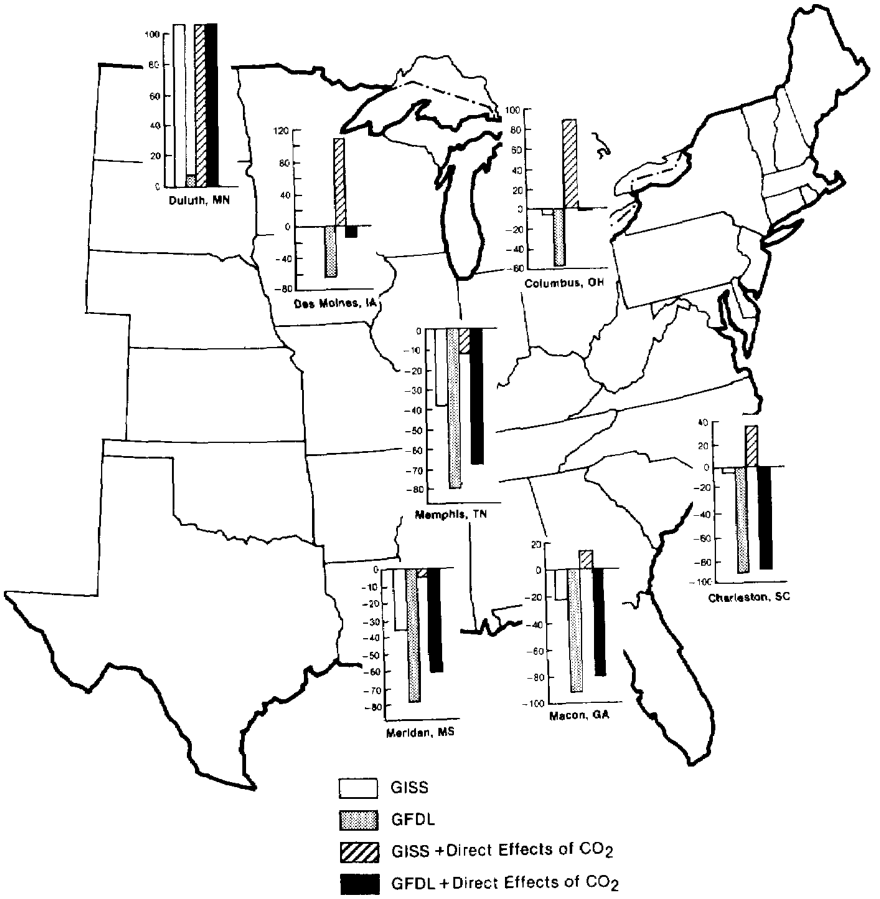

Figure 6-4. Percent change in rainfed soybean yields simulated by the SOYGRO model for baseline (1951-80) and GISS and GFDL climate change scenarios with and without the direct effects of CO_2 for selected locations (Peart et al., Volume C; Ritchie et al., Volume C).

agricultural chemicals from farmers' fields). Considerable uncertainty exists regarding the future availability of surface water and groundwater supplies with climate change, and concerning the competing demands for and costs of using or extracting the water (see Chapter 9: Water Resources).

Regional and National Economics Study

The estimated yield changes from the crop modeling studies (not including California) and projected changes in irrigation water demand and availability were introduced into an agricultural economic model to translate the physical effects of climate change into economic consequences. Adams et al. (see Volume C) estimated the regional and national economic implications of changes in yields of wheat, corn, soybeans, and other crops and in the demand for and availability of water associated with alternative global climate change scenarios.

Study Design

A spatial equilibrium agricultural model developed by Adams et al. (1984) was used to represent production and consumption of numerous agricultural commodities for the U.S. farm production regions as designated by the USDA (Figure 6-5). The model has been used to estimate agricultural losses due to increased ultraviolet-B (UV-B) radiation caused by stratospheric ozone depletion (Adams et al., 1984). It consists of farm-level models for production regions, integrated with a national-level model of the agricultural sector. Acreage available for production is based on current definition of agricultural land classes. Both irrigated and nonirrigated crop production and water supply relationships are included for most regions. The model simulates a long-run, perfectly competitive equilibrium and was developed using 1980-83 economic and environmental parameters.

A set of model runs was conducted, using the GISS and GFDL climate change scenarios, with and without the direct effects on crop yields. Potential changes in technology and in future U.S. and world food demand due to population growth were also introduced into the climate change analysis.

Limitations

The economic approach used in this study has several limitations. The economic model is static in the sense that it simulates an equilibrium response to climate change, rather than a path of future changes. Substitution of crop varieties, new crops, and adjustments in farm management techniques were not included; thus, the negative effects of climate change were possibly overestimated. Since CO_2 levels were assumed to be high in the crop modeling study, estimates of the beneficial direct effects of CO_2 on crop yields may have biased the economic results in the positive direction in some scenarios.

Furthermore, changes in yields used as inputs to the economic model were modeled for only wheat, corn, and soybeans for a limited number of sites and regions. The regional crop yield analyses cover 72% of current U.S. corn production, 33% of wheat production, and 57% of the soybean output. National estimates were extrapolated from these for all other crop commodities in the model. Changes in risk, where risk is defined as increases in variance of crop yields, were not explicitly included in the economic analysis. The accuracy of the estimates of changes in water supply and crop water requirements derived from the GCMs cannot be ascertained. Potential increases in the demand for water by nonagricultural users, which would reduce water available for irrigation, were not included. All of these assumptions introduce uncertainties into the results.

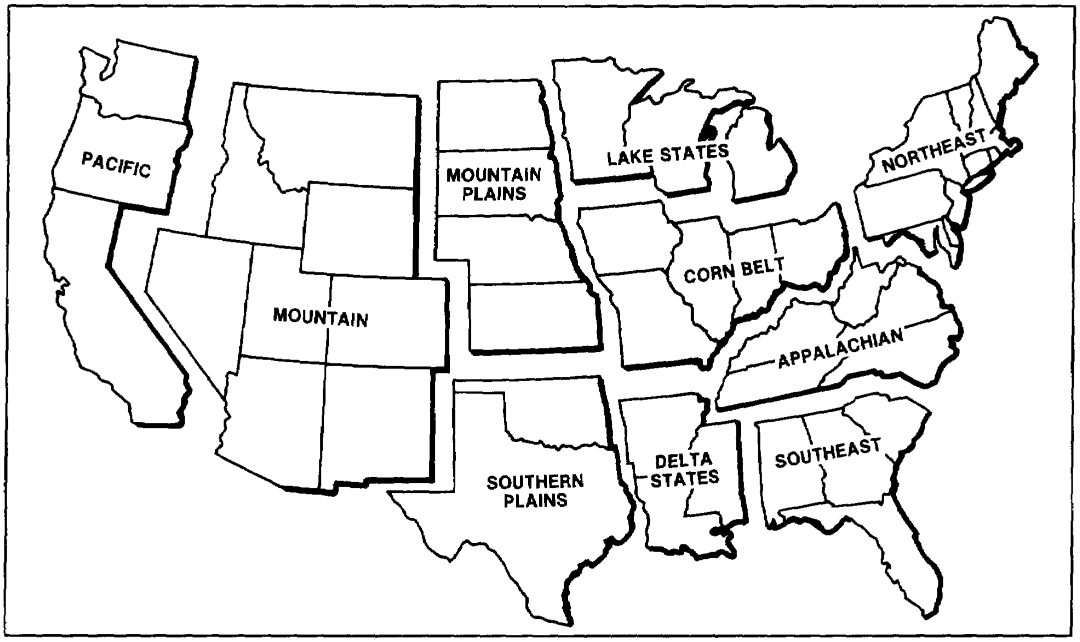

Figure 6-5. Farm production regions in the United States (USDA, 1976).

Table 6.4. Aggregate Economic Effects of GISS and GFDL Doubled CO_2 Climate Change on U.S. Agriculture with and without the Direct Effects of CO_2 on Crop Yields.

	Economic effects (billions of 1982 dollars)		
Run	Consumer	Producer	Total
GISS Analysis 4a: without CO_2	-7.3	1.5	-5.9
GISS Analysis 4: with CO_2	9.4	1.3	10.6
GFDL analysis 4: without CO_2	-37.5	3.9	-33.6
GFDL Analysis 4: with CO_2	-10.3	0.6	-9.7

[a] Analysis 4 includes the crop yield and irrigation water supply demand consequences of climate change throughout the United States
Source: Adams et al. (Volume C).

Potential changes in international agricultural supply, demand, and prices due to climate change are not explicitly included in the model. Such changes could have major impacts on U.S. agriculture. For example, warming may enhance the agricultural capabilities of high-latitude countries such as Canada and the U.S.S.R. While the net effect of climate change on the rest of the world is uncertain, global changes could overwhelm U.S. national impacts. A net negative effect on agriculture abroad would improve the position of U.S. agricultural producers through enhanced exports, but could increase the negative impacts on U.S. consumers through increases in global commodity prices.

Results

It is important to note that the results of the economic study are not predictions. Rather, they are initial estimates of how the current agricultural system would respond to the projected climate change scenarios.

The economic model showed a small to moderate aggregate loss in economic welfare associated with the estimated crop yield and hydrologic changes derived from the climate change scenarios (see Table 6-4). For the moderate GISS climate change scenario, net losses were small; for the more extreme GFDL scenario, they were greater. The magnitudes of these changes, which are annual, may be compared with the estimated $2.5 billion (in 1982 dollars) in agricultural losses due to increased UV-B radiation caused by stratospheric ozone depletion of 15% (Adams et al., 1984). In general, consumers lose and producers gain because of the increased prices of agricultural commodities and inelastic demand (i.e., insensitivity to price changes) for agricultural crops.

Higher CO_2 levels could reduce negative economic impacts (Table 6-4). Under the less severe GISS climate scenario, the CO_2 direct effects were estimated to sufficiently counter the climatic effects in most regions, so that both producers and consumers gain. With the more severe GFDL climate change scenario combined with the direct effects of CO_2, lower yields led to higher prices, but not by as muA as occurred with the climate change scenarios alone. However, significant changes in regional agricultural land use occurred even when the beneficial direct effects of CO_2 were taken into account.

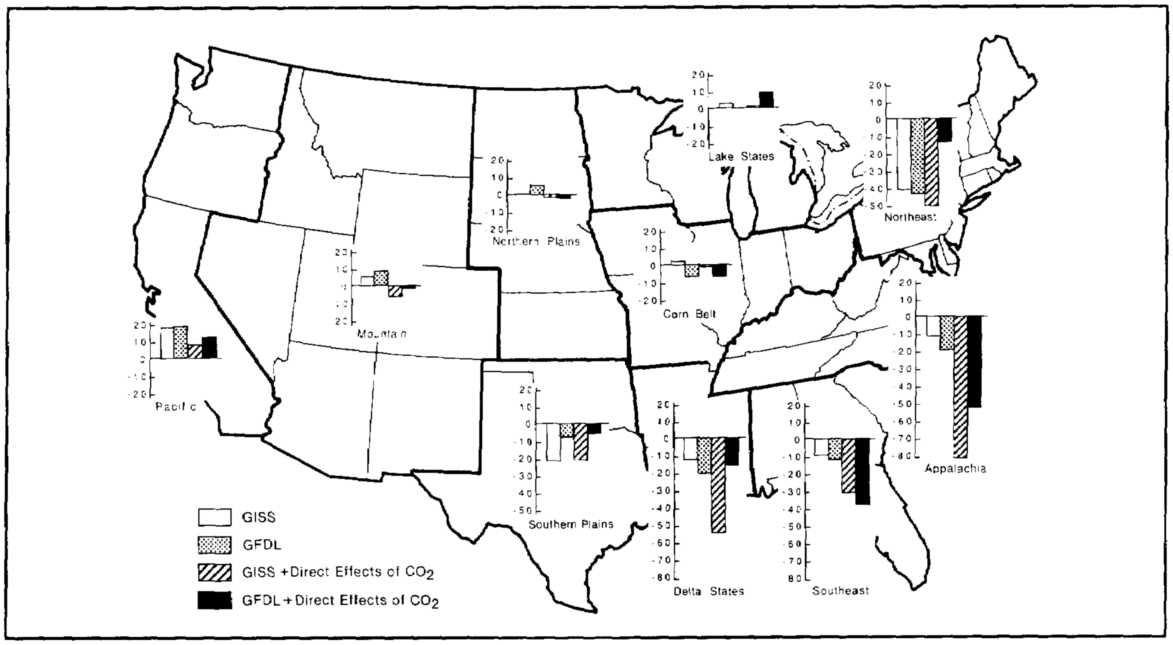

Figure 6.6. Percent change in regional agricultural acreage simulated by an economic model of the U.S. agricultural sector for the GISS and GFDL climate change scenarios with and without the direct effects of CO_2 on crop yields (Adams et al., Volume C).

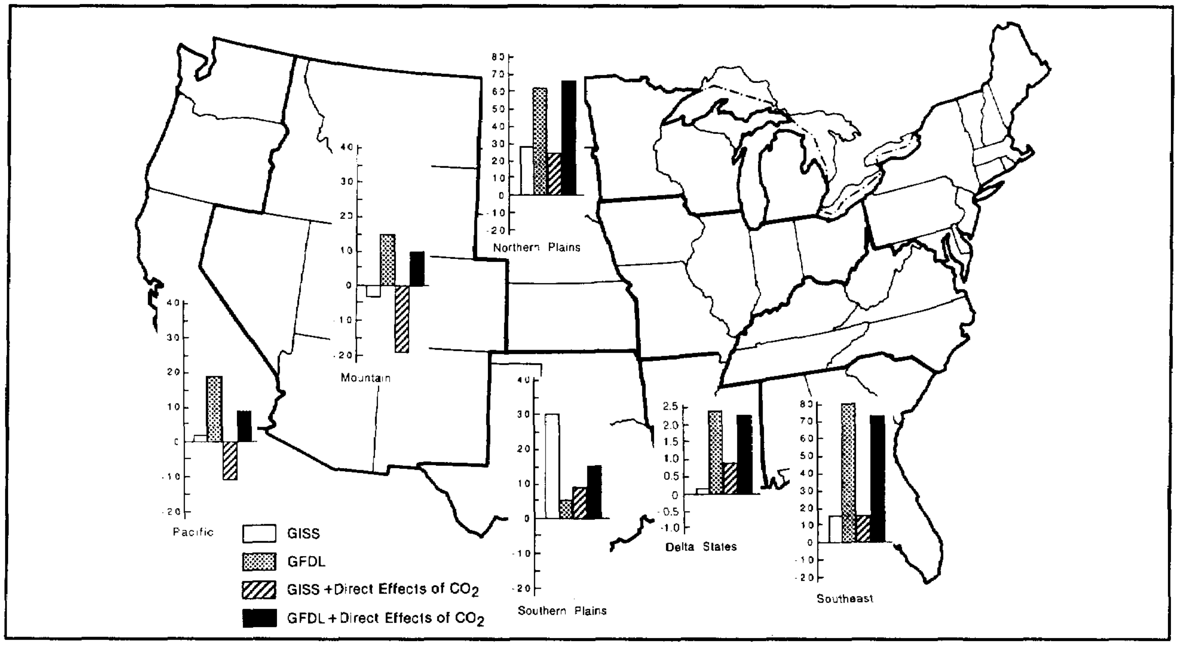

Figure 6-7. Change (100,000s of acres) in regional irrigation acreage simulated by an economic model of the U.S. agriculture sector for the GISS ans GFDL climate change scenarios with and without the direct effects of CO_2 on crop yields. Changes are not shown in the Great Lakes, Corn Belt, Appalachia, and Northeast because currently irrigated acreage is small (2% of the total U.S. irrigated acreage) in these regions (Adams et al., Volume C).

Production of most crops was reduced because of yield declines and limited availability of land and resources. With climate change alone, corn production decreased 12 and 47% in the GISS and GFDL scenarios, respectively, while soybean production was estimated to be reduced by 12 and 53% for the same scenarios. In all scenarios, land under production in Appalachia, the Southeast, the Mississippi Delta, and the Southern Plains could decrease on average by 11 to 37%, while in the Lake States, the Northern Plains, and the Pacific it could increase by small amounts (see Figure 6-6). While availability of agricultural soils was included in the economic analysis, the sustainability of crop production in northern areas was not studied.

Irrigated acreage was estimated to increase in all areas, primarily because irrigation becomes economically feasible as agricultural prices rise (see Figure 6-7). These changes reflect both increased demand by farmers for irrigation water and changes in water availability as estimated by the GCM scenarios, but do not take into account changes in competition with industrial or municipal users.

