

Global Atmospheric Change

A Background Paper for a Generic Environmental Impact Statement on Timber Harvesting and Forest Management in Minnesota

Prepared for:

**Minnesota Environmental Quality Board
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October 21, 1992

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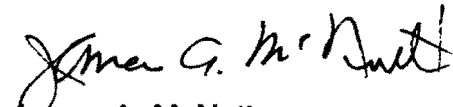
Dear Dr. Kilgore:

Pursuant to the State of Minnesota's GEIS contract (No. 30000-18408-01) with Jaakko Pöyry Consulting, Inc., as formally executed on May 15, 1991, and amended with Supplement No. 1 on July 10, 1991, and Supplement No. 2 on July 27, 1992, the sixth task included preparation of background. One of these papers, Global Atmospheric Change is hereby submitted for review and approval.

The material contained in this document is presented in accordance with the terms outlined in Attachment A to the base contract, Section III, Subsection F.

We look forward to a favorable review and approval of this work product in due course.

Respectfully yours,



James A. McNutt
Executive Vice President
and GEIS Project Manager

cc: Art Veverka
Bob Dunn
Doug Parsonson
Alan Ek

SUMMARY

Emissions of CO₂, caused mainly by fossil fuel burning, and other greenhouse gases, are likely to enhance the earth's natural greenhouse effect, causing significant warming over the next century. Global circulation models (GCMs) are computer models of the earth's atmosphere capable of simulating the earth's current climate, including seasonal changes. Several GCMs produced by independent teams of scientists agree that an increase in the mean air temperature at the earth's surface of 1.5° to 4.5° C will result if the concentration in the atmosphere of CO₂ doubles (2xCO₂ scenario). The length of time required for atmospheric CO₂ concentrations to double will depend on the rate at which people reduce the use of fossil fuels, but may occur sometime between the years 2030 and 2100. Current versions of GCMs have poor spatial resolution. However, preliminary results suggest that interior continental areas such as Minnesota may warm more than the global average. Although estimates of precipitation are still very uncertain, a majority of the five GCMs surveyed for this report predict that Minnesota will have decreased summer soil moisture under 2xCO₂ scenarios. On the other hand, a majority also predict increased winter soil moisture, which could partially compensate for drier summers.

Should significant warming occur in Minnesota, a northward shift in vegetation types such as the prairie-forest border is likely, so that the state will have less forest acreage in the future. The warm period, 7,000 years before the present (ybp), when temperatures of the current interglacial period reached their peak in the midwest, provide a reasonable analog for future warming. Summer temperatures at that time were 1 to 2° C warmer than at the present time, and the prairie-forest border was located about 100 miles to the northeast of its current location.

Several different speculative simulations of response of forests to warming agree in general with the altithermal analog. Empirical models that look at the climate at the edge of the current range of a species or vegetation type and project where the same limiting climate variables would occur under 2xCO₂ scenarios, predict significant displacements in species ranges. The predicted geographical displacements vary with the GCM used. For example, the western edge of the sugar maple range would only move a few tens of miles eastward under the GISS GCM 2xCO₂ scenario, which predicts increased rainfall in Minnesota. The increased rainfall would compensate for the warmer temperatures. However, under the GFDL 2xCO₂ scenario, the southwestern edge of the sugar maple range would move north of Lake Nipigon, Ontario. Forest stand dynamic models predict that under a 2xCO₂ scenario, spruce-aspen-birch forests in northern Minnesota will change to sugar maple forest on deep loamy soils, or pine/oak savanna on shallow and/or sandy soils. If significant warming occurs, the overall predicted

patterns are for southern Minnesota forest types to displace northern types, and southern forest types to be displaced by grassland.

Depletion of ozone in the earth's stratosphere is another factor that may exacerbate the effects of global warming. With a thinned ozone layer, more ultraviolet light than usual may impinge on forest canopies, possibly causing physiological damage to trees and reducing productivity.

Air pollution is unlikely to cause significant damage other than very locally near point sources of pollution. Although eastern Minnesota has rainfall slightly more acidic than natural rainfall, the state is outside the area with rainfall pH low enough to cause long-term significant forest damage. Levels of ozone, nitrogen oxides and sulfur dioxide are not high enough to cause widespread forest damage in Minnesota.