Technological changes, such as higher yielding crop varieties, chemicals, fertilizers, and mechanical power, have historically enabled agriculture to increase production with the same amount of, or less, land, labor, and other resources. When the effect of future technological change (based on yield increases from 1955 to 1987) was modeled along with the less severe GISS climate change (without the direct effects of CO_2), most of the adverse climate effects were estimated to be offset. Under the severe GFDL climate change scenario, continued and substantial improvements in yields would be required to overcome the climate change effects. Stated another way, the adverse effects of climate change could negate most of the higher output attributable to improved technology over the next 50 years. It is important to note, however, that the rate of future technological advances is very difficult to predict. Increasing food demand from higher U.S. and world population aggravated the estimated economic losses from the climate change scenarios.

Implications

Food Supply and Exports

The economic analysis implies that although climate change could reduce the productive capacity of U.S. agriculture, major disruption in the supply of basic commodities for American consumers would not occur. Domestic consumers would face slightly to moderately higher prices under some analyses, but supplies could be adequate to meet current and projected domestic demand. However, if droughts occur more frequently under changed climate, effects on agriculture may be more severe.

Exported commodities in some scenarios decline by up to 70%, assuming the demand for exports remains constant. Thus, climate change could affect the United States in its role as a reliable supplier of agricultural export commodities. It is likely that supply of and demand for agricultural commodities could shift among international regions, and responses of U.S. agriculture will take place in this global context. There is a great need to determine the nature of these changes in global agriculture by analyzing the potential impacts of climate change on both major world agricultural production regions and potentially vulnerable food deficit regions.

Regional Economics and Land Use

Regional shifts in U.S. agricultural production patterns (not only grain crops but also vegetables and fruits) are highly likely, as all climate change scenarios tested show that the southern areas of the United States become less productive relative to the northern areas. This is primarily because the high temperatures estimated for climate change would stress crop production more in southern areas than in northern areas where crops are currently limited by lower temperatures and shorter growing seasons. However, increased agricultural production may be difficult to sustain in the North, because some soils may be less fertile and may have lower water-holding capacity. Crops grown in soils with lower water-holding capacity require more evenly distributed rainfall to produce comparable yields.

Regional changes in agriculture would have important implications for rural communities. As production areas shift, climate change effects would reverberate through these communities and are likely to result in structural changes in local economies, such as relocation of markets and transportation networks. At its most extreme, climate change could cause dislocation of rural communities through farm abandonment.

Environmental Concerns

Regional agricultural adjustments could place environmental resources at risk. Where agricultural acreage would increase, demands for natural resources, such as soil and water, might intensify current pressures on environmental elements, such as rivers, lakes, aquifers, wetlands, and wildlife habitats. Northern States, such as Minnesota and North Dakota, could become more productive for annual crops like corn and soybeans because of warmer temperatures and a longer frost-free growing season. Given the presence of forests and wetlands in these regions, increased agricultural production in the area might threaten natural ecosystems, including wildlife habitats such as prairie potholes for ducks and flyways for bird migrations.

In addition, many of the glacial till soils in the northern latitudes are not as productive as Corn Belt soils. Thus, large increases in production of crops would most likely require greater applications of chemical fertilizers. The use of these fertilizers in humid regions on glacial till and sandy soils is now creating an environmental hazard to the underlying groundwater, receiving waters, and aquatic habitats in many areas. With climate change, water and fertilizer use would have to be carefully managed to minimize still more leaching of water-soluble nutrients such as nitrogen and potash.

Demand for Water for Irrigation

Water is the single most critical factor in determining the development, survival, and productivity of crops. The amount of water that crops use and thus the demand for irritation water are governed largely by the evaporation process. Higher air temperatures due to increasing trace gases in the atmosphere could heighten evaporative demands. Increased irrigation to satisfy these higher demands could accelerate depletion of groundwater and surface water resources. Also, the rate of evaporation might outstrip precipitation, thus decreasing crop yields.

Studies reported in the California and the Great Plains case studies (see Chapters 14 and 15) explicitly examined the potential changes in demand for water for irrigation. The studies did not consider changes in competing demands for water such as industrial and residential use, which also may change in a warmer climate. The California study, however, considered changes in supply due to earlier snowmelt and sea level rise. In these regions, water is a critical resource for agriculture; California and the parts of the Great Plains fed by the Ogallala Aquifer, in particular, depend very heavily on irrigation for crop production.

<u>Irrigation Requirements in the Great Plains</u>

Allen and Gichuki (see Volume C) computed irrigation water requirements for sites in the Great Plains for the baseline climate and the GISS and GFDL climate change scenarios. The direct effect of CO_2 on water use was also included. (For study design and limitations, see Chapter 17: Great Plains.) Major changes in irrigation water requirements were estimated for all locations in the Great Plains and for all crops (see Figure 6-8). The most significant would be the persistent increases in seasonal net irrigation water requirements for alfalfa, which would be driven by the climate changes in temperature, wind, humidity, and solar radiation, and by the lengthening of the growing season. Decreases in irrigation requirements were estimated for winter wheat in most regions. These decreases would be the result of earlier planting dates and shorter crop life cycle due to high temperatures. When crop varieties appropriate to the longer growing season were modeled, irrigation water requirements for winter wheat were estimated to increase. Simulated irrigation water requirements during peak periods increased in almost all areas (see Figure 6-9).

While farmers in the Great Plains would probably shift to longer season crops, climate change conditions (warmer temperatures and drying in some areas) during the later summer months could increase irrigation requirements and elevate leaf temperatures to a point that exceeds optimum temperatures required for high productivity. This might make it uneconomical to take full advantage of the longer growing season, especially if the higher CO_2 levels increase photosynthesis and offset the effects of a shorter season to some degree.

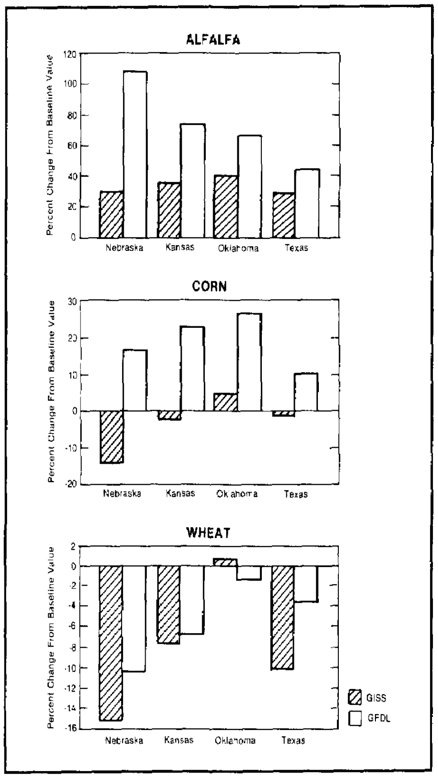

Figure 6-8. Percent change in net seasonal irrigation requirements for GISS and GFDL climate change scenarios with direct effect of CO_2 on crop water use included (Allen and Gichuki, Volume C).

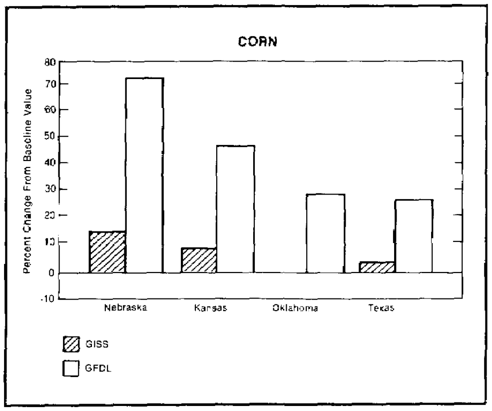

Figure 6-9. Percent change in peak irrigation requirements of corn for GISS and GFDL climate change scenarios with direct effect of CO_2 on crop water use included (Allen and Gichuki, Volume C).

Water Resources for Agriculture in California

In the California regional case study, Dudek (see Volume C) characterized the potential shifts in demand for water for agricultural production that would accompany shifts in cropping patterns driven by changing climate. Changes in competing demands for water from industrial or municipal users were not considered. (For description of study design and limitations, see Chapter 14: California.) When climate change was considered alone, groundwater extraction and surface water use were estimated to decline in California as a result of changes in both supply of (derived from GCM climate change scenarios) and agricultural demand for water. When the direct effects of CO_2. on crop yields were included, groundwater extraction would increase because of improved yields of all crops except corn and because of enhanced economic welfare. Institutional responses to changes in surface and groundwater use could include water transfers, which could improve irrigation efficiency. When water markets were included in the simulations, economic welfare was improved by 6 to 15% over the base, while crop acreage increased and groundwater extraction decreased.

Implications for Demand for Irrigation Water

Expanded use of irrigation is implied from the regional crop modeling studies for the Great Lakes, the Southeast, and the Great Plains (see Chapters 15, 16, and 17, respectively). Increases in irrigated acreage are also estimated for most regions when the economics of crop production are factored in (see Adams et al., Volume C). When these results are considered along with the irrigation studies, it appears that climate change is likely to increase the demand for water from the agricultural sector in many regions.

In the Great Plains, heightened evaporative demand and variability of rainfall may increase the need for irrigation in dryland farming regions. The simulated changes in irrigation water requirements are varied, and specific crops and locations probably would be affected differently. Higher peak irrigation water requirements for some crops may require larger capacity irrigation systems and may enlarge energy demands.

Intensified extraction of water poses serious environmental and economic problems, especially in areas where groundwater is being overdrawn. Streamflows also may slacken if more surface water is used for irrigation, thereby aggravating water quality problems. This in turn would harm fish, wildlife, and recreational activities.

Regional changes in cropping locations and patterns of water use also could exacerbate agricultural, nonpoint source pollution, and could further deplete groundwater resources. Institutional responses, such as markets for water transfers, could help improve irrigation water management and alleviate some of these negative effects.

The economic and social costs of shifting the location of irrigated agriculture could be considerable. The construction of irrigation systems consisting of reservoirs, wells, ditches, pipes, pumps, and sprinklers currently requires about $1,500 to $5,000 per hectare in capital investment (Postel, 1986).

Direct Effects of CO_2 on Crops

Global increases in CO_2 are likely to influence crop metabolism, growth, and development directly through physiological processes and indirectly through climate. Rose (see Volume C) reviewed recent experimental work performed on the direct effects of CO_2 on crops, with emphasis on wheat, corn, soybeans, and cotton.

Elevated concentrations of CO_2 directly affect plant processes such as photosynthesis and transpiration. Higher CO_2 concentrations are also expected to influence these processes indirectly through predicted increases in temperature and other changes in climate variables such as precipitation. Because experimental research has rarely simultaneously studied both the direct and indirect effects of plant responses, it is difficult to assess the relative contributions of elevated CO_2 and climate changes to predictions of crop responses.

Research on the physiological effects has focused primarily on responses of rates of photosynthesis and transpiration to increasing concentrations of atmospheric CO_2. Photosynthesis rates have increased in these crops in relatively ideal experimental environments. At moderate temperatures, most crops will probably show increases in size and possibly yield as CO_2 concentrations rise. However, plants also have internal regulation mechanisms that may lessen these effects under field conditions.

Transpiration rates per unit leaf area decrease, while total transpiration from the entire plant sometimes increases because of greater leaf area. Drought-stressed plants exposed to high partial pressures of CO_2 should be better able to cope with water deficits. Leaf temperatures in all species are expected to rise even more than air temperatures; this may inhibit plant processes that are sensitive to high temperature.

Few studies have examined the interactive effects of CO_2, water, nutrients, light, temperature, pollutants, and sensitivity to daylength on photosynthesis and transpiration. Even fewer studies have examined the effects of these interactions on the growth and development of the whole plant. Therefore, considerable uncertainty exists concerning the extent to which the beneficial effects of increasing CO_2 will be seen in crops growing in the field under normal farming conditions with climate change.

Climate Impacts on Pest-Plant Interactions

Compared with the existing information on the potential effects of climate change on crop production, relatively little effort has been directed toward assessing the influence of climate change on plant-pest interactions. Atmospheric increases in temperature and CO_2, and changes in moisture regimes, all can directly or indirectly affect interactions between pests and crops. Changes in pests will also depend on regional shifts in crop production. Although crop pests may be defined as weeds, insects, or disease pathogens, the EPA work on this subject focused on insects.

Study Design and Results

Stinner et al. (see Volume C) conducted a literature survey and modeling experiments on the major mechanisms through which climate change may affect pest-plant interactions. This study emphasized the major insect pest and pathogen species of corn and soybeans. The survey indicates that temperature and precipitation patterns are the key variables that affect crop-pest interactions. The temperature increases associated with the climate change scenarios would bring about the following trends: (1) increased survival for migratory and nonmigratory insect pest species in the winter; (2) northern range extensions of current pests in the higher latitudes and migration of southern species into the northern Grain Belt regions; (3) an increase in pest species with more than one generation per year in the northern Grain Belt; (4) earlier establishment of pest populations in the growing season; and (5) increased abundance of pests during more susceptible crop growth stages.

The potential changes in the overwintering ranges of four major pests were mapped for the GISS and GFDL climate change scenarios and were compared to present ranges. The overwintering capability of the four major pests may extend northward with both climate change scenarios.

For example, the potato leafhopper, a serious pest on soybeans and other crops, at present overwinters only in a narrow band along the coast of the Gulf of Mexico (Figure 6-10). Warmer winter temperatures in the GFDL and GISS scenarios could cause a doubling or tripling of the overwintering range in the United States, respectively. This would increase the invasion populations in the northern states by similar factors. The invasions also would be earlier in the growing season, assuming planting dates do not change. Both features are likely to lead to greater insect density and damage. This pattern is repeated with the other three pests studied and indicates that these pests, and possibly others, may move northward and invade cropping systems earlier in the growing season under climate change conditions.

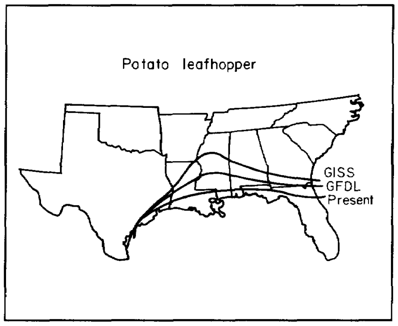

Figure 6-10. Present and potential (GISS and GFDL climate change scenarios) overwintering range of the potato leafhopper, Empoasca fabae, a major pest of soybeans (Stinner et al., Volume C).

The Soybean Integrated Crop Management (SICM) model (Jones et al., 1986) was run with the GISS and GFDL climate change scenarios to estimate changes in damages caused by corn earworm. Modeling results show that earworm damage to soybeans would increase in severity in the Grain Belt under a warmer climate. Such damage could cause grain farmers in the Midwest to suffer significant economic losses. These results were particularly marked with the warmer and drier GFDL scenario.

Limitations

Lack of knowledge about the physiological effects of CO_2 on crop plants and lack of experimental evidence of direct CO_2 effects on insect-plant interactions make the study of pestplant interactions particularly difficult. Only one cultivar was used in the modeling study under both the baseline and the climate change scenarios, and planting dates remained the same. In reality, farmers would probably switch to a more climatically adapted cultivar as climate changed, and they would advance planting dates in response to longer growing seasons.

Implications

Increased pest-related crop damage could intensify pesticide use. The economic and environmental ramifications of such an increase could be substantial, not only in current farming regions but also in new areas if agriculture shifts to the more northern regions such as the northern Plains, the Great Lakes States, and the Pacific Northwest (see Figure 6-6).

Increased use of pesticides would create additional threats to the integrity of ecosystems through soil and water contamination and could increase risks to public health. If agricultural production is not to rely increasingly on chemicals that are potentially harmful to the environment, an increased need will exist for alternative pest management strategies such as biological control, genetic resistance, and innovative cropping systems.

Effects of Climate Change on Water Quality

Agricultural pesticides are ranked as a high-priority pollution problem in many rural regions.

Potentially toxic agricultural chemicals can be transported away from fields via runoff of surface soils and via downward leaching and percolation through the soil. An understanding of these processes is needed to evaluate potential threats to drinking water quality caused by climate change.

Study Design

Johnson et al. (see Volume C) modeled the partitioning of agricultural pesticides among uptake, degradation, surface runoff, and soil leaching for wheat, corn, and cotton production regions in the Great Plains and the Corn Belt. (For details of the study, see Chapter 17: Great Plains.) They used the **Pesticide Root Zone Model (PRZM)** (Carsel et al., 1984), which simulates the vertical movement of pesticides in the soil. The model consists of hydrological and chemical transport components that simulate runoff, erosion, plant uptake, leaching, decay, foliar washoff, and volatilization of a pesticide. The interactions among soil, tillage, management systems; pesticide transport, and climate change were studied.

Limitations

The frequency and duration of precipitation remain the same in the climate change scenarios, even though these storm characteristics are critical factors in determining the transport of agricultural chemicals and may change. The scenarios assume that the number of days with rainfall does not change, but the intensity of rainfall increases or decreases. Runoff and leaching estimates would most likely be different if the number of days of rainfall changed and daily rainfall amounts were held constant.

The PRZM is a one-dimensional, point model that does not simulate the transport of water below the root zone. Thus, results on a regional basis must be extrapolated with care. The direct effects of CO_2 on crop growth, which may increase the size of the plants and the extent to which crops cover the soil, are not included.

Table 6-5. Summary of GISS and GFDL GCM Model Consensus of PRZM Pesticide Transport by Copping Region and Pesticide[a]

Crop and pesticide type	Surface pesticide runoff losses	Surface pesticide erosion losses	Pesticide leaching
Spring wheat			
Highly soluble/short-lived	+	+	-
Highly soluble/long-lived		+	-
Slightly soluble/long-lived			-
Winter wheat			
Highly soluble/short-lived		+	+
Highly soluble/long-lived	+		-
Slightly soluble/long-lived			-
Cotton			
Highly soluble/short-lived	+		+
Highly soluble/long-lived	+	+	-
Slightly soluble/long-lived	+	+	-
Corn			
Highly soluble/short-lived	-	-	
Highly soluble/long-lived		-	-
Slightly soluble/long-lived	-	-	-

[a] + indicates that median values increase under climate change; - indicated that median values decrease under climate change; blank indicates no consensus among median values.

[b] Example: median values of all tillage, soil, weather scenarios for highly soluble/short-lived pesticides in the spring wheat crop area.

Source: Johnson et al. (Volume C).

Results

Regional changes in chemical loadings of water and sediment are likely due to climate change but probably will not be uniform. There appears to be some consensus between the GCM scenarios concerning the estimated regional changes (Table 6-5). Modeled pesticides in runoff increase in the cotton production area, and pesticides carried by sediments decrease in the spring wheat and corn regions. Leaching of pesticides tends to be less everywhere owing to changes in seasonal precipitation and increased evaporation.

Implications

When the changes in water quality from the predicted climate change scenarios are considered in conjunction with the estimated increases in pests and implied higher applications of pesticides described in the study on pest-plant interactions, the potential for changes in the nation's water quality becomes apparent. Any deterioration in water quality could adversely affect public drinking water supplies and human health.

Climate Variability

The impacts of climate change result not only from a slow change in the mean of a climate variable but often from shifts in the frequency of extreme events. Droughts, freezes, and prolonged periods of hot weather have strong effects on agricultural production. Although the agricultural modeling studies did not include the effects of potential changes in climate variability, a review of literature on agriculture and extreme events that focuses on the nature and magnitudes of significant impacts is included in Chapter 3: Climate Variability.

Corn, soybeans, wheat, and sorghum are sensitive to high maximum temperatures during blooming. Lower yields of corn, wheat, and soybeans have been correlated with high temperatures. The damaging effect of runs of hot days on corn yields was particularly evident in the U.S. Corn Belt in 1983.

Although the problems associated with low temperatures may diminish with climate change, risks of frost damage to crops may change in the growing areas of certain crops. Citrus trees are very vulnerable to low minimum temperatures. Winter wheat is often damaged by low temperatures known as winter kill, especially in the absence of snow. Even with warmer winters and fewer frosts, more damage may occur at less extreme temperatures. For example, the effect of freezing temperatures is exacerbated if crops have not yet been hardened by cold temperatures or if the crops are no longer dormant and a cold snap occurs.

Drought is a major cause of year-to-year variability in crop production. In the Dust Bowl years of the 1930s, yields of wheat and corn in the Great Plains dropped to as much as 50% below normal. In 1988, agricultural disaster in areas of the northern Great Plains demonstrated a high vulnerability to drought, and nationwide corn yields decreased by nearly 40%. Reduction in vegetative cover associated with drought also brings about severe wind erosion of soils, which will affect future crop productivity. Low yields of forage crops during droughts result in food shortages for livestock and premature selling of livestock. If frequency of drought increases with climate change, impacts on agriculture can be severe.

Farm-Level Management and Adjustments to Climate Change

Adjustments to existing production practices would be the first course of action in the face of climate change. The net effect of climate change with adjustment by farmers may be significantly different from the estimated effects of climate change alone.

Study Design

Several studies addressed possible adjustments that could modify the effects of climate change. These adjustments include changes in planting and harvesting dates, tillage practices, crop varieties, application of agricultural chemicals, irrigation technology, and institutional responses for water resource management.

Results

Ritchie et al. demonstrated that the yield reduction in corn in the Great Lakes could be partly overcome with selection of new varieties that have a longer growing season (see Chapter 15: Great Lakes). Rosenzweig (see Chapter 17: Great Plains) showed that adjusting the planting date of winter wheat to later in the fall would not ameliorate the effects of climate change, but that changing to varieties more suited to the predicted climate could overcome yield decreases at some locations.

Dudek's California study found that flexible institutional responses to climate change would help to compensate partly for negative climate change effects (see Chapter 14: California). By allowing movement of water around the state by transferral of water rights, California's water resource managers could alleviate some groundwater extraction and compensate for surface water reductions.

Easterling (see Chapter 15: Great Lakes) found that potential farmer adjustments to climate change include changes in tillage practices, increased application of fertilizers, selection of more full-season and heat-resistant varieties, changes in planting densities, higher use of pesticides, earlier harvest, and reduced artificial drying. Different adjustments could occur at different times in the cropping season. With the hotter and drier GFDL scenario, farmers may have to adopt production practices different from those in use today. Climate changes that leave soils drier during summer than they are at present will most likely lead to an increased use of irrigation in the Corn Belt. This increased irrigation is also supported by the projected price increases for all crops grown in Illinois.

Implications

Although detrimental climate change effects on agriculture may be partly offset naturally by increased photosynthesis and water-use efficiency caused by higher levels of atmospheric carbon dioxide, farmers themselves would use a variety of adjustments to adapt to climate change. Market forces also would aid adaptation to climate change because they help to allocate resources efficiently. Each crop and region would respond differently to climate change, and adjustment strategies would need to be tailored to each situation.

Costs of adjustments are likely to vary considerably from region to region. Costs would be relatively small in regions where farmers can switch from one variety to another or from one grain crop to another, thus enabling continued use of existing farm machinery and marketing outlets. However, at locations near the present limit of major agricultural regions (e.g., the boundary between wheat farming and ranching), relatively small changes in climate may require a substantial switch in type of farming. This may require substantial costs in new equipment and other changes in agricultural infrastructure. Severe climate change may necessitate farm abandonment in some regions.

Improvements in agricultural technology also may be expected to ease adjustment through development of appropriate farming practices, crop varieties, and livestock species. Adjustment and adaptation to climate change should be included in agricultural research programs to enable this process to occur.

Livestock

Animal products are a critical source of protein, energy, vitamins, and minerals. U.S. livestock production, mainly from cattle, swine, sheep, and poultry, was estimated to be worth over $31 billion in 1986 (USDA, 1987).

Climate is known to significantly affect many aspects of animal health and production. The direct effects of climate warming on animal health include differences in incidence of heat and cold stress, changes in weight gain, and decline in reproductive capabilities. Indirect effects may involve trends in the availability and prices of animal feeds and the expanded geographic distribution and activity of disease-carrying vectors.

Higher winter temperatures may lower the incidence of respiratory diseases in livestock (Webster, 1981). Conversely, warmer summers may necessitate more hours of indoor cooling during which pathogens are confined to housing structures. Climate warming may significantly increase the costs of air-conditioning in poultry housing. Changes in reproductive capabilities such as decreased ovulation rates, shortened intensity and duration of estrus, decreased fertility of males, and increased embryonic mortality also have been shown to occur with high temperatures (Ames, 1981).

Climate change may also affect the

survivability, activity, and geographic distribution of vectors responsible for the transmission of infectious diseases in livestock. The activity and reproduction of disease-carrying vectors infecting livestock, humans, and crops are driven primarily by temperature, humidity, and precipitation. These impacts are likely to be similar to those on mortality and morbidity of disease in humans (see Chapter 12: Human Health), and they also are similar to changes predicted for crop pests.

Design of Studies

Stem et al. (see Volume C) studied the available literature on four livestock diseases to evaluate the range of potential changes in disease distribution and occurrence under climate change conditions. Schmidtmann and Miller (see Volume C) used a population dynamics simulation model to estimate the effects of the GFDL climate change scenario on the life cycle of the horn fly, a ubiquitous pest of pastured cattle throughout the United States.

Limitations

The horn fly model is based on population counts taken at various times under different weather and management conditions. However, the prediction of current horn fly populations appears to be well correlated with observations. The model is not validated for the high temperatures predicted for the climate change. Schmidtmann and Miller used only the hottest climate change scenario, GFDL; the other scenarios may have resulted in a smaller geographic shift in the range of the horn fly. It should also be noted that the horn fly analysis is based on current livestock management, breeds, and distribution. Possible changes in these factors are beyond the scope of thus study. For example, changes in location and extent of grassland regions and forage production caused by climate warming would affect livestock production and horn fly distributions.

Results

Stem et al. found that under warmer conditions, livestock diseases currently causing serious economic losses in tropical countries could spread into the United States. Rift Valley fever is transmitted principally by mosquitoes, and the disease may spread as rising winter temperatures become able to support an increase in the mosquito population (see Figure 6-11). African swine fever also may become a greater threat.

The ranges and activities of disease-carrying agents of blue tongue and anaplasmosis, diseases currently causing severe losses in cattle and sheep production in the United States, may expand. If disease-carrying insects increase their winter survival and reproduce year-round in more states, the geographical distribution of blue tongue, which is caused by a virus, may expand northward and eastward. Anaplasmosis, a rickettsial infection of ruminants, is the second most important disease of cattle in the United States. Distribution of the insect carrier's habitat could expand to northern states with climate change, and the insects' day-today activity may increase; this process may also cause an increase in disease transmission.

The horn fly causes annual losses of $730.3 million in the beef and dairy cattle industries (Drummond, 1987). Schmidtmann and Miller found that with the very warm GFDL climate change scenario, the horn fly season throughout most of the United States could be extended by 8 to 10 weeks. The increase in horn fly populations could substantially reduce the average daily gain of growing beef cattle. Also under the GFDL. simulation, increased pest activity was estimated in dairy cattle in the North and Northwest -- a result that could significantly decrease milk production. Conversely, under the same scenario, the. summertime activity of the horn fly could decrease in the South because the warmer climate would exceed the horn fly's tolerance to high temperatures.

Implications

With climate change, patterns of livestock diseases and pests may also change. Tropical livestock diseases may become an increased threat, because more geographical areas are potential ranges for the insect carriers of the diseases. Temperature conditions may improve in the winter but may be exacerbated in the summer. Reproductive capabilities may be lower. Livestock production would also be affected if rangeland areas shift and forage production levels change.

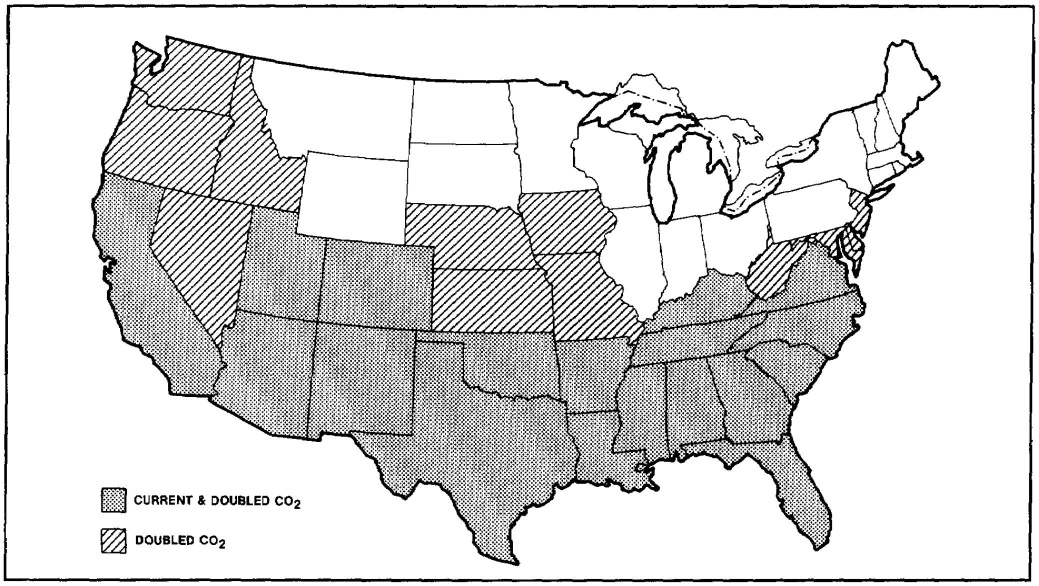

Figure 6-11. States where significant Culex app. activity permits establishment of Rift valley fever for current and doubled CO_2 levels (Stem, et al., Volume C).

ECONOMIC AND ECOLOGICAL IMPLICATIONS OF AGRICULTURAL STUDIES

The U.S. agricultural system has historically been able to adopt new technologies rapidly and may be less vulnerable to climate change than natural ecosystems. In fact, global warming may cause a number of benefits. Potential benefits of CO_2-induced climate change include increases in length of growing season and in air temperatures, which would benefit regions where crop growth is constrained by short summers and low temperatures. Longer growing seasons would likely lead to increased yields of hay and other perennial crops. Energy costs for grain drying may be reduced, since annual crops would reach maturity earlier and would have more opportunity to dry in the fields. Furthermore, in places where precipitation increases during the growing season, irrigation requirements could be reduced. If irrigation requirements are lessened, demand on regional water resources and associated costs to farmers may fall.

However, many reasons to avoid complacency about the predicted climate change remain. Concern for our major resources (especially land and water), rural communities, and the environment is justified. While many critical uncertainties exist regarding the magnitude and timing of impacts, it appears that climate change is likely to affect U.S. agriculture significantly in the coming century.

Costs and Timing of Adjustment

Since our agricultural production system primarily consists of specialized farms producing commodities in geographically specialized production patterns, the costs of adjusting to changed comparative advantage among agricultural regions, with ensuing changed resource use and changed agricultural infrastructure, may be quite **high in some regions.** These shifts would also entail involvement of and costs to the federal government.

If warming occurs rapidly, U.S. agriculture will have less time to adjust and costs may be greater. As climate continues to warm, costs may rise at an increasing rate. Finally, unless CO_2 and other trace gas emissions are limited, we may be facing a continual and possibly accelerating rate of atmospheric accumulations and climate change. As the agricultural system strives to adapt to a changing climate, there may be no chance of optimizing for static conditions. Rather, the system maybe caught in forever playing catch-up.

Effects of CO_2

It is also important to note that the crop modeling studies showed that the direct CO_2 effects on crop photosynthesis and water-use ehiciency ameliorate the negative effects of climate change in some locations under certain climate conditions; however, such effects do not occur uniformly, and they do not occur everywhere. Regional changes in U.S. agriculture occurred with the GISS and GFDL climate change scenarios both with and without the direct effects of CO_2. While much work must be done to improve both climate and crop models, policy analysis should consider that the beneficial direct effects of CO_2 may not offset the negative effects of climate change.

Environmental Quality

Changes in the agricultural production system are likely to have significant impacts on resource use and the environment. Many of the agricultural studies suggest that climate warming could result in accelerated rates of demand for water for irrigation (see Chapter 9: Water Resources), increases in pesticide usage to control changes in pest vectors, and changes in water quality from agricultural chemicals. Decreases in biological diversity may limit the adaptive capacity of agriculture, which requires a broad base of germ plasm for modifying current crops and developing new ones (see Chapter 8: Biodiversity).

A northward migration of agriculture would increase the use of irrigation and fertilizers on sandy soils, thus endangering underlying groundwater quality. From South Dakota to southern Canada, critical prairie wetlands may be lost to drainage and conversion to cropland. Many of these areas are important wildlife habitats. Shifts in agricultural activities may increase the susceptibility of soils to wind and water erosion. Climate change could thus exacerbate many of the current trends in environmental pollution and resource use associated with agriculture as well as initiate new ones.

Sea level rise, an associated impact of climate change, will threaten low-lying coastal agricultural regions with seasonal -- and in some instances permanent -- flooding, saltwater intrusion of freshwater aquifers and rivers, and salt contamination of soils. Agricultural lands in coastal regions may be lost. (See Chapter 9: Water Resources, and Chapter 7: Sea Level Rise, for linkages with agriculture.)

Furthermore, climate change will act on agriculture simultaneously with other environmental stresses. Levels of UV-B radiation caused by depletion of stratospheric ozone are likely to increase in the future, as are levels of tropospheric ozone and acid precipitation. The interactions among these multiple stresses and climate change need to be studied in agricultural settings.

Global Agriculture

Finally, US. agriculture is an integral part of the global, international agricultural system. Consequently, the adjustment of U.S. agriculture to climate change cannot be considered in isolation from the rest of the world. The optimal configuration of U.S. adjustments will depend very much on how simultaneous changes in regional climates affect global agriculture and how other countries, in turn, respond to those changes.

POLICY IMPLICATIONS

Since climate change appears likely to reconfigure the agricultural activities and demographics of rural America, policies should be examined in light of these potential effects. Agricultural policies should be designed to ease adjustments to climate change and to ensure the sustainability of our natural and human resources (see Schuh, Volume C, and Dudek, Volume C). Following are specific policy areas that policymakers could investigate to respond appropriately to the projected climate change.