There are several factors that will influence the rate and magnitude of change in forests that are difficult to simulate. Theoretically, increased concentrations of CO₂ should have direct effects on plant growth, making them more efficient in water use, thereby compensating for drought stress brought on by warmer temperatures. Research on direct CO₂ effects is in early stages, and there are conflicting results among studies as to whether there will actually be a significant compensatory effect. Warmer summer weather could increase the frequency of severe wildfires and windstorms, accelerating the rate of change in forest species composition. Climatic warming will probably not proceed evenly over time, but instead will follow the natural tendency towards periods of several very warm years in a row, alternating with periods of less warm years (serial correlation). This could lead to periods with extremely severe fire weather and high heat or drought induced mortality. Other factors that could modify the response of forests to global change include changes in pest-host relationships, changes in seasonal distribution of precipitation, the currently unknown ability of individual trees to tolerate changes in climate, and the ability of trees to shift their range northward at rates much faster than those that have occurred due to natural climate change over the last 20,000 years. No one simulation of forest response to climatic change takes all of these factors into account, but there are models that take some into account individually.

Forest management activities add another unknown element to global change. The movement of vegetation now depends on both natural and human vectors. Extensive tree planting, fire control and development of drought-tolerant varieties can lead to establishment of forests outside a species' current or future natural range. In addition, the Minnesota forest products industry and public land managers could respond to global warming by altering spatial and temporal patterns of harvest. For example, stands with high heat-induced mortality could be harvested and reforested with species

adapted to a warmer climate. These activities could compensate—to an unknown degree—for the effects of global change on Minnesota forests.

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1

INTRODUCTION

The purpose of this paper is to document the extent to which research has been conducted that documents the relationship and/or interaction between global atmospheric change and Minnesota forests.

Global atmospheric change is a broad term herein defined to mean:

1. *Global warming.*—A potential increase in air temperature at the earth's surface brought about by human-caused increases in atmospheric concentrations of greenhouse gases, such as carbon dioxide.
2. *Ozone depletion.*—Thinning of the earth's stratospheric ozone layer by Chlorofluorocarbons (CFCs or freons).
3. *Air Pollution.*—Addition of gaseous chemicals such as sulfur dioxide, nitrogen oxides and hydrocarbons to the atmosphere. These chemicals can directly affect tree growth and also react in the atmosphere to form acid rain and excess ozone near the ground.

This paper will concentrate heavily on global warming, a subject with the greatest potential impact and a large number of studies in progress that is relevant to Minnesota. Research on global warming and ozone depletion is in early stages, and the predictions about potential effects are necessarily speculative. However, research on air pollution is much more advanced. A brief discussion of air pollution is included in section 4 of this paper.

2

GLOBAL WARMING

2.1

Background on Global Warming

The greenhouse effect versus global warming

The greenhouse effect is a natural phenomenon that has existed on the earth for several billion years. It was (and is) caused by atmospheric gases like water vapor, CO₂, NO_x, and methane (CH₄). These gases are transparent to incoming sunlight, which warms the earth's surface (ground, objects near the ground, and water). The warmed surface then radiates to the atmosphere infrared radiation. The greenhouse gases are not transparent to infrared radiation, which is prevented from escaping the atmosphere to outer space as rapidly as it otherwise might. Higher surface air temperatures are the result. For any given level of greenhouse gases in the atmosphere, the earth's surface air temperature will reach an equilibrium between absorbed

solar radiation and outgoing heat. Currently, the earth is 60° F warmer than it would be without a greenhouse effect (Schneider 1989). With no greenhouse effect, daytime high temperatures in Minnesota in July would not even reach the freezing point. The earth is simply not close enough to the sun to support life without a greenhouse effect.

Global warming, on the other hand, is usually intended to mean the enhancement of the greenhouse effect by human-caused increases in natural greenhouse gases (CO₂, CH₄, NO_x), plus CFCs, which are artificial chemicals.

Likelihood of global warming

There are several facts about the greenhouse effect that are well-supported by data, and about which there is no controversy in the scientific literature:

1. There currently is, and has been for several billion years, a very significant greenhouse effect on the earth.
2. This greenhouse effect is caused by atmospheric gases, including CO₂ and methane.
3. The concentration of CO₂ in the atmosphere, as reconstructed from air bubbles trapped in the antarctic ice sheet, has been highly correlated with temperature over the last 160,000 years (Fifield 1988).
4. The concentration of CO₂ and methane has been increasing in recent years. CO₂ concentrations have risen 25% in the last 100 years—from 270 ppm in 1850 to 350 ppm in 1987. Methane concentrations have nearly doubled in the last 100 years—from 900 ppb in 1880 to 1700 ppb today (Graedel and Crutzen 1989).
5. Recent increases in CO₂ and methane have been caused largely by human activities. CO₂ concentrations are expected to reach 400 to 550 ppm by the year 2030, the exact concentration depending on the degree of reduction of fossil fuel use (Graedel and Crutzen 1989).