Commodity Policies

Agricultural pricing and production policies should promote efficient adjustment to the changing conditions of global supply and demand induced by the greenhouse effect, which may include shifts in comparative advantage among regions and increased likelihood of droughts in some regions. Although these shifts may be slow, the cumulative effects may be large and they deserve close monitoring. Market forces as well as government programs would play a crucial role in creating the flexibility to respond to climate changes by sending signals on the efficient use of resources, and in mitigating their ultimate impact as they have done in the past. Agricultural policies should be evaluated to ensure that they are appropriate to both current and possible future conditions in regard to their ability to facilitate adaptation to climate change. For example, flexibility in shifting crop types and farm practices will speed adjustments.

Land-Use Programs

Federal legislation aimed at reducing the use of newly plowed grasslands, e.g., the "Sod-Buster Bill," and the related "Swamp-Buster Bill," which restricts agricultural encroachment into wetlands subject to flooding and water-logging, are examples of new policies meant to protect marginal lands. The basic goals of these new laws, which are part of the 1985 Farm Bill, are to protect the most erodible farmland by removing it from crop production and to use conservation as a tool for reducing overproduction. Nearly 80 million acres of U.S. cropland were retired under these and other farm programs in 1988. Policy research should address how these programs may fare under changing climate conditions.

Another program established in the 1985 Farm Bill that may help alleviate the negative effects of climate change is the Conservation Reserve Program. This program is aimed at removing from crop production the cropland classified as "highly erodible" by the Soil Conservation Service. The bill created a new form of long-term contract of up to 10 years and provides payments to farmers who apply conservation practices, such as maintaining a grass cover, on those acres. If successful, the Conservation Reserve Program may reduce the impact of climate fluctuations on total grain production by taking the most sensitive lands out of use.

The 1988 drought, however, demonstrated that the Conservation Reserve Program may be difficult to maintain in the face of climate stress. As the drought worsened during the summer, use of the set-aside lands was requested so that badly hit farmers could salvage some economic benefits from these acres. Such conflicts may be more common in the future, and land retirement strategies must be weighed against possible needed increases in production.

Awareness of potential changes in agricultural land use due to regional climate change should be built into land-use planning programs, especially in regions where agricultural activities may expand into natural, unmanaged ecosystems. Large-scale drainage and water projects would need environmental impact studies to carefully assess this potential expansion of agricultural land (see Baldwin, Volume J).

Water-Resource Management Programs

Current water supply policies do not generally encourage optimum water-use efficiency. A greater degree of water efficiency should promote flexibility in light of the potential for increased irrigation demands with climate change. Policies such as water transfers and markets should be considered for irrigated areas.

Water Quality Policy

The increased use of agricultural chemicals, along with changes in the hydrological cycle, potentially threaten both soil and water supplies, and eventually, public health. Negative consequences could be avoided or lessened by including potential climate change effects in water quality planning and by supporting alternative pest management strategies that use such techniques as biological control, genetic resistance, and innovative cropping systems.

Risk Management and Drought Policy

Changes in the frequency, intensity, and location of extreme events are important for agriculture and the regional income that it produces. The adequacy of the private crop insurance and federal disaster payment programs should be assessed in the face of climatic uncertainty. For example, only about 20 to 25% of potentially insurable acreage is currently covered by crop insurance. Farmers tend to rely on federal disaster relief programs to bail them out of such disasters as droughts, floods, hail, and windstorms. Financial risk is also part of the credit structure that covers land, equipment, and production in modern farming.

The frequency and magnitude of climate extremes may be altered with climate change. Responding to the changes may be costly for the government if crops fail frequently. The Drought Relief

Bill for the drought of 1988 is scheduled to cost $3.9 billion to cover just 1 year of a climatic extreme. On the other hand, some areas that currently suffer from climate extremes may benefit from climate change. Risk policy mechanisms for relief, recovery, and mitigation of climate change should be examined so that they will be ready to help farmers adjust.

A national drought policy is strongly needed to coordinate federal response to the possibility of increased frequency and duration of future droughts due to climate change. Even without climate change, such a policy is needed not only for the agricultural sector but also for other sectors.

International Trade Agreements

Policies designed to ease the adjustment to greenhouse effects must be global in scope because the effects, although varied, are global in nature. Comparative advantage will likely shift significantly both within the United States and in other countries. Population and economic activities also would change geographically with climate change, thus affecting the location of demand for agricultural products. It is already a goal of U.S. agricultural policy to incorporate global conditions of supply and demand into the agricultural sector. The potential seriousness of the impacts on the agricultural production system of the greenhouse effect may provide added incentive to establish such policies both nationally and internationally. The vulnerability of current and potential food-deficit regions to climate change should also be considered.

Agricultural Contributions to the Greenhouse Effect

Agriculture itself is an active contributor to the greenhouse effect. Clearing of forested land for agriculture often involves burning of trees and shrubs that release CO_2. The biomass that is not burned tends to decay gradually, also emitting CO_2. Agricultural activities release other radiatively active trace gases. Flooded rice fields emit methane (CH4) as a product of the anaerobic decomposition of organic matter. Ruminants also release methane as a consequence of their digestive processes. In addition, soils may volatilize some of the nitrogenous fertilizer applied to them in the form of nitrous oxide (N_20). Finding effective ways to reduce these emissions presents a major challenge to the agricultural research community. In this regard, the Conservation Reserve Program and forestation efforts could provide a partial solution, since vegetation fixes CO_2 from the air. (See Lashof and Tirpak, 1989, for further discussion of agriculture's contribution to the greenhouse effect.)

Agricultural Research

The agricultural research community should enhance climate change research from the field level to the national policy level. It should continue to breed heat- and drought-resistant crop varieties and new crop species in preparation for global warming. Research in biotechnology may also be directed toward alleviating the negative effects of climate change. Improved water-use and irrigation efficiency also take on renewed importance in the light of potential climate change. Energy requirements of the agricultural system under climate change should be defined, given the potential for increases in energy-intensive activities such as irrigation and application of agricultural chemicals. Research attention also should be directed toward reducing agricultural emissions of trace gases.

RESEARCH NEEDS

1. International agriculture -- Study the potential shifts in international comparative advantage and the vulnerability of fooddeficit regions, and evaluate the implications of such shifts for the United States.

   One of the most crucial areas for further research is the projection of potential climate change effects at the international level. Potential changes in agricultural yields and production of major crops, and impacts on regions that are food-deficient now or that may become food-deficient in the future, all need to be studied. Economics and policy research should consider the implications of shifts in global agriculture for the levels of U.S. crop exports and the role of the United States as a reliable supplier of agricultural export commodities.

2. Crop and livestock productivity -- Study the interactive effects of climate variability and change, CO_2, tropospheric ozone, UV-B from stratospheric ozone depletion, and other environmental and societal variables on agricultural productivity. Determine how changed climatic variability may amplify or lessen the preliminary EPA results.

   Because of the significant production changes indicated by these studies, the need for better simulation of the direct effects of CO_2 in the crop models, and the limited adjustment studies performed, further crop research should be conducted on a longer term basis. Necessary work includes resolving the differences in forecasts of the GCMs, and designing more appropriate scenarios including transient climate change and changes in climatic variability. Physiologically based submodels are needed for the effects of increased CO_2 on various crops. The effects on other major crops such as cotton also should be studied. Crop models should be improved in their simulation of the effects of increasing temperatures.

   Research on the direct CO_2 effects on crops to this point has provide windows of knowledge concerning certain crops at specific stages of their life cycles. Both the direct and the climate change effects of high CO_2 are probably quite different at different stages of development. Research should evaluate the interactive effects of CO_2 and temperature over the whole life cycle of the plant, with varying conditions of water and nutrition, rather than with plants under optimal conditions. Then crop response to the combined climatic and physiological effects of CO_2 may be predicted more realistically. Much more research on climate change and livestock production is needed. Important research areas include crop-livestock interactions, reproduction, and diseases.

3. Adaptation strategies -- Study the dynamic nature of climate change: What is the rate of adaptation of regional agricultural systems compared with the rate of climate change? Evaluate the thresholds of sensitivity of U.S. agriculture. Studies should analyze the ability of various aspects of the agricultural production systems to adapt to various rates and degrees of climate change to determine these thresholds of sensitivity. It would also be useful to identify the costs of different types of adjustments and the regions most likely to experience greater costs.

4. Agricultural economics -- Expand the national analysis to include crops and regions not now included (for example, cotton and grasslands, and the western regions of the United States). Conduct further analyses of regional shifts in agriculture. Studies that link water resource and agriculture models are needed to estimate changes in water demand among agriculture and competing users. Thus, estimates of actual changes in irrigated acreage could be made.

5. Environmental impacts -- Elucidate the impacts of climate change on water quantity, water quality, and other components of the environment caused by shifts in crop and livestock production and related industries.

6. Agricultural emissions of trace gases -- Discover effective ways to reduce emissions of methane from livestock, nitrous oxide from fertilizer application, and other agricultural sources of trace gases.

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CHAPTER 7
SEA LEVEL RISE

by James G. Titus

FINDINGS

Global warming could cause sea level to rise 0.5 to 2 meters by 2100. Such a rise would inundate wetlands and lowlands, erode beaches, exacerbate coastal flooding, and increase the salinity of estuaries and aquifers.

- A 1-meter rise could drown approximately 25 to 80% of the U.S. coastal wetlands; ability to survive would depend largely on whether they could migrate inland or whether levees and bulkheads blocked their migration. Even current sea level trends threaten the wetlands of Louisiana.
- A 1-meter rise could inundate 5,000 to 10,000square miles of dryland if shores were not protected and 4,000 to 9,000 square miles of dryland if only developed areas were protected.
- Most coastal barrier island communities would probably respond to sea level rise by raising land with sand pumped from offshore. Wide and heavily urbanized islands may use levees, while communities on lightly developed islands may adjust to a gradual landward migration of the islands.
- Protecting developed areas against such inundation and erosion by building bulkheadsand levees, pumping sand, and raising barrier islands could cost $73 to $111 billion (cumulative capital costs in 1985 dollars) for a 1-meter rise by the year 2100 (compared with $6 to $11 billion under current sea level trends). Of this total, $50 to $75 billion would be spent (cumulative capital costs in 1985 dollars) to elevate beaches, houses, land, and roadways by the year 2100 to protect barrier islands (compared with $4 billion under current trends). Developed barrier islands would likely be protected from sea level rise because of their high property values.
- The Southeast would bear approximately 90% of the land loss and 66% of the shore protection costs.

Policy Implications

- Many of the necessary responses to sea level rise, such as rebuilding ports, constructing levees, and pumping sand onto beaches, need not be implemented until the rise is imminent. On the other hand, the cost of incorporating sea level rise into a wide variety of engineering and land use decisions would be negligible compared with the costs of not responding until sea level rises.
- Many wetland ecosystems are likely to survive sea level rise only if appropriate measures are implemented in the near future. At the state and local levels, these measures include land use planning, regulation, and redefinitions of property rights. The State of Maine has already issued regulations to enable wetlands to migrate landward by requiring that structures be removed as sea level rises.
- The coastal wetlands protected under Section 404 of the Clean Water Act will gradually be inundated. The act does not authorize measures to ensure survival of wetland ecosystems as sea level rises.
- The National Flood Insurance Program may wish to consider the implications of sea level rise on its future liabilities. A recent HUD authorization act requires this program to purchase property threatened with erosion. The act may imply a commitment by the

federal government to compensate property owners for losses due to sea level rise.

- The need to take action is particularly urgent in coastal Louisiana, which is already losing 100 square kilometers per year.

CAUSES, EFFECTS, AND RESPONSES

Global warming from the greenhouse effect could raise sea level approximately 1 meter by expanding ocean water, melting mountain glaciers, and causing ice sheets in Greenland to melt or slide into the oceans. Such a rise would inundate coastal wetlands and lowlands, erode beaches, increase the risk of flooding, and increase the salinity of estuaries, aquifers, and wetlands.

In the last 5 years, many coastal communities throughout the world have started to prepare for the possibility of such a rise. In the United States, Maine has enacted a policy declaring that shorefront buildings will have to be moved to enable beaches and wetlands to migrate inland to higher ground. Maryland has shifted its shore-protection strategy from a technology that can not accommodate sea level rise to one that can. Seven coastal states have held large public meetings on how to prepare for a rising sea. Australia, the Netherlands, and the Republic of Maldives are beginning to undergo a similar process.

Causes

Ocean levels have always fluctuated with changes in global temperatures. During the ice ages when the earth was 5°C (9°F) colder than today, much of the ocean's water was frozen in glaciers and sea level often was more than 100 meters (300 feet) below the present level (Dorm et al., 1962; Kennett, 1982; Oldale, 1985). Conversely, during the last interglacial period (100,000 years ago) when the average temperature was about 1°C (2°F) warmer than today, sea level was approximately 20 feet higher than the current sea level (Mercer, 1968).

When considering shorter periods of time, worldwide sea level rise must be distinguished from relative sea level rise. Although climate change alters worldwide sea level, the rate of sea level rise relative to a particular coast has greater practical importance and is all that monitoring stations can measure. Because most coasts are sinking (and a few are rising), the range of relative sea level rise varies from more than 3 feet per century in Louisiana and parts of California and Texas to 1 foot per century along most of the Atlantic and gulf coasts, to a slight drop in much of the Pacific Northwest (Figure 7-1). Areas such as Louisiana provide natural laboratories for assessing the possible effects of future sea level rise (Lyle et al., 1987).

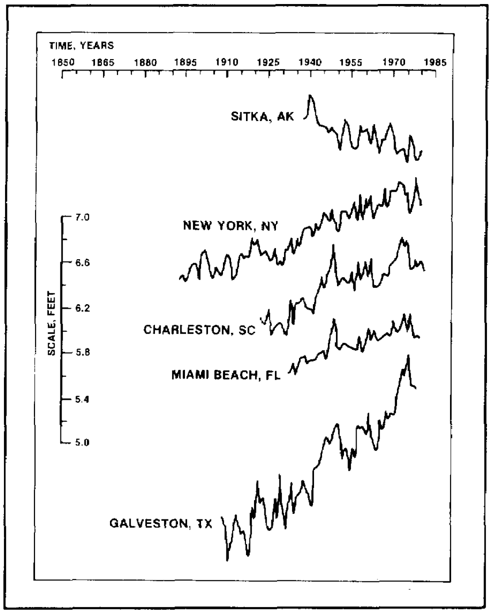

Figure 7-1. Time series graph of sea level trends for New York, Charleston, Miami, Galveston, and Siika (Lyle et al., 1987).

Global sea level trends have generally been estimated by combining the trends at tidal stations around the world. Studies combining these measurements suggest that during the last century, worldwide sea level has risen 10 to 15 centimeters (4 to 6 inches) (Barnett, 1984; Fairbridge and Krebs, 1962). Much of this rise has been attributed to the global warming that has occurred during the last century (Meier, 1984; Gornitz et al., 1982). Hughes (1983) and Bentley (1983) estimated that a complete disintegration of West Antarctica in response to global warming would require a 200- to 500-year period, and that such a disintegration would raise sea level 20 feet. Most recent assessments, however, have focused on the likely rise by the year 2100. Figure 7-2 illustrates recent estimates of sea level rise, which generally fall into the range of 50 io 200 centimeters.

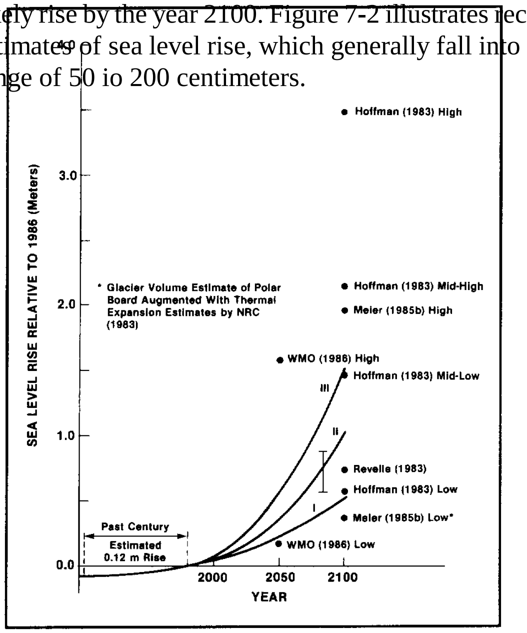

Figure 7-2. Estimates of future sea level rise (derived from Hoffman, 1983, 1986; Meier, 1985; Revelle, 1983).

Although most studies have focused on the impact of global warming on global sea level, the greenhouse effect would not necessarily raise sea level by the same amount everywhere. Removal of water from the world's ice sheets would move the earth's center of gravity away from Greenland and Antarctica and would thus redistribute the oceans' water toward the new center of gravity. Along the U.S. coast, this effect would generally increase sea level rise by less than 10%. Sea level could actually drop, however, at Cape Horn and along the coast of Iceland. Climate change could also affect local sea level by changing ocean currents, winds, and atmospheric pressure; no one has estimated these impacts.

Effects

In this section and in the following sections, the effects of and responses to sea level rise are presented separately. However, the distinction is largely academic and is solely for presentation purposes. In many cases, the responses to sea level rise are sufficiently well established and the probability of no response is sufficiently low that it would be misleading to discuss the potential effects without also discussing responses. For example, much of Manhattan Island is less than 2 meters above high tide; the effect of sea level rise would almost certainly be the increased use of coastal engineering structures and not the inundation of downtown New York.

A rise in sea level would inundate wetlands and lowlands, accelerate coastal erosion, exacerbate coastal flooding, threaten coastal structures, raise water tables, and increase the salinity of rivers, bays, and aquifers (Barth and Titus, 1984). Most of the wetlands and lowlands are found along the gulf coast and along the Atlantic coast south of central New Jersey, although a large area also exists around San Francisco Bay. Similarly, the areas vulnerable to erosion and flooding are also predominately in the Southeast; potential salinity problems are spread more evenly along the U.S. Atlantic coast. We now discuss some of the impacts that would result if no responses were initiated to address sea level rise.

Destruction of Coastal Wetlands

Coastal wetlands are generally found between the highest tide of the year and mean sea level. Wetlands have kept pace with the past rate of sea level rise because they collect sediment and produce peat upon which they can build; meanwhile, they expanded inland as lowlands were inundated (Figure 7-3). Wetlands accrete vertically and expand inland. Thus, as Figure 7-3 illustrates, the present area of wetlands is generally far greater than the area that would be available for new wetlands as sea level rises (Titus et al., 1984b; Titus, 1986). The potential loss would be the greatest in Louisiana (see Chapter 16: Southeast).

In many areas, people have built bulkheads just above the marsh. If sea level rises, the wetlands will be squeezed between the sea and the bulkheads (see Figure 7-3). Previous studies have estimated that if the development in coastal areas were removed to allow new wetlands to form inland, a 1.5- to 2-meter rise would destroy 30 to 70% of the U.S. coastal wetlands. If levees and bulkheads were erected to protect today's dryland, the loss could be 50 to 80% (Titus, 1988; Armentano et al., 1988).

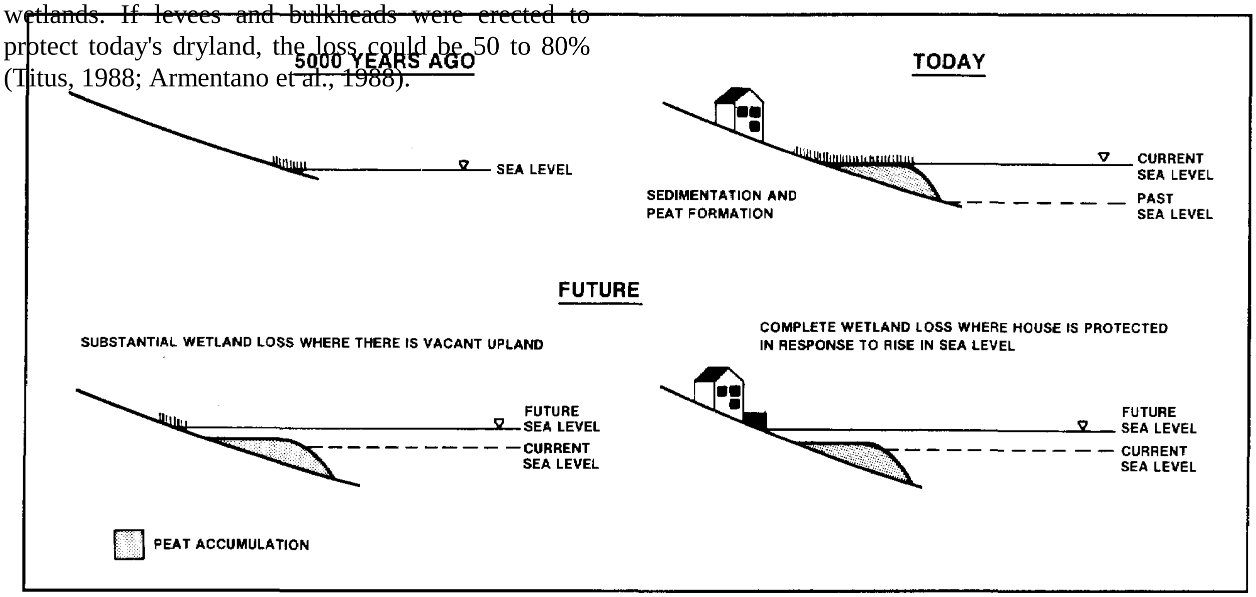

Figure 7-3. Evolution of marsh as sea rises. Coastal marshes have kept pace with the slow rate of sea level rise that has characterized the last several thousand years. Thus, the area of marsh has expanded over time as new lands have been inundated. If in the future, sea level rises faster than the ability of the marsh to keep pace, the marsh area will contract. Construction of bulkheads to protect economic development may prevent new marsh from forming and result in a total loss of marsh in some areas.

Such a loss would reduce the available habitat for birds and juvenile fish and would reduce the production of organic materials on which estuarine fish rely.

The dryland within 2 meters of high tide includes forests, farms, low parts of some port cities, cities that sank after they were built and are now protected with levees, and the bay sides of barrier islands. The low forests and farms are generally in the mid-Atlantic and Southeast regions; these would provide potential areas for new wetland formation. Major port cities with low areas include Boston, New York, Charleston, and Miami. New Orleans is generally 8 feet below sea level, and parts of Galveston, Texas City, and areas around the San Francisco Bay are also well below sea level. Because they are already protected by levees, these cities are more concerned with flooding than with inundation.

Inundation and Erosion of Beaches and Barrier Islands

Some of the most important vulnerable areas are the recreational barrier islands and spits (peninsulas) of the Atlantic and gulf coasts. Coastal barriers are generally long narrow islands and spits with the ocean on one side and a bay on the other. Typically, the oceanfront block of an island ranges from 5 to 10 feet above high tide, and the bay side is 2 to 3 feet above high water. Thus, even a 1meter sea level rise would threaten much of this valuable land with inundation.

Erosion threatens the high part of these islands and is generally viewed as a more immediate problem than the inundation of the bay sides. As Figure 7-4 shows, a rise in sea level can cause an ocean beach to retreat considerably more than it would from the effects of inundation alone. The visible part of the beach is much steeper than the underwater portion, which comprises most of the active "surf zone." While inundation alone is determined by the slope of the land just above the water, Bruun (1962) and others have shown that the total shoreline retreat from a sea level rise depends on the average slope of the entire beach profile.

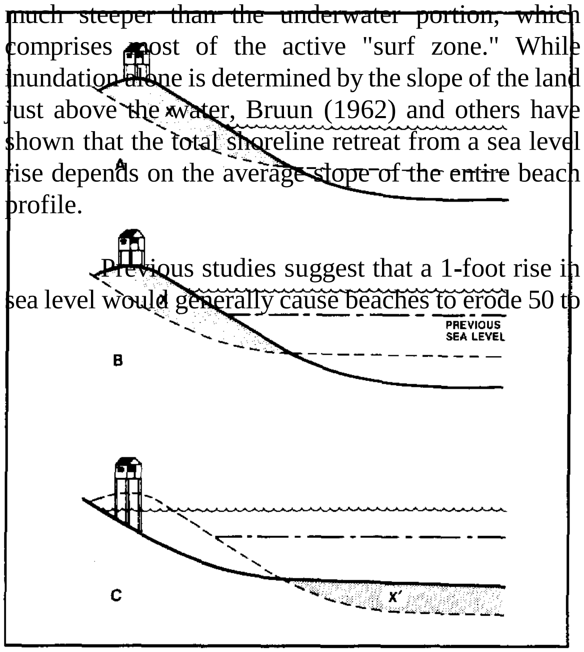

Figure 7-4. The Bruun Rule: (A) initial condition; (B) immediate inundation when sea level rises; (C) subsequent erosion due to sea level rise. A rise in sea level immediately results in shoreline retreat due to inundation, shown in the first two examples. However, a 1-meter rise in sea level implies that the offshore bottom must also rise 1 meter. The sand required to raise the bottom (X') can be supplied by beach nourishment. Otherwise, waves will erode the necessary sand (X) from upper part of the beach as shown in (C).

Previous studies suggest that a 1-foot rise in sea level would generally cause beaches to erode 50 to 100 feet from the Northeast to Maryland (e.g., Kyper and Sorensen, 1985; Everts, 1985); 200 feet along the Carolinas (Kana et al., 1984); 100 to 1,000 feet along the Florida coast (Bruun, 1962); 200 to 400 feet along the California coast (Wilcoxen, 1986); and perhaps several miles in Louisiana. Because most U.S. recreational beaches are less than 100 feet wide at high tide, even a 1-foot rise in sea level would require a response. In many areas, undeveloped barrier islands could keep up with rising sea level by "over-washing" landward. In Louisiana, however, barrier islands are breaking up and exposing the wetlands behind them to gulf waves; consequently, the Louisiana barrier islands have rapidly eroded.

Flooding

If sea level rises, flooding would increase along the coast for four reasons: (1) A higher sea level provides a higher base for storm surges to build upon. A 1-meter sea level rise would enable a 15-year storm to flood many areas that today are flooded only by a 100-year storm (e.g., Kana et al., 1984; Leatherman, 1984). (2) Beach erosion also would leave oceanfront properties more vulnerable to storm waves. (3) Higher water levels would reduce coastal drainage and thus would increase flooding attributable to rainstorms. In artificially drained areas such as New Orleans, the increased need for pumping could exceed current capacities. (4) Finally, a rise in sea level would raise water tables and would flood basements, and in cases where the groundwater is just below the surface, perhaps raise it above the surface.

Saltwater Intrusion

A rise in sea level would enable saltwater to penetrate farther inland and upstream into rivers, bays, wetlands, and aquifers. Salinity increases would be harmful to some aquatic plants and animals, and would threaten human uses of water. For example, increased salinity already has been cited as a factor contributing to reduced oyster harvests in the Delaware and Chesapeake Bays, and to conversion of cypress swamps to open lakes in Louisiana. Moreover, New York, Philadelphia, and much of California's Central Valley obtain their water from areas located just upstream from areas where the water is salty during droughts. Farmers in central New Jersey and the city of Camden rely on the Potomac-Raritan-Magothy Aquifer, which could become salty if sea level rises (Hull and Titus, 1986). The South Florida Water Management District already spends millions of dollars every year to prevent Miami's Biscayne Aquifer from becoming contaminated with seawater.

Responses

The possible responses to inundation, erosion, and flooding fall broadly into three categories: erecting walls to hold back the sea, allowing the sea to advance and adapting to the advance, and raising the land. Both the slow rise in sea level over the last thousand years and the areas where land has been sinking more rapidly offer numerous historical examples of all three responses.

For over five centuries, the Dutch and others have used dikes and windmills to prevent inundation from the North Sea. By contrast, many cities have been rebuilt landward as structures have eroded; the town of Dunwich, England, has rebuilt its church seven times in the last seven centuries. More recently, rapidly subsiding communities (e.g., Galveston, Texas) have used fill to raise land elevations; the U.S. Army Corps of Engineers and coastal states regularly pump sand from offshore locations to counteract beach erosion. Venice, a hybrid of all three responses, has allowed the sea to advance into the canals, has raised some lowlands, and has erected storm protection barriers.

Most assessments in the United States have concluded that low-lying coastal cities would be protected with bulkheads, levees, and pumping systems, and that sparsely developed areas would adapt to a naturally retreating shoreline (e.g., Dean et al., 1987; Gibbs, 1984; Schelling, 1983). This conclusion has generally been based on estimates that the cost of structural protection would be far less than the value of the urban areas being protected but would be greater than the value of undeveloped land.

Studies on the possible responses of barrier islands and moderately developed mainland communities show less agreement but generally suggest that environmental factors would be as important as economics. Some have suggested that barrier islands should use seawalls and other "hard" engineering approaches (e.g., Kyper and Sorensen, 1985; Sorensen et al., 1984). Others have pointed to the esthetic problems associated with losing beaches and have advocated a gradual retreat from the shore (Howard et al., 1985). Noting that new houses on barrier islands are generally elevated on pilings, Titus (1986) suggested that communities could hold back the sea but keep a natural beach by extending the current practice of pumping sand onto beaches to raising entire islands in place.

Responses to erosion are more likely to have adverse environmental impacts along sheltered water than on the open coast (Titus, 1986). Because the beach generally is a barrier island's most important asset, economics would tend to encourage these communities to preserve their natural shorelines; actions that would prevent the island from breaking up also would protect the adjacent wetlands. However, along most mainland shorelines, economic self-interest would encourage property owners to erect bulkheads; these would prevent new wetland formation from offsetting the loss of wetlands that were inundated.

Most of the measures for counteracting saltwater intrusion attributable to sea level rise have also been employed to address current problems. For example, the Delaware River Basin Commission protects Philadelphia's freshwater intake on the river and New Jersey aquifers recharged by the river by storing water in reservoirs during the wet season and releasing it during droughts, thereby forcing the saltwater back toward the sea. Other communities have protected coastal aquifers by erecting underground barriers and by maintaining freshwater pressure through the use of impoundments and injection wells.

HOLDING BACK THE SEA: A NATIONAL ASSESSMENT

The studies referenced in the previous section have illustrated a wide variety of possible effects from and responses to a rise in sea level from the greenhouse effect. Although they have identified the implications of the risk of sea level rise for specific locations and decisions, these studies have not estimated the nationwide magnitude of the impacts. This report seeks to fill that void.

It was not possible to estimate the nationwide value of every impact of sea level rise. The studies thus far conducted suggest that the majority of the environmental and economic costs would be associated with shoreline retreat and measures to hold back the sea, which can be more easily assessed on a nationwide basis. Because the eventual impact will depend on what people actually do, a number of important questions can be addressed within this context:

- Would a gradual abandonment of moderately developed mainland areas significantly increase the amount of wetlands that survived a rise in sea level?

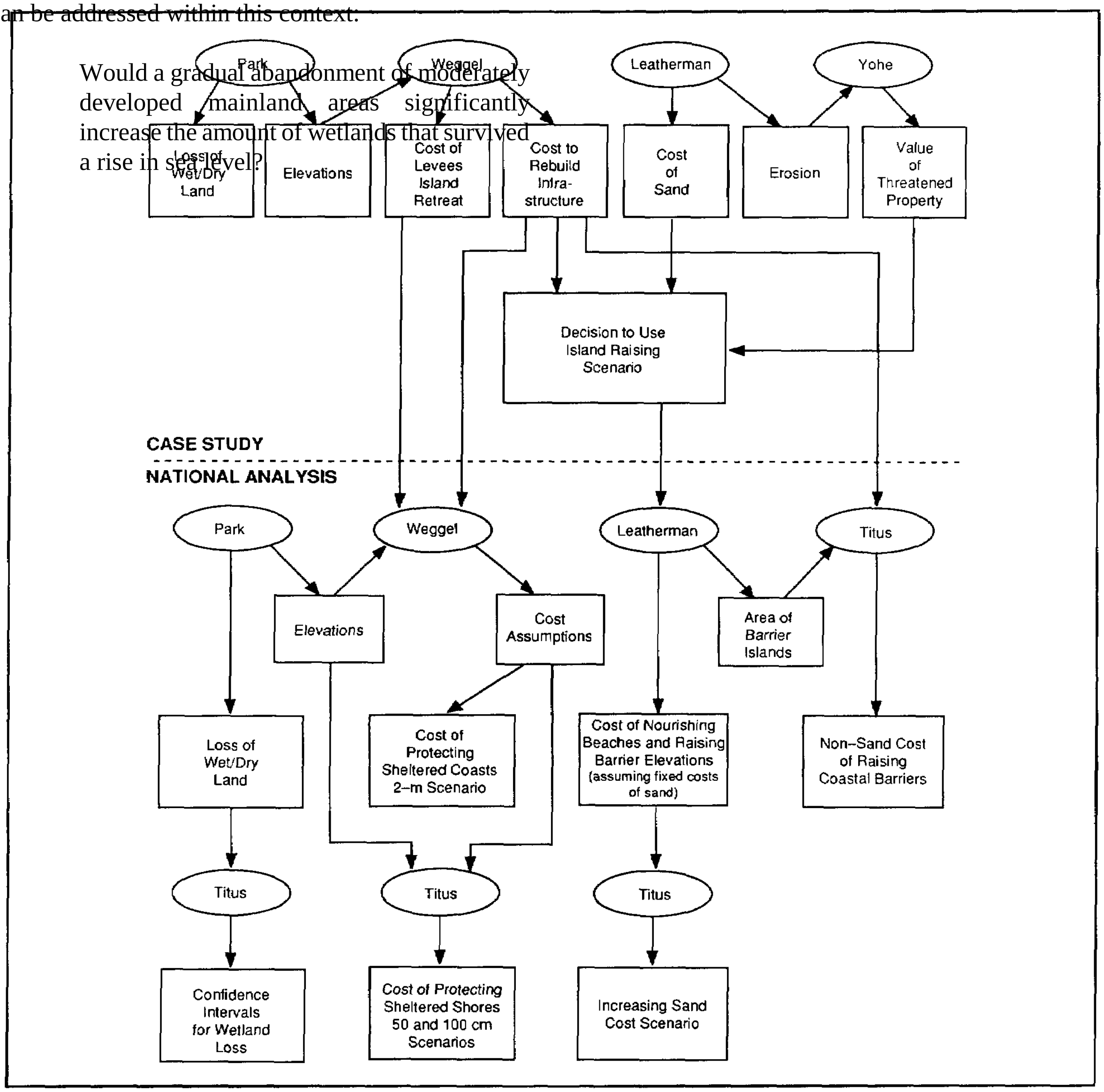

Figure 7-5. Overview of sea level rise studies and authors.