Although global warming is not an established fact at this time, the facts listed above make it seem likely that global warming due to pollution of the atmosphere will occur in the future. This likelihood will remain unless some other event occurs, such as a reduction in the sun's output of energy, or a series of volcanic eruptions that throw dust into the atmosphere that will filter out sunlight. What is most controversial at the current time is (1) how much warmer the air temperatures at the earth's surface will get, and (2) when global warming will be noticeable against the background of natural variability in temperatures. There is considerable uncertainty as to the magnitude of warming likely to occur, the regional distribution of

temperature change around the earth, and the effects of a possible lag time between increase of greenhouse gases in the atmosphere and onset of warming. There is also large uncertainty in predictions of rates of accumulation of greenhouse gases in the atmosphere. Accumulation will depend on the degree to which fossil fuel use is increased or curtailed, the amount of deforestation, planting of trees, and absorption of greenhouse gases by the oceans.

2.2

Prediction of Climate—Global Circulation Models

General circulation models (GCMs) simulate the dynamics of the earth's atmosphere, including possible responses to changes in greenhouse gases. The GCMs divide the earth into grid squares, generally every 4 or 5 degrees of latitude and longitude. GCM-simulated climate at each grid square will depend on the balance between amount of solar radiation received, and amount reflected, the remainder being converted to heat that will warm the atmosphere. Once differences in air temperature and pressure among adjacent grid cells develop, transfer of heat among cells will lead to simulation of the earth's atmospheric circulation system. Interactions among layers in the atmosphere and among the atmosphere and the oceans and land surfaces occur. All of these interactions can be described by equations based on laws of physics related to conservation of energy, mass and momentum.

There are five major GCMs developed by various research groups, and each uses different assumptions and different equations describing the transfer of heat among grid cells, vertical layers of the atmosphere, the oceans and land surfaces. All five have published simulations (table 2.1), usually for scenarios with double the current concentration of CO₂—referred to as 2xCO₂ scenarios—and all are continuing to refine their models.

Table 2.1. GCMs cited in this report.

| GCM | Acronym | Reference |
|---|---------|-----------------------------|
| National Center for Atmospheric Research (Boulder CO) | NCAR | Washington and Meehl (1989) |
| Oregon State University | OSU | Schlesinger and Zhao (1987) |
| NASA Goddard Institute For Space Studies (New York, NY) | GISS | Hansen et al. (1983) |
| Geophysical Fluid Dynamics Laboratory (Princeton, NJ) | GFDL | Manabe and Wetherald (1987) |
| United Kingdom Meteorological Office | UKMO | Mitchell and Lupton (1984) |

The GCMs predict a worldwide average temperature increase of 1.5 to 4.5°C for scenarios where atmospheric CO₂ is doubled relative to a standard concentration, such as the concentration in the late 1800s before major expansion of the industrial revolution occurred around the world. In general, the GCMs predict that interior continental areas, such as Minnesota, will warm substantially more than coastal areas, but the regional predictions may not be very accurate at this time. Kellogg and Zhao (1988) analyzed output for 2xCO₂ scenarios from all five GCMs, and produced maps outlining regions with increased or decreased soil moisture for both winter and summer in North America. Four of the five models predict increased winter soil moisture for Minnesota, while the fifth (UKMO) predicts decreased winter soil moisture in western Minnesota, but an increase in northeastern Minnesota. Three of the five GCMs predict decreased summer soil moisture in Minnesota, one (NCAR) predicts a decrease only in western Minnesota, and one (GISS) predicts increased summer soil moisture in Minnesota (figure 2.1).

Assessing Accuracy of the GCM Predictions

The GCMs have been tested by examining their ability to predict temperature changes worldwide for the current climate. The models are capable of producing a reasonable prediction of temperatures as the seasons change over the year in response to changing input of solar radiation (Schlesinger and Mitchell 1987). However, this does not provide a good test of the GCM's ability to simulate changes over several decades, that may be driven by variables other than solar input. The 0.5°C increase in mean world temperature over the last century provides a good test of this, since it coincides with a rise in CO₂ concentration of 25 percent. In this context, most GCMs predict a full 1°C rise in temperature, twice the actual (Schneider 1989). The discrepancy could be due to inaccurate measurement of the global temperature rise, to other atmospheric changes such as an increase in dust, to a time lag in warming caused by the large heat absorption capacity of the oceans, or poor performance by the GCMs. It is not known which of these is the cause of the difference between observed temperature and predicted temperature. However, most climate modelers only claim that their models are accurate within a factor of 2 (Schneider 1989).