- Would the concave profiles of coastal areas ensure that more wetlands would be lost than gained, regardless of land-use decisions?

- Should barrier islands be raised in place by pumping sand and elevating structures and utilities?
- Would a landward migration of developed barrier islands or encircling them with dikes and levees be feasible alternatives?
- How much property would be lost if barrier islands were abandoned?

STRUCTURE OF STUDIES FOR THIS REPORT

A central theme underlying these questions is that the implications of sea level rise for a community depend greatly on whether people adjust to the natural impact of shoreline retreat or undertake efforts to hold back the sea. Because no one knows the extent to which each of these approaches would be applied, this study was designed to estimate the impacts of sea level rise for (1) holding back the sea, and (2) natural shoreline retreat.

The tasks were split into five discrete projects:

1. Park et al. estimated the loss of coastal wetlands and dryland.

2. Leatherman estimated the cost of pumping sand onto open coastal beaches and barrier islands.

3. Weggel et al. estimated the cost of protecting sheltered shores with levees and bulkheads.

4. Yohe began a national economic assessment by estimating the value of threatened property.

5. Titus and Greene synthesized the results of other studies to estimate ranges of the nationwide impacts.

Figure 7-5 illustrates the relationships between the various reports. (All of the sea level rise studies are in Volume B of the Appendices to this report.) As the top portion shows, the assessment began with a case study of Long Beach Island, New Jersey, which was necessary for evaluating methods and providing data for purposes of extrapolation. The Park and Leatherman studies performed the same calculations for the case study site that they would subsequently perform for the other sites in the nationwide analysis. However, Weggel and Yohe conducted more detailed assessments of the case study whose results were used in the Leatherman and Titus studies.

Because it would not be feasible for Leatherman to examine more than one option for the cost of protecting the open coast, Weggel estimated the cost of protecting Long Beach Island by three approaches: (1) raising the island in place; (2) gradually rebuilding the island landward; and (3) encircling the island with dikes and levees. Yohe estimated the value of threatened structures. Titus analyzed Weggel's and Yohe's results and concluded that raising barrier islands would be the most reasonable option for the Leatherman study and noted that the cost of this option would be considerably less than the resources that would be lost if the islands were not protected as shown in Figure 7-6.

Once the case study was complete, Park, Leatherman, and Weggel proceeded independently with their studies (although Park provided Weggel with elevation data). When those studies were complete, Titus synthesized their results, developing a nationwide estimate of the cost of holding back the sea and interpolating Weggel's 200-centimeter results for the 50- and 100centimeter scenarios.

In presenting results from the Park and Weggel studies, the sites were grouped into seven coastal regions, four of which are in the Southeast: New England, mid-Atlantic, south Atlantic, south Florida/gulf coast peninsula, Louisiana, other gulf (Texas, Mississippi, Alabama, Florida Panhandle), and the Pacific coast. Figure 7-7 illustrates these regions.

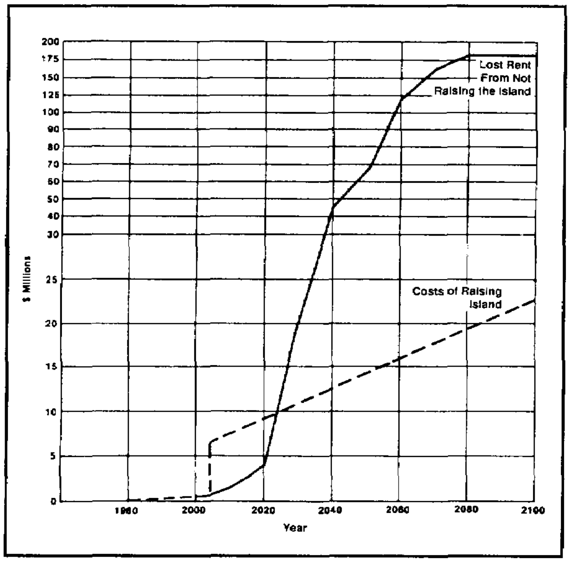

Figure 7-6. Annual cost of raising island versus annual costs (lost rent) from not protecting the island (in 1986 dollars) (Titus and Greene, Volume B).

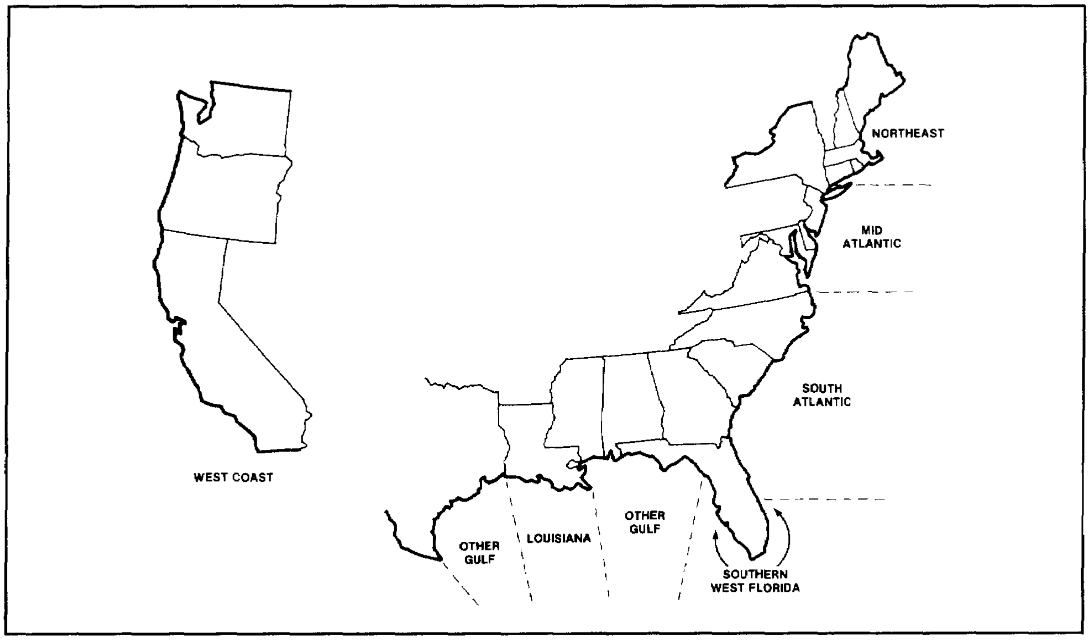

Figure 7-7. Costal regions used in this study.

SCENARIOS OF SEA LEVEL RISE

Although the researchers considered a variety of scenarios of future sea level rise, this report focuses on the impacts of three scenarios: rises of 50, 100, and 200 centimeters by the year 2100. All three of these scenarios are based on quantitative estimates of sea level rise. No probabilities were associated with these scenarios. Following the convention of a recent National Research Council report (Dean et al., 1987), the rise was interpolated throughout the 21st century using a quadratic (parabola). For each site, local subsidence was added to determine relative sea level rise. Figure 7-8 shows the scenarios for the coast of Florida where relative sea level rise will be typical of most of the U.S. coast. Sea level would rise 1 foot by 2025, 2040, and 2060 for the three scenarios and 2 feet by 2045, 2065, and 2100.

RESULTS OF SEA LEVEL STUDIES IN THIS REPORT

Loss of Coastal Wetlands and Dryland

Park (Volume B) sought to test a number of hypotheses presented in previous publications:

- A rise in sea level greater than the rate of vertical wetland accretion would result in a net loss of coastal wetlands.

- The loss of wetlands would be greatest if all developed areas were protected, less if shorelines retreated naturally, and least if barrier islands were protected while mainland shores retreated naturally.

- The loss of coastal wetlands would be greatest in the Southeast, particularly Louisiana.

Study Design

Park's study was based on a sample of 46 coastal sites that were selected at regular intervals. This guaranteed that particular regions would be represented in proportion to their total area in the coastal zone. The sites chosen accounted for 10% of the U.S. coastal zone excluding Alaska and Hawaii. To estimate the potential loss of wet and dry land, Park first had to characterize their elevations. For wetlands, he used satellite imagery to determine plant species for 60- by 80-meter parcels. Using estimates from the literature on the frequency of flooding that can be tolerated by various wetland plants, Park determined the percentage of time that particular parcels are currently under water.

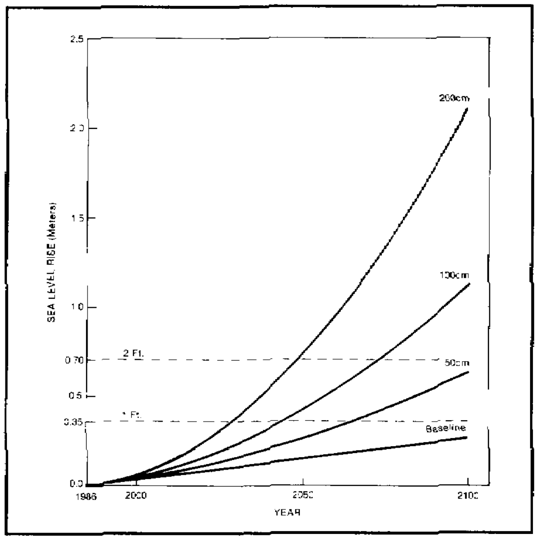

Figure 7-8. Sea level scenarios (Miami Beach).

From this, Park inferred wetland elevation based on the known tidal range. For dryland, he used spot elevation measurements to interpolate between contours on U.S. Geological Survey topographic maps.

Park estimated the net loss of wetlands and dryland for no protection, protection of developed areas, and protection of all shores. For the no-protection scenario, estimating the loss of dryland is straightforward. However, for calculating net wetland loss, Park had to estimate the loss of existing wetlands as well as the creation of new wetlands. For calculating losses, Park used published vertical accretion rates (see Armentano et al., 1988), although he allowed for some acceleration of vertical accretion in areas with ample supplies of sediment, such as tidal deltas. Park assumed that dryland would convert to wetlands within 5 years of being inundated.

For sites in the Southeast, Park also allowed for the gradual replacement of salt marshes by mangrove swamps. The upper limit for mangroves is around Fort Lauderdale. Park used the GISS transient scenario to determine the year particular sites would be as warm as Fort Lauderdale is today and assumed that mangroves would begin to replace marsh after that year.

Limitations

The greatest uncertainty in Park's analysis is a poor understanding of the potential rates of vertical accretion. Although this could substantially affect the results for low sea level rise scenarios, the practical significance is small for a rise of 1 meter because it is generally recognized that wetlands could not keep pace with the rise of 1 to 2 centimeters per year that such a scenario implies for the second half of the 21st century.

Errors can be made when determining vegetation type based on the use of infrared "signatures" that satellites receive. Park noted, for example, that in California the redwoods have a signature similar to that of marsh grass. For only a few sites, Park was able to corroborate his estimates of vegetation type.

Park's study did not consider the potential implications of alternative methods of managing riverflow. This limitation is particularly serious regarding application to Louisiana, where widely varying measures have been proposed to increase the amount of water and sediment delivered to the wetlands. Finally, the study makes no attempt to predict which undeveloped areas might be developed in the next century.

At the coarse (500-meter) scale Park used, the assumption of protecting only developed areas amounts to not protecting a number of mainland areas where the shoreline is developed but areas behind the shoreline are not. Therefore, Park's estimates for protecting developed areas should be interpreted as applying to the case where only densely developed areas are protected. Finally, Park's assumption that dryland would convert to vegetated wetlands within 5 years of being inundated probably led him to underestimate the net loss of wetlands due to sea level rise.

Results

Park's results supported the hypotheses suggested by previous studies. Figure 7-9 shows nationwide wetlands loss for various (0- to 3-meter) sea level rises for the three policy options investigated. For a 1-meter rise, 66% of all coastal wetlands would be lost if all shorelines were protected, 49% would be lost if only developed areas were protected, and 46% would be lost if shorelines retreated naturally.

As expected, the greatest losses of wetlands would be in the Southeast, which currently contains 85% of U.S. coastal wetlands (Figure 7-9). For a 1-meter sea level rise, 6,000 to 8,600 square miles (depending on which policy is implemented) of U.S. wetlands would be lost; 90 to 95% of this area would be in the Southeast, and 40 to 50% would be in Louisiana alone. By contrast, neither the Northeast nor the West would lose more than 10% of its wetlands if only currently developed areas are protected.

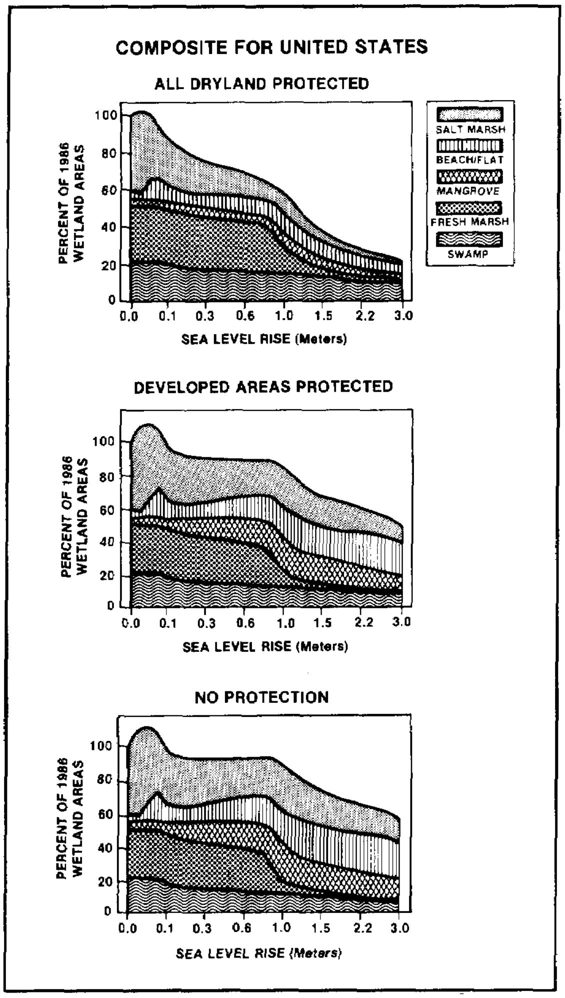

Figure 7-9. Nationwide wetlands loss for three shoreline-protection options. Note: These wetlands include beaches and flats that are not vegetated wetlands; however, results cited in the text refer to vegetated wetlands (Park, Volume B).

Figure 7-10 illustrates Park's estimates of the inundation of dryland for the seven coastal regions. If shorelines retreated naturally, a 1-meter rise would inundate 7,700 square miles of dryland, an area the size of Massachusetts. Rises of 50 and 200 centimeters would result in losses of 5,000 and 12,000 square miles, respectively. Approximately 70% of the dryland losses would occur in the Southeast, particularly Florida, Louisiana, and North Carolina. The eastern shores of the Chesapeake and Delaware Bays also would lose considerable acreage.

Costs of Defending Sheltered Shorelines

Study Design

This study began by examining Long Beach Island in depth. This site and five other sites were used to develop engineering rules of thumb for the cost of protecting coastal lowlands from inundation. Examining the costs of raising barrier islands required an assessment of two alternatives: (1) building a levee around the island; and (2) allowing the island to migrate landward.

After visiting Long Beach Island and the adjacent mainland, Weggel (Volume B) designed and estimated costs for an encirclement scheme consisting of a levee around the island and a drainage system that included pumping and underground retention of stormwater. For island migration, he used the Bruun Rule to estimate oceanside erosion and navigation charts to calculate the amount of sand necessary to fill the bay an equivalent distance landward. For island raising and island migration, Weggel used the literature to estimate the costs of elevating and moving houses and of rebuilding roads and utilities.

Weggel's approach for estimating the nationwide costs was to examine a number of index sites in depth and thereby develop generalized cost estimates for protecting different types of shorelines. He used the topographic information collected by Park for a sample of 95 sites to determine the area and shoreline length that had to be protected. He then applied the cost estimation factors to each site and extrapolated the sample to the entire coast.