Limitations of the GCM Predictions

Four major limitations common to all GCMs are:

1. Coarse spatial resolution, which makes it difficult to predict changes in climate for specific regions of the earth. For example, the resolution is too coarse to model the influence of the Great Lakes on the climate of the Upper Midwest.

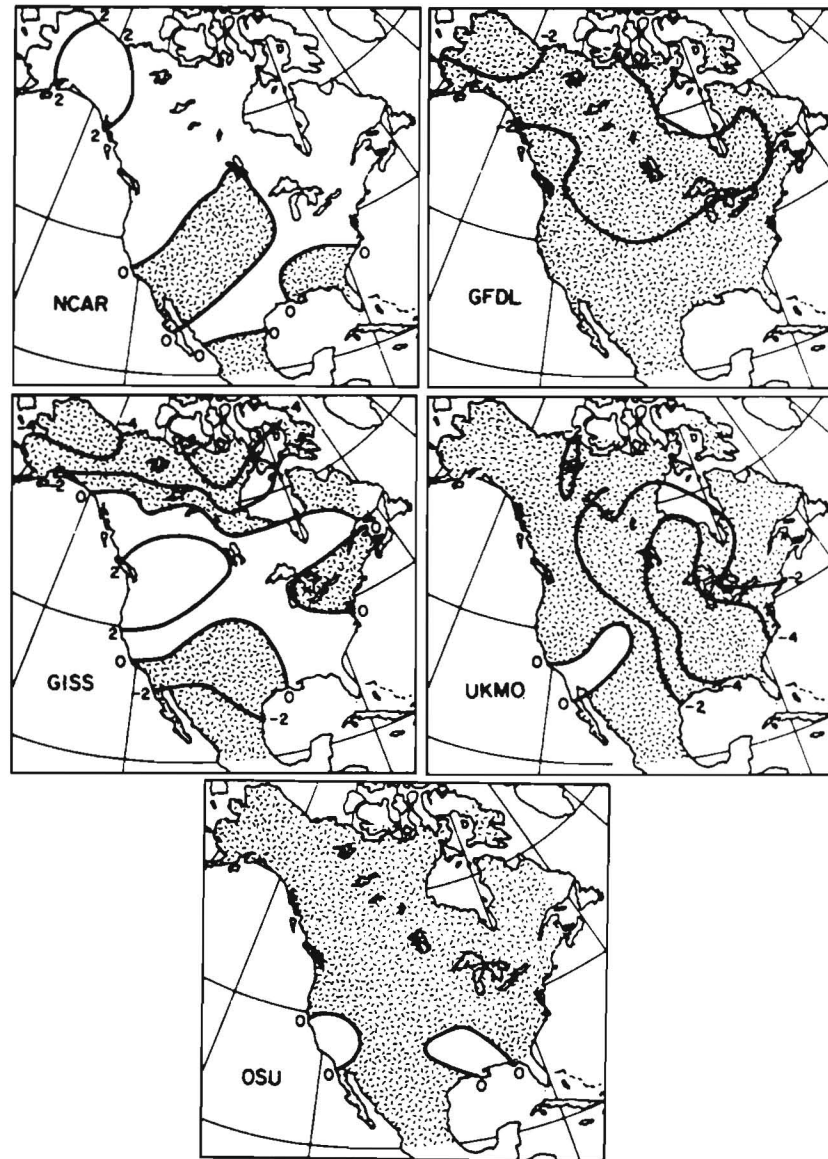


Figure 2.1. July soil moisture change for a CO₂ doubling minus control simulations for five different general-circulation models (in centimeters of soil moisture). Stippled regions show soil moisture decreases. (Source: Kellogg, W. W., and Z-C. Zhao. 1988. Sensitivity of soil moisture to doubling of carbon dioxide in climate model experiments. Part I: North America. *J. of Climate* 1(4):348-66.)

2. There will be more cloud cover under a warmer climate and there is disagreement as to the effects that increased cloud cover will have on the earth's energy balance. Clouds may act to reinforce global warming, by insulating and holding in heat, or to reduce global warming, by reflecting more sunlight away from the earth. At this time it is not clear which of these functions of clouds will predominate under a warmer climate.

3. Predicting precipitation, is always more difficult than predicting temperature, even in daily weather forecasts. There is much more disagreement among GCMs as to predictions of patterns of precipitation during a $2\times\text{CO}_2$ scenario, than there is for temperature. Because higher precipitation can partially negate the effects of global warming, it will be important to resolve this issue.
4. The details of the ocean's role in absorbing and transferring heat, and storing carbon, is currently unknown. Each of the GCMs makes different assumptions about the effects of the oceans on climate.