After assessing Long Beach Island, Weggel conducted less detailed studies of the following areas:

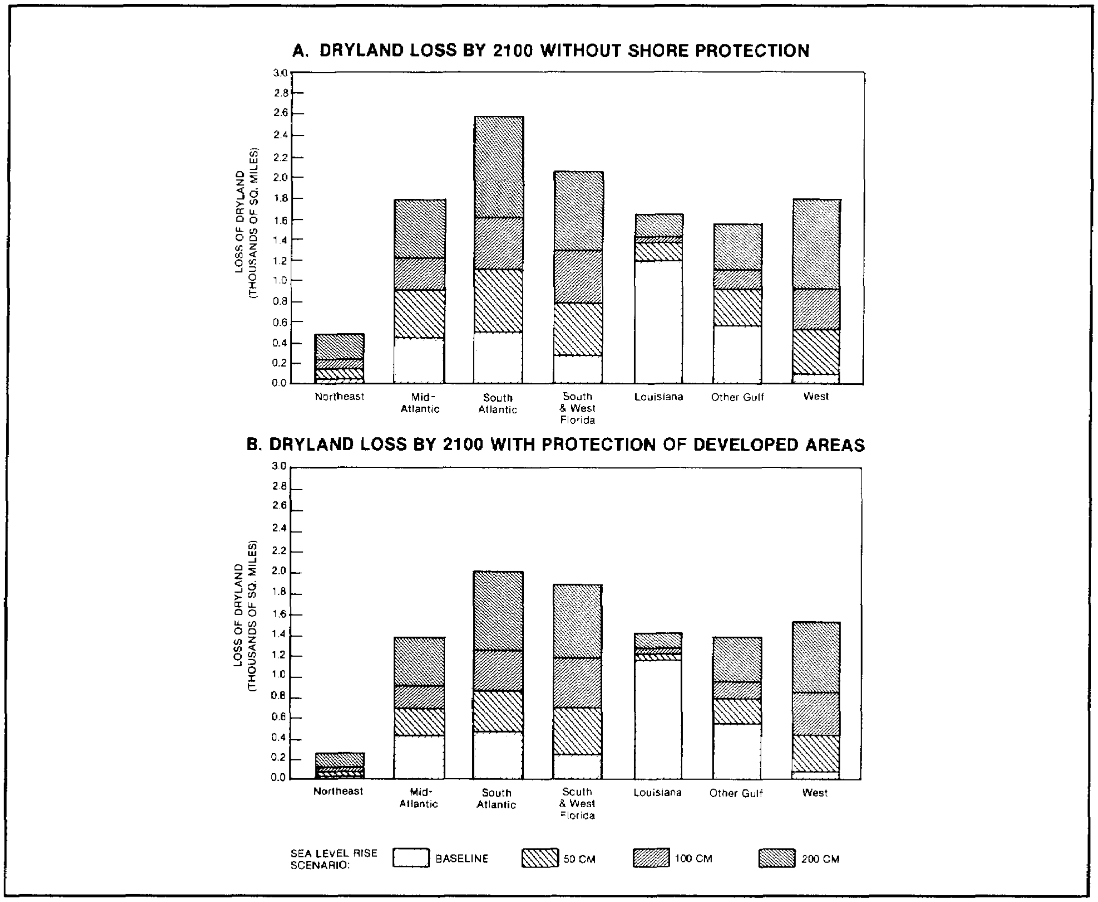

Figure 7-10. Loss of dryland by 2100: (A) if no areas are protected, and (B) if developed areas are protected with levees (derived from Park, Volume B; see also Titus and Greene, Volume B).

metropolitan New York; Dividing Creek, New Jersey; Miami and Miami Beach; the area around Corpus Christi, Texas; and parts of San Francisco Bay.

Limitations

The most serious limitation of the Weggel study is that cruder methods are used for the national assessment than for the index sites. Even for the index sites, the cost estimates are based on the literature, not on site-specific designs that take into consideration wave data for bulkheads and potential savings from tolerating substandard roads. Weggel did not estimate the cost of pumping rainwater out of areas protected by levees.

Finally, Weggel was able to examine only one scenario: a 2-meter rise by 2100. This scenario was chosen over the more likely 1-meter scenario because an interpolation from 2 meters to 1 meter would be more reliable than an extrapolation from 1 meter to 2 meters. (See the discussion of Titus and Greene for results of the interpolation.)

Results

Case Study of Long Beach Island

Weggel's cumulative cost estimates clearly indicate that raising Long Beach Island would be much less expensive ($1.7 billion) than allowing it to migrate landward ($7.7 billion). Although the cost of building a levee around the island ($800 million) would be less, the "present value" would be greater. Weggel concluded that the levee would have to be built in the 2020s, whereas the island could be raised gradually between 2020 and 2100. Thus, the (discounted) present value of the levee cost would be greater, and raising the necessary capital for a levee at any one time could be more difficult than gradually rebuilding the roads and elevating houses as the island was raised. Moreover, a levee would eliminate the waterfront view. A final disadvantage of building a levee is that one must design for a specific magnitude of sea level rise; by contrast, an island could be raised incrementally.

The Weggel analysis shows that landward migration is more expensive than island raising, primarily because of the increased costs of rebuilding infrastructure. Thus, migration might be less expensive in the case of a very lightly developed island. Levees might be more practical for wide barrier islands where most people do not have a waterfront view.

Nationwide Costs

Table 7-2 shows Weggel's estimates for the index sites and his nationwide estimate. The index sites represent two distinct patterns. Because urban areas such as New York and Miami would be entirely protected by levees, the cost of moving buildings and rebuilding roads and utilities would be relatively small. On the other hand, Weggel concluded that in more rural areas such as Dividing Creek, New Jersey, only the pockets of development would be protected. The roads that connected them would have to be elevated or replaced with bridges, and the small number of isolated buildings would have to be moved.

Weggel estimates that the nationwide cost of protecting developed shorelines would be $25 billion, assuming bulkheads are built, and $80 billion assuming levees are built. Unlike wetlands loss, the cost of protecting developed areas from the sea would be concentrated more in the Northeast than in the Southeast because a much greater portion of the southeastern coast is undeveloped.

Table 7-1. Total Cost of Protecting Long Beach Island from a 2-Meter Rise in Sea Level (millions of 1986 dollars)

Protective measure	Encirclement	Island raising	Island mitigation
Sand Costs			
Beach	290	290	0
Land creation/maintenance	NA	270	321
Moving/elevating houses	NA	74	37
Roads/utilities	0	1072	7352
Levee and drainage	542	0	0
Total	832	1706	7710

NA = Not applicable.
Source: Leatherman (Volume B); Weggel (Volume B)

Table 7-2. Cumulative Cost of Protecting Sheltered Waters for a 2-Meter Rise in Sea Level (millions of 1986 dollars)

	New bulkhead	Raise old bulkhead	Move building	Roads/ utilities	Total
Index sites					
New York	57	205	0.5	9.5	272.3
Long Beach Island	3	4	2.7	3.8	13.7
Dividing Creek	4	6	4.8	18.2	33.0
Miami area	11	111	0.3	8.3	130.7
Corpus Christi	11	29	2.8	40.9	83.4
San Francisco Bay[a]	3	19	2.0	20.0	44.0
Nationwide estimate					
	<u>low</u>		<u>high</u>		
Northeast	6,932		23,607		
Mid-Atlantic	4,354		14,603		
Southeast	9,249		29,883		
West	4,097		12.802		
Nation	24,633		80,176		

[a] Site names refer to the name of the U.S. Geological Survey quadrant, not to the geographical area of the same name.
Source: Weggel et al. (Volume B).

Case Study of the Value of Threatened Coastal Property

<u>Study Design</u>

Yohe's (Volume B) objective was to estimate the loss of property that would result from not holding back the sea. Using estimates of erosion and inundation for Long Beach Island from Leatherman and Park et al., Yohe determined which land would be lost from sea level rise for a sample of strips spanning the island from the ocean to the bay. He then used the Ocean County, New Jersey, tax assessor's estimates of the value of the land and structures that would be lost, assuming that the premium associated with a view of the bay or ocean would be transferred to another property owner and not lost to the community. He estimated the annual stream of rents that would be lost by assuming that the required return on real estate is 10% after tax. Yohe assumed that a property on the bay side was "lost" whenever it was flooded at high tide, and that property on the ocean side was "lost" when the house was within 40 feet of the spring high tide mark. (See Titus and Greene, Volume B, for discussion.)

<u>Limitations</u>

Yohe's results for a sea level rise of less than 18 inches are sensitive to the assumption regarding when a property would be lost. On the bay side, people might learn to tolerate tidal inundation. Unless a major storm occurred, people could probably occupy oceanfront houses until they were flooded at high tide. However, the resulting loss of recreational use of the beach probably would have a greater impact than abandoning the structure. Tax maps do not always provide up-to-date estimates of property values. However, the distinction between the tax assessor's most recent estimate of market value and the current market value is small compared with the possible changes in property values that will occur over the next century; hence, Titus and Greene used tax assessors estimates of market values.

Results

Yohe's results suggest that the cost of gradually raising Long Beach Island would be far less than the value of the resources that would be protected. Figure 7-6 compares Yohe's estimates of the annual loss in rents resulting from not holding back the sea with Weggel's estimates of the annual cost of raising the island for the 2-meter scenario. With the exception of the 2020s, the annual loss in rents resulting from not holding back the sea would be far less than the annual costs of pumping sand and elevating structures. Titus and Greene point out that the cost would be approximately $1,000 per year per house, equivalent to 1 week's rent (peak season).

Nationwide Cost of Pumping Sand Onto Recreational Beaches

Leatherman's goal (Volume B) was to estimate the cost of defending the U.S. ocean coast from a rise in sea level.

Study Design

Owing to time constraints, it was possible to consider only one technology. Based on the Long Beach Island results, Leatherman assumed that the cost of elevating recreational beaches and coastal barrier islands by pumping in offshore sand would provide a more representative cost estimate than assuming that barrier islands would be abandoned, would migrate landward, or would be encircled with dikes and levees.

The first step in Leatherman's analysis was to estimate the area of (1) the beach system, (2) the low bayside, and (3) the slightly elevated oceanside of the island. Given the areas, the volume of sand was estimated by assuming that the beach system would be raised by the amount of sea level rise. The bay and ocean sides of the island would not be raised until after a sea level rise of 1 and 3 feet, respectively. Cost estimates for the sand were derived from inventories conducted by the U.S. Army Corps of Engineers.

Leatherman applied this method to all recreational beaches from Delaware Bay to the mouth of the Rio Grande, as well as California, which accounts for 80% of the nation's beaches. He also examined one representative site in each of the remaining states.

Limitations

Although the samples of sites in the Northeast and Northwest are representative, complete coverage would have been more accurate. Furthermore, Leatherman used conservative assumptions in estimating the unit costs of sand. Generally, a fraction of the sand placed on a beach washes away because the sand's grain is too small. Moreover, as dredges have to move farther offshore to find sand, costs will increase.

For Florida, Leatherman used published estimates of the percentage of fine-grain sand and assumed that the dredging cost would rise $1 per cubic yard for every additional mile offshore the dredge had to move. For the other states, however, he assumed that the deposits mined would have no t-me-grain sand and that dredging costs would not increase. (To test the sensitivity of this assumption, Titus and Greene developed an increasing-cost scenario.) Leatherman assumed no storm worse than the 1-year storm, which underestimates the sand volumes required.

A final limitation of the Leatherman study is that it represents the cost of applying a single technology throughout the ocean coasts of the United States. Undoubtedly, some communities (particularly Galveston and other wide barrier islands in Texas) would find it less expensive to erect levees and seawalls or to accept a natural shoreline retreat.

Results

Table 7-3 illustrates Leatherman's estimates. A total of 1,900 miles of shoreline would be nourished. Of 746 square miles of coastal barrier islands that would be raised for a 4-foot sea level rise, 208 square miles would be for a 2-foot rise. As the table shows, two-thirds of the nationwide costs would be borne by four southeastern states: Texas, Louisiana, Florida, and South Carolina.

Figure 7-11 illustrates the cumulative nationwide costs over time. For the 50- and 200-centimeter scenarios, the cumulative cost would be $2.3 to $4.4 billion through 2020, $11 to $20 billion through 2060, and $14 to $58 billion through 2100. By

Table 7-3. Cost of Placing Sand on U.S. Recreational Beaches and Coastal Barrier Islands and Spits (millions of 1986 dollars).

	Sea level rise by 2100			
State	Baseline	50 cm	100 cm	200 cm
Maine[a]	22.8	119.4	216.8	412.2
New Hampshire[a]	8.1	38.9	73.4	142.0
Massachusetts[a]	168.4	489.5	841.6	1,545.8
Rhode Island[a]	16.3	92.0	160.6	298.2
Connecticut[a]	101.7	516.4	944.1	1,799.5
New York[a]	143.6	769.6	1,373.6	2,581.4
New Jersey[a]	157.6	902.1	1,733.3	3,492.5
Delaware	4.8	33.6	71.1	161.8
Maryland	5.7	34.5	83.3	212.8
Virginia	30.4	200.8	386.5	798.0
North Carolina	137.4	655.7	1,271.2	3,240.4
South Carolina	183.5	1,157.9	2,147.7	4,347.7
Georgia	25.9	153.6	262.6	640.3
Florida (Atlantic coast)	120.1	786.6	1,791.0[b]	7,745.5[b]
Florida (Gulf coast)	149.4	904.3	1,688.4[b]	4,091.6[b]
Alabama	11.0	59.0	105.3	259.6
Mississippi	13.4	71.9	128.3	369.5
Louisiana	1,955.8	2,623.1	3,492.7	5,231.7
Texas	349.6	4,188.3	8,489.7	17,608.3
California	35.7	147.1	324.3	625.7
Oregon[a]	21.9	60.5	152.5	336.3
Washington State[a]	51.6	143.0	360.1	794.4
Hawaii[a]	73.5	337.6	646.9	1,267.5
Nation	3,788.0	14,512.0	26,745.0	58,002.0

[a] Indicates states where estimate was based on extrapolating a representative site to the entire state. All other states have 100% coverage.

[b] Florida estimates account for the percentage of fine-grain sediment, which generally washes away, and for cost escalation as least expensive sand deposits are exhausted. All other estimates conservatively ignore this issue.

Source: Leatherman (Volume B) (baseline derived from Leatherman).

contrast, if current trends continue, the total cost of sea level rise for beach nourishment would be about $35 million per year.

Synthesis of the Three National Studies

Study Design

Although Weggel used Park's topographic data, the analysis in the three nationwide studies proceeded independently. Titus and Greene's primary objectives (Volume B) were to combine various results to estimate the nationwide cost of holding back the sea for various sea level rise scenarios and to derive the ranges for the specific impacts. The objectives were as follows:

1. Use Park's results to weigh weggel's high and low scenarios according to whether levees or bulkheads would be necessary, and interpolate Weggel's cost estimate for the 2-meter rise to rises of 50 and 100 centimeters;
2. Use results from Leatherman and Weggel, along with census data, to estimate the nationwide cost (other than pumping sand) of raising barrier islands;
3. Develop an increasing-cost scenario for the cost of protecting the open ocean coast; and
4. Develop statistical confidence intervals for wetland loss, impacts of the various policy options, and costs of protecting developed shores.

Titus and Greene developed a single estimate for protecting each site with bulkheads and levees by assuming that the portion of developed areas protected with levees would be equal to the portion of the lowlands that Park estimated would be inundated. They interpolated the resulting 2-meter estimate to 50-and 100-centimeter estimates, based on Weggel's assumption that the cost of building bulkheads and levees rises as a function of the structure's height.

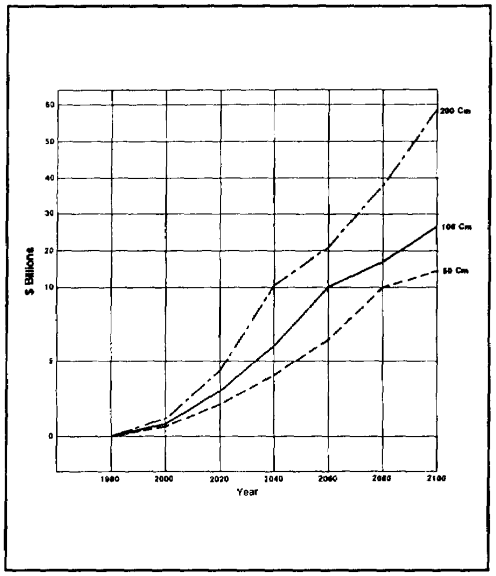

Figure 7-11. Nationwide cost of sand for protecting ocean coast (in 1986 dollars) (Leatherman, Volume B).