All four of the major limitations just discussed are being actively pursued by the scientists working on the GCMs. Part of the problem has been that computers are not powerful to run the GCMs at a finer level of resolution. In addition, more data are also required to improve the predictive ability of the models. However, with the advent of more powerful computers and large data sets from satellite monitoring of clouds, major improvements in climate prediction are expected during the next several years.

2.3

Global Warming and Vegetation Change

This section looks at the general implication of global warming on forests—a northward shift of the ranges of tree species—and provides background for the specific models and predictions in the next section. Several effects that either may compensate for, or reinforce, the effects of warming are discussed. However, given the current level of knowledge about relationships between atmospheric conditions, climate, and plant and ecosystem responses, predictions about the effects of warming must be recognized as highly speculative.

Effect of Warmer Summers

With warmer summers, there may be more evaporation, more cloud formation, and more precipitation. However, the higher level of evaporation may more than equal the increase in precipitation, leaving the soil drier unless there is a really large increase in summer rainfall. Three of the five GCMs suggest this will be the case. The qualitative response of the vegetation to drier growing seasons will be a northeastward shift in vegetation types, including the prairie-forest border.

2.3.1

Hypothetical Compensating Effects

Fire suppression.—The location of various vegetation types in presettlement Minnesota was determined not only by summer temperature and soil dryness, but by fire frequency. Fires kept the prairie-forest border

further to the northeast than would be predicted from climatic requirements of the tree species alone. With fire suppression, woodlots with maple-basswood forest now occur in southwestern Minnesota, an area 1 to 2°C warmer than the bigwoods region in summer, and an area formerly occupied by prairie. Also, summer temperatures within the Twin Cities metro area are 2°C warmer in summer than the surrounding rural areas (Winkler et al. 1981). This urban heat island has developed over the past 100 years, yet remnant sugar maple, basswood and bur oak trees in Minneapolis city parks continue to grow and reproduce. Thus, as long as fire suppression is effective there is probably 2°C leeway in warming before great shifts in the ranges of some species will take place. Extrapolation of effects of the urban heat island should be used with caution, however, because other species and northern genotypes of sugar maple, basswood and bur oak may not respond the same way.

Use of drought-resistant tree varieties.—Foresters could respond to warmer summers by breeding new varieties of trees or bringing in varieties from regions currently experiencing a climate similar to that predicted for the future in Minnesota. For example, Black Hills spruce is a natural ecotype of white spruce found in relatively dry southwestern South Dakota. It is already planted in the Twin Cities metro area urban heat island, where it grows much better than the Minnesota native white spruce. Black maple, a close relative of sugar maple found in central Iowa is another possible choice for future Minnesota forests. Similarly, red oak from southern Minnesota would make a good reforestation choice for northern Minnesota if summer climates warm significantly during the coming century.

Winter precipitation.—Four of the five GCMs predict more dormant season precipitation and soil moisture in Minnesota under 2xCO₂ scenarios than is currently occurring. The ground may not be frozen as long as it currently is, due to warmer fall and spring temperatures and possibly heavier snowfall that insulates the ground during cold spells. This would allow precipitation to soak in and recharge subsoil moisture during the winter and may compensate for a series of drier summers. With more winter recharge of subsoil moisture, trees would be able to draw on the stored water during summer droughts when the surface of the soil is dry, effectively making the vegetation more mesic than summer climate alone would indicate. This is exactly what currently takes place in the Pacific Northwest, which has very dry summers.

Longer growing season.—Global warming would increase the number of warm spring and fall days therefore increasing the growing season. Even if mid summers become too hot for growth, there may be more growth during the early and late parts of the growing season, when evaporation rates are relatively low.

Direct CO₂ effects (CO₂ fertilization).—Elevated concentrations of CO₂ cause faster growth of seedlings of most tree species in the greenhouse (Kramer and Sionit 1987). Relatively high CO₂ concentrations may also make seedlings more drought resistant (Tolley and Strain 1984, Norby et al. 1986). However, no studies have been done that look at CO₂ effects over a long time on mature trees in a natural setting. Thus, it is uncertain whether the enhancement of growth by high levels of CO₂ will compensate for the drought effects of global warming.

If enhanced concentrations of CO₂ increase water use efficiency of plants during times of heat and drought stress, then other factors such as nutrient supply or growing space may become limiting (Brown and Higginbotham 1986). Moreover, there is some evidence that some species respond to long-term enhancement of CO₂ by changing morphology of leaves in such a way that increased productivity is not necessarily maintained over time (Farrar and Williams 1991).

The really important question is whether or not primary productivity of a forest site will be increased in the field over the long term by enhanced CO₂ concentrations. Any factor in a dry place like the prairie-forest border in Minnesota that effectively makes a site more mesic, will usually increase primary productivity. These factors include more available water and cooler temperatures. If enhanced CO₂ makes trees more efficient in water use, then species adapted to more mesic (wet) sites may be able to establish on more xeric (dry) sites. However, there will also be more evaporation with higher temperatures, and the magnitude of this loss could overwhelm the CO₂ effect, if it occurs. There is insufficient information with which to judge the degree to which direct CO₂ effects may compensate for the effects of global warming.

2.3.2

Hypothetical Reinforcing Effect

Increase in disturbance frequency.—An increase in surface air temperature is expected to be accompanied by a colder upper atmosphere. This would lead to a large temperature difference with elevation and produce more severe convective storms. An increase in severe storm frequency leads to a proportional decline in the number of large trees on the landscape and the proportion of the landscape occupied by old-growth forests (Frelich and Lorimer 1991). More frequent opening up of large gaps by heavy windstorms would also give invading warm-climate species more opportunities to replace the current species, accelerating the rate of change in vegetation patterns.

With warmer temperatures, evaporation may increase more than rainfall, leading to more severe fire weather. Because the edge of the prairie-

forest border goes through Minnesota, and the precipitation to evaporation ratio is barely positive in much of the state's forests, small changes in water balance can lead to major changes in fire frequency (Clark 1988). For example, Clark's data show that Itasca had a fire cycle of 44 years between fires during the relatively warm fifteenth and sixteenth centuries, which extended to 88 years during the cool, moist *little ice age* from 1640 to 1880 (Clark 1988). Flannigan and Van Wagner (1991) analyzed potential fire weather for 2xCO₂ scenarios for the GFDL, GISS and OSU GCMs at six stations in Canada. They calculated seasonal severity rating which is an index of the average severity of fire weather during the April to October fire season. The index depends on daily temperature, humidity, precipitation and windspeed. The average seasonal severity rating for all six stations and all three GCMs is about 46 percent greater than under current weather conditions. The predicted seasonal severity index for Sioux Lookout, Ontario—the station closest to Minnesota, increased 72 percent. The increase in annual area burned would be similar to the increase in seasonal severity rating (Flannigan and Van Wagner 1991).

An increase in fire frequency can lead to rapid response of vegetation to climate change. If Minnesota would experience two or three consecutive summers like the summer of 1988—an event which is more and more likely to occur as global warming proceeds—large uncontrollable fires like those in Yellowstone National Park in 1988 could speed the conversion of large areas of forest to new vegetation types more adapted to a warmer climate. As fire frequency increases, there is a tendency on sandy soils to switch from a disturbance regime with infrequent intense fire to frequent less intense fire, because there is less fuel buildup between fires. This type of switch in disturbance regime would lead to establishment of more savanna type (more open) vegetation. Depending on the warmth of the growing season at a given location either jack and red pine or pin and bur oak would become established.

2.4

Models of Vegetation Response to Global Warming

2.4.1

Major Types of Models

Two major types of models that simulate vegetation response to climate change have been developed. *Stand dynamic models* simulate changes in species composition on individual plots over time. They typically do this by comparing changes in the proportion of total biomass made up by each species. These models have simple functional relationships between tree

growth rates and summer temperature (*growing degree days*¹), moisture (number of days of drought), and amount of light (depending on latitude and shading by larger trees). The Linkages model (Pastor and Post 1985) also has a feedback loop where nitrogen availability is a function of litter quality of trees on the plot. Each species of tree has an optimum growth rate under conditions of optimum light, water, temperature, and nitrogen supply.

To predict the actual growth of a tree, the optimal growth is reduced by some proportion to reflect the most limiting factor. For example, the relationship between growth rate and growing degree days is parabolic, so that a given species grows at the optimal rate in the middle of the range, but growth falls to zero as either the northern or southern edge of the range is approached, if all other factors are equal. As the edge of the range is approached, growing degree days will eventually limit growth more than water or other factors.

Mortality in stand dynamic models is a function of both age, and low growth rate, which may be caused by lack of water, low nitrogen levels, high or low temperatures, or shading by other trees. New trees are recruited into a simulated plot by selecting new seedlings at random from a list of species which are capable of growing on the forest floor, under the climate conditions being simulated, and density of shade and water availability on the forest floor.

In general, climate change is simulated by growing plots (usually < 1 acre in size) under the current climate for several hundred years, then gradually changing, over a century or so, the current temperature and rainfall to that predicted by a GCM for 2xCO₂. The simulation is usually then run for several centuries to give the forest time to fully adjust to the new climate. As the warming climate is simulated, changes in species composition will occur as the number of growing degree days, availability of water, and perhaps availability of nitrogen shift away from the optimum for some species and towards the optimum for others.

The second type of simulation, *empirical models*, are based on observations of the distribution or range limits of tree species and climate variables such as temperature and rainfall. Projected changes to species distributions are made by finding the combinations of temperature and rainfall that appear to limit the range of a species now, and where these same combinations would occur in the future, as determined by output from one of the GCMs. The output from this type of model is a comparison of the current and the predicted future range for a species or group of species. This comparative

¹Growing degree days for a given location is the cumulative sum of daily mean temperature -50°F, for all days during the growing season.

information is not provided by stand dynamic models. On the other hand, empirical models are not able to examine successional sequences, or transient responses, at one location. Also, a major simplifying assumption is made that species range is determined by temperature and/or rainfall. In some cases, disturbance can greatly influence a species' range. For example, frequent burning of oak savanna in presettlement times in Minnesota prevented maple-basswood forest from expanding toward the southwest. In effect, maple-basswood forest was not able to occupy all of its potential range as determined by climate alone.

Some empirical models are based on the relationship between current climate and pollen distribution, which is a proxy for vegetation types or species ranges. These models are unique because they can be used to look into the past as well as to model the future. Fossil pollen preserved in lakes and bogs is used to identify responses of the vegetation to past climates. These responses are then linked to predicted climate changes generated using GCMs. Thus, it is possible to compare rates of vegetation change in the past with future projected rates of change.

2.4.2 Capabilities of Models

Seven specific vegetation response models give predictions relevant to Minnesota. Several aspects of their capabilities and assumptions can critically affect interpretation of their results, and these are discussed point by point here. Table 2.2 summarizes the properties of each model with respect to these points.

- *GCMs Used.* Assumptions for feedbacks between air temperature and clouds and the oceans vary among GCMs. As a result, different temperature and rainfall combinations are predicted for the middle portion of North America (see section 2.2).
- *Direct CO₂ Effects.* Only one of the models (Solomon 1988) attempts to simulate direct effects of CO₂, higher concentrations of which may make trees more tolerant of higher temperatures and drought (see section 2.3).
- *Transient Response.* These responses are beyond the scope of empirical models, which present a before and after global warming look at species distribution. The stand dynamic models generally employ smooth linear changes in climate, which may not be the actual situation. See the following discussions of disturbance and serial correlation.

Table 2.2. Capabilities of the major simulations of vegetation response to global warming.

| Model Capabilities* | Stand Dynamic Models | | | | | Empirical Models | |
|--|-------------------------------------|--|--|-------------------------------------|-------------------------------------|----------------------------------|--|
| | Overpeck et al. 1990 | Pastor and Post 1988 | Cohen and Pastor 1991 | Solomon 1988 | Botkin and Nisbet 1992 | Overpeck et al. 1991 | Davis and Zabinski 1992 |
| Model/data used | FORENA | LINKAGES | LINKAGES | FORENA | JABOWA | Pollen-climate response surface | Temperature and rainfall at range limits |
| Type of prediction | Biomass changes on individual plots | Biomass changes on individual plots | Biomass changes on individual plots | Biomass changes on individual plots | Biomass changes on individual plots | Range shift for group of species | Range shift for individual species |
| GCMs used | GISS | UKMO | UKMO | UKMO | GISS | GISS, GFDL, OSU | GISS, GFDL |
| Direct CO ₂ effects | No | No | No | Yes | No | No | No |
| Transient response | Yes | Yes | Yes | Yes | Yes | No | No |
| Competition | Mechanistic -light and water | Mechanistic -light, water and nitrogen | Mechanistic -light, water and nitrogen | Mechanistic -light and water | Mechanistic -light and water | No | No |
| Disturbance | Yes/No | No | No | No | No | No | No |
| Soil differences at each site | No | Yes | Yes | No | No | NA | NA |
| Serial correlation | No | No | Yes | No | No | No | No |
| Sensitivity of model to factors affecting range limits | No | No | No | No | Yes | No | No |

*None of the models incorporates dispersal limitations, ecotypic differentiation, photoperiod response, initial conditions of the current forest, or forest management.

- **Competition.** Simulation of competition is beyond the scope of empirical models. Stand dynamic models have mechanistic competition, in which trees on a plot may shade each other, or use water or nitrogen more efficiently than other trees or species.
- **Disturbance.** Disturbance may speed the response of forests to global warming by causing high mortality that allows new species to enter the forest more quickly (see section 2.3). Modeling of disturbance effects is beyond the scope of empirical models. One of the stand dynamic models (Overpeck et al. 1990) looks at how fires may speed up the rate of conversion from current vegetation to future global

warming-adapted vegetation. The other three assume that replacement will occur tree-by-tree as the climate warms.

- *Herbivory.* None of the models currently considers the impact of browsing tree seedlings by large mammals such as deer, or changes in abundance of leaf-eating insect pests that may occur if the climate warms. Changes in herbivory could result in high mortality of species which are currently favored. For example, red pine and oaks in southern Minnesota both had high mortality after the 1988 drought, and insects were the major cause (Sucoff, pers. comm.).
- *Soil Differences.* The frequency of droughts is exacerbated on sandy soils and minimized on clayey soils. Therefore, differences in productivity of forest stands between sandy and clayey soils will become greater if the climate becomes drier. The empirical models have not attempted to look at this question. All of the stand dynamic models make use of soil parameters as they occur at simulated sites, however only two of the stand dynamic models (Pastor and Post 1988, Cohen and Pastor 1991) examine potential differences between soils at one location.
- *Serial Correlation in Climatic Variables.* One of the models (Cohen and Pastor 1991) looks at the potential effect of extreme events on the transient response of future composition of the forest. It is possible that as the climate warms, 2 or 3 summers like the summer of 1988 will occur in a row. Such an event could cause high mortality throughout Minnesota forests, resulting in a more rapid transition to other forest types than would occur when randomly correlated temperatures occur. Serial correlation is not applicable to the empirical models.
- *Dispersal Limitations.* All of the models assume no limitation in dispersal for any tree species. In other words, they assume seeds of the appropriate species will be available at all locations as they become available for colonization during the period of warming. This may not be reasonable for species with large seeds, which would have great difficulty moving to new areas of suitable habitat over short time periods and/or in a fragmented landscape. Planting and seeding by people could compensate for lack of natural dispersal into areas with a newly suitable climate for some species.
- *Ecotypic Differentiation.* None of the models considers the possibility that ecotypes within each species may be adapted to specific climates. If there are northern and southern ecotypes within a species, the northern ecotype during global warming may find itself in a climate similar to that of the southern ecotype today. Thus, if

the northern ecotype is not moved north during global warming, and the southern ecotype moved into the former range of the northern ecotype, this species could be drastically reduced in productivity or go extinct. On the other hand, if there are no ecotypes, and individual trees have a high degree of plasticity in response to climatic change, then trees living in the zone of overlap between the current range and future range will be able to survive. The threat to forest productivity and biodiversity would no be so great.

- ***Factors Affecting Range Limits.*** The stand dynamics models assume that northern and southern range limits of species coincide with minimum and maximum growing degree days that a species can tolerate, and the empirical models assume that tree range is related to January and July mean temperatures. All models assume that the western range limit of a given species coincides with the maximum drought (warmest and/or driest summers) a species can tolerate. There is a potential problem with these assumptions. Factors such as competition and disturbance may cause the actual range of a species to be inside of its potential range as determined by climatic variables. One of the models (Botkin and Nisbet 1992) looks at the effects of different limits to maximum and minimum growing degree days for several species in Minnesota.
- ***Photoperiod Response.*** None of the models take into account possible effects on tree growth of the change in day length at different latitudes. Tree species may not be hardy as they move north, because cold resistance involves adaptation to photoperiod. It is not certain that tree species will be able to adapt within a century to the longer summer day lengths that occur north of their current range.
- ***Comprehensive Initial Conditions.*** None of the stand dynamics models use realistic initial conditions, such as the 14,256 Minnesota FIA plots at the start. The models probably do a good job of simulating what will happen given the initial conditions specified (described in section 2.4.3 below for each model), which were chosen for illustrative purposes. However, the models do not allow assessment of the changes in the Minnesota landscape as a whole. A simulation incorporating the initial conditions for a large region like Minnesota is currently beyond the scope and capability of models like Forena, Linkages or Jabowa.
- ***Forest Management.*** None of the models incorporate the effects of harvesting, site preparation, seeding, planting, and competition control, which silvicultural research indicates can have major impacts on a species' success. These models also do not estimate the

potential impact of development of drought-resistant varieties of trees for future planting. It should be noted however, that simulation of forest management was beyond the objectives of the studies cited.

2.4.3

Predictions of the Models Relevant to Minnesota

Stand Dynamic Models

1. *Forena—Overpeck et al. (1990).*

This model was run using two forest types that are analagous to Minnesota forest