Cost of Protecting Sheltered Shores Cost of Raising Barrier Islands Other Than Dredging

Weggel's case study of Long Beach Island provided cost estimates for elevating structures and rebuilding roads, while Leatherman estimated the area that would have to be raised. Many barrier islands have development densities different from those of Long Beach Island because they have large tracts of undeveloped land or larger lot sizes. Therefore, Titus and Greene used census data to estimate a confidence interval for the average building density of barrier islands, and they applied Weggel's cost factors.

Sensitivity of Sand Costs to Increasing Scarcity of Sand

Titus and Greene used Leatherman's escalating cost assumptions for Florida to estimate sand pumping costs for the rest of the nation.

Confidence Intervals

The Park and Weggel studies involved sampling, but the researchers did not calculate statistical confidence intervals. Therefore, Titus and Greene developed 95% confidence intervals for the cost of protecting sheltered coasts, the area of wetlands loss for various scenarios.

Limitations

Besides all of the limitations that apply to the Park, Leatherman, and Weggel studies, a number of others apply to Titus and Greene.

Cost of Protecting Sheltered Shores

Titus and Greene assumed that the portion of the coast requiring levees (instead of bulkheads) would be equal to the portion of lowlands that otherwise would be inundated. This assumption tends to understate the need for levees. For example, a community that is 75% high ground often would still have very low land along all of its shoreline and hence would require a levee along 100% of the shore. But Titus and Greene assume that only 25% would be protected by levees.

Cost of Raising Banier Islands

The data provided by Weggel focused only on elevating roads, buildings, and bulkheads. Thus, Titus and Greene do not consider the cost of replacing sewers, water mains, or buried cables. On the other hand, Weggel's cost factors assume that rebuilt roads would be up to engineering standards; it is possible that communities would tolerate substandard roads. In addition, the census data Titus and Greene used were only available for incorporated communities, many of which are part barrier island and part mainland; thus, the data provide only a rough measure of typical road density.

Sensitivity of Sand Costs to Increased Scarcity of Sand

Finally, Titus and Greene made no attempt to determine how realistic their assumption was that sand costs would increase by the same pattern nationwide as they would in Florida.

Results

Loss of Wetlands and Dryland

Table 7-4 illustrates 95% confidence intervals for the nationwide losses of wetlands and dryland. If all shorelines were protected, a 1-meter rise would result in a loss of 50 to 82% of U.S. coastal wetlands, and a 2-meter rise would result in a loss of 66 to 90%. If only the densely developed areas were protected, the losses would be 29 to 69% and 61 to 80% for the 1- and 2-meter scenarios, respectively. Except for the Northeast, no protection results in only slightly lower wetland loss than protecting only densely developed areas. Although the estimates for the Northeast, midAtlantic, the gulf regions outside Louisiana, and the Florida peninsula are not statistically significant (at the 95% confidence levels), results suggest that wetlands loss would be least in the Northeast and Northwest.

Table 7-4. Nationwide Loss of Wetlands and Dryland[a] (95% confidence intervals)

	Square miles[b]			
	Baseline	50-cm rise	100-cm rise	200-cm rise
Wetlands				
Total protection	N.C.	4944-8077 (38-61)	6503-10843 (50-82)	8653-11843 (66-90)
Standard protection	1168-3341 (9-25)	2591-5934 (20-45)	3813-9068 (29-69)	4350-10995 (33-80)
No protection	N.C.	2216-5592 (17-43)	3388-8703 (26-66)	3758-10025 (29-76)
Dryland				
Total protection	0	0	0	0
Standard protection	1906-3510	2180-6147	4136-9186	6438-13496
Total protection	N.C.	3315-7311	5123-10330	8791-15394

a Wetlands loss refers to vegetative wetlands only. b Numbers in parentheses are percentages N.C.= not calculated.
Source: Titus and Greene (Volume B).

Table 7-5. Cumulative Nationwide Cost of Protecting Barrier Islands and Developed Mainland Through the Year 2100 (billions of 1986 dollars)[a]

	Sea level scenario			
	Baseline	50-cm rise	100-cm rise	200-cm rise
Open coast				
Sand	3.8	15-20	27-41	58-100
Raise houses, roads, utilities	0	9-13	21-57	75-115
Sheltered shores	1.0-2.4	5-13	11-33	30-101
Total[b]	4.8-6.2	32-43	73-111	119-309

[a] Costs due to sea level rise only

[b] Ranges for totals are basd in the square root of the sum of the squared ranges.

Source: Titus and Green (Volume B).

Costs of Holding Back the Sea

Table 7-5 illustrates the Titus and Greene estimates of the costs of holding back the sea. The low range for the sand costs is based on Leatherman's study, and the high range is based on the increasing cost scenario Titus and Greene developed. The uncertainty range for the costs of elevating structures reflects the uncertainty in census data regarding the current density of development. High and low estimates for the cost of protecting sheltered shorelines are based on the sampling errors of the estimates for the 46 sites that both Park et al. and Weggel et al. examined.

Titus and Greene estimated that the cumulative nationwide cost of protecting currently developed areas in the face of a 1-meter rise would be from $73 to 111 billion, with costs for the 50- and 200-centimeter scenarios ranging from $32 to 309 billion. These costs would imply a severalfold increase in annual expenditures for coastal defense. Nevertheless, compared with the value of coastal property, the costs are small.

POLICY IMPLICATIONS

Wetlands Protection

The nationwide analysis showed that a 50- to 200-centimeter rise in sea level could reduce the coastal wetlands acreage (outside Louisiana) by 17 to 76% if no mainland areas were protected, by 20 to 80% if only currently developed areas were protected, and by 38 to 90% if all mainland areas were protected. These estimates of the areal losses understate the differences in impacts for the various land-use options. Although a substantial loss would occur even with no protection, most of today's wetland shorelines would still have wetlands; the strip simply would be narrower. By contrast, protecting all mainland areas would generally replace natural shorelines with bulkheads and levees. This distinction is important because for many species of fish, the length of a wetland shoreline is more critical than the total area.

Options for State and Local Governments

Titus (1986) examined three approaches for maintaining wetland shorelines in the face of a rising sea: (1) no further development in lowlands; (2) no action now but a gradual abandonment of lowlands as sea level rises; and (3) allowing future development only with a binding agreement to allow such development to revert to nature if it is threatened by inundation.

The first option would encounter legal or financial hurdles. The extent to which the "due-process" clause of the Constitution would allow governments to prevent development in anticipation of sea level rise has not been specifically addressed by the courts. Although purchases of land would be feasible for parks and refuges, the cost of buying the majority of lowlands would be prohibitive. Moreover, this approach requires preparation for a rise in sea level of a given magnitude; if and when the sea rises beyond that point, the wetlands would be lost. Finally, preventing future development would not solve the loss of wetlands resulting from areas that have already been developed.

Enacting no policy today and addressing the issue as sea level rises would avoid the costs of planning for the wrong amount of sea level rise but would probably result in less wetlands protection. People are developing coastal property on the assumption that they can use the land indefinitely. It would be difficult for any level of government to tell property owners that they must abandon their land with only a few years' notice, and the cost of purchasing developed areas would be even greater than the cost of buying undeveloped areas.

Economic theory suggests that under the third alternative, people would develop a property only if the temporary use provided benefits greater than the costs of writing it off early. This approach would result in the greatest degree of flexibility, because it would allow real estate markets to incorporate sea level rise and to determine the most efficient use of land as long as it remains dry.

This approach could be implemented by regulations that prohibit construction of bulkheads as sea level rises or by the use of conditional longterm leases that expire when high tide falls above a property's elevation.

The State of Maine (1987) has implemented this third approach through its coastal dune regulations, which state that people building houses along the shore should assume that they will have to move their houses if their presence prevents the natural migration of coastal wetlands, dunes, or other natural shorelines. A number of states also have regulations that discourage bulkheads, although they do not specifically address sea level rise. The option can be implemented through cooperative arrangements between developers, conservancy groups, and local governments. (See Titus and Greene, Volume B, for additional details.)

The Federal Role

Section 404 of the Clean Water Act discourages development of existing wetlands, but it does not address development of areas that might one day be necessary for wetland migration. This program will provide lasting benefits, even if most coastal wetlands are inundated. Although marshes and swamps would be inundated, the shallow waters that formed could provide habitat for fish and submerged aquatic vegetation. No one has assessed the need for a federal program to protect wetlands in the face of rising sea level.

Coastal Protection

State and Local Efforts

State and local governments currently decide which areas would be protected and which would be allowed to erode. Currently, few localities contribute more than 10% of the cost of beach nourishment, with the states taking on an increasing share from the federal government. However, many coastal officials doubt that their states could raise the necessary funds if global warming increased the costs of coastal protection over the next century by $50 to $300 billion. If state funds could not be found, the communities themselves would have to take on the necessary expenditures or adapt to erosion.

Long Beach Island, New Jersey, illustrates the potential difficulties. The annual cost of raising the island would average $200 to $1,000 per house over the next century (Titus and Greene, Volume B). Although this amount is less than one week's rent during the summer, it would more than double property taxes, an action that is difficult for local governments to contemplate. Moreover, the island is divided into six jurisdictions, all of which would have to participate.

More lightly developed communities may decide that the benefits of holding back the sea are not worthwhile. Sand costs would be much less for an island that migrated. Although Weggel estimated that higher costs would be associated with allowing Long Beach Island to migrate landward than with raising the island in place, this conclusion resulted largely from the cost of rebuilding sewers and other utilities that would still be useful if the island were raised.

Regardless of how a barrier island community intends to respond to sea level rise, the eventual costs can be reduced by deciding on a response well in advance. The cost of raising an island can be reduced if roads and utilities are routinely elevated or if they have to be rebuilt for other reasons (e.g., Titus et al., 1987). The cost of a landward migration also can be reduced by discouraging reconstruction of oceanfront houses destroyed by storms (Titus et al., 1984a). The ability to fund the required measures also would be increased by fostering the necessary public debate well before the funds are needed.

Federal Efforts

While state governments generally are responsible for protecting recreational beaches, the U.S. Army Corps of Engineers is responsible for several major federal projects to rebuild beaches and for efforts to curtail land loss in Louisiana. The long-term success of these efforts would be improved if the corps were authorized to develop comprehensive long-term plans to address the impacts of sea level rise.

Beach Erosion

In its erosion-control efforts, the corps has recently shifted its focus from hard structures (e.g., seawalls, bulkheads, and groins) to soft approaches, such as pumping sand onto beaches. This shift is consistent with the implications of sea level rise: groins and seawalls will not prevent loss of beaches due to sea level rise. Although more sand will have to be pumped than current analyses suggest, this approach could ensure the survival of the nation's beaches.

Nevertheless, consideration of accelerated sea level rise would change the cost-benefit ratios of many corps erosion control projects. As with the operations of reservoirs (discussed in Chapter 16: Southeast), the corps is authorized to consider flood protection but not recreation. When they evaluated the benefits of erosion control at Ocean City, Maryland, the corps concluded that less than 10% of the benefits would be for flood control (most were related to recreation). Had they considered accelerated sea level rise, however, the estimated flood protection benefits from having a protective beach would have constituted a considerably higher fraction of the total benefits (Titus, 1985).

Wetlands Loss in Louisiana

By preventing freshwater and sediment from reaching the coastal wetlands, federal management of the Mississippi River is increasing the vulnerability of coastal Louisiana to a sea level rise (e.g., Houck, 1983). For example, current navigation routes require the U.S. Army Corps of Engineers to limit the amount of water flowing through the Atchafalaya River and to close natural breaches in the main channel of the Mississippi; these actions limit the amount of freshwater and sediment reaching the wetlands. Alternative routes have been proposed that would enable water and sediment to reach the wetlands (Louisiana Wetland Protection Panel, 1987). These include dredging additional canals parallel to the existing Mississippi River gulf outlet or constructing a deepwater port east of the city.

Either of these options would cost a few billion dollars. By contrast, annual resources for correcting land loss in Louisiana have been in the tens of millions of dollars. As a result, mitigation activities have focused on freshwater diversion structures and on other strategies that can reduce current wetland loss attributable to high salinities but that would not substantially reduce wetlands loss if sea level rises 50 to 200 centimeters (Louisiana Wetland Protection Panel, 1987).

The prospect of even a 50-centimeter rise in sea level suggests that solving the Louisiana wetlands loss problem is much more urgent than is commonly assumed. Because federal activities are now a major cause of land loss, and would have to be modified to enable wetlands to survive a rising sea, the problem is unlikely to be solved without a congressional mandate. A recent interagency report concluded that "no one has systematically determined what must be done to save 10, 25, or 50 percent of Louisiana's coastal ecosystem" (Louisiana Wetland Protection Panel, 1987). Until someone estimates the costs and likely results of strategies with a chance of protecting a significant fraction of the wetlands in face of rising sea level, it will be difficult for Congress to devise a long-term solution.

Flood Insurance

In 1968, Congress created the National Flood Insurance Program with the objective of reducing federal disaster relief resulting from floods. The Federal Emergency Management Agency (FEMA), which already had responsibility for administering disaster relief, was placed in charge of this program as well.

The National Flood Insurance Program sought to offer localities an incentive to prevent flood-prone construction. In return for requiring that any construction in a floodplain be designed to withstand a 100-year flood, the federal government would provide subsidized insurance to existing homes and a fair-market rate for any new construction (which was itself a benefit, since private insurers generally did not offer flood insurance). Moreover, as long as a community joined the program, it would continue to be eligible for federal disaster relief; if it did not join, it would no longer be eligible. As a result of this program, new coastal houses are generally elevated on pilings.

Although Congress intended to prevent coastal disasters, the National Flood Insurance Act does not require strategic assessments of long-term issues (see Riebsame, Volume J). Thus, FEMA has not conducted strategic assessments of how the program could be managed to minimize flood damage from shoreline retreat caused by both present and future rates of sea level rise.

Congress recently enacted the Upton-Jones Amendment (Public Housing Act of 1988), which commits the federal government to pay for rebuilding or relocating houses that are about to erode into the sea. Although the cost of this provision is modest today, a sea level rise could commit the federal government to purchase the houses on all barrier islands that did not choose to hold back the sea. Furthermore, this commitment could increase the number of communities that decided not to hold back the sea.

The planned implementation of actuarially sound insurance rates would ensure that as sea level rise increased property risk, insurance rates would rise to reflect the risk. This would discourage construction of vulnerable houses, unless their value was great enough to outweigh the likely damages from floods. However, statutes limiting the rate at which flood insurance rates can increase could keep rates from rising as rapidly as the risk of flooding, thereby increasing the federal subsidy.

No assessment of the impacts of sea level rise on the federal flood insurance program has been undertaken.

Sewers and Drains

Sea level rise also would have important impacts on coastal sewage and drainage systems. Wilcoxen (1986) examined the implications of the failure to consider accelerated sea level rise in the design of San Francisco's West Side (sewerage) Transport, which is a large, steel-reinforced concrete box buried under the city's ocean beach. He found that beach erosion will gradually expose the transport to the ocean, leaving the system vulnerable to undermining and eventual collapse. Protection costs for the $100 million project would likely amount to an additional $70 million. Wilcoxen concludes that had sea level rise been considered, the project probably would have been sited elsewhere.

The impacts of sea level rise on the construction grants program probably would be less in most other cases. As sea level rises, larger pumps will be necessary to transport effluents from settling ponds to the adjacent body of water. However, sea level rise would not necessarily require alternative siting. The projects serving barrier islands often are located on the mainland, and projects located on barrier islands are generally elevated well above flood levels. If barrier islands are raised in response to sea level as the nationwide analysis suggests, sewerage treatment plants will be a small part of the infrastructure that has to be modified.

Engineering assessments have concluded that it is already cost-beneficial to consider sea level rise in the construction of coastal drainage systems in urban areas. For example, the extra cost of installing the larger pipes necessary to accommodate a 1-foot rise in sea level would add less than 10% to the cost of rebuilding a drainage system in Charleston, South Carolina; however, failure to consider sea level rise would require premature rebuilding of the $4 million system (Titus et al., 1987).

RESEARCH NEEDS

A much better understanding of erosion processes is needed to (1) understand how much erosion will take place if no action is taken; and (2) help identify the most cost-effective means for protecting sandy shores. An improved understanding of how wetland accretion responds to different temperatures, higher CO_2 concentrations, changing mineral content, and the drowning of adjacent wetlands is needed. This will refine our ability to project future wetlands loss and, perhaps, devise measures for artificially enhancing their vertical growth.

This report did not examine the impacts of increased flooding because flood models have not been applied to the large numbers of coastal sites that would be necessary to conduct a nationwide assessment. Time-dependent estuarine salinity models, such as that of the Delaware River Basin Commission, should be applied to major estuaries to examine impacts on ecosystems and drinking water supplies.

Assessments of the impacts of global warming on coastal environments would be greatly improved by better estimates of future sea level rise. In addition to the improved ocean modeling that will be necessary for better projections of surface air temperatures (see Chapter 2: Climate Change), this will also require a substantial increase in the resources allocated for monitoring and modeling glacial processes. Finally, this report assumed that winds, waves, and storms remained constant; future studies will need estimates of the changes in these climatic variables.

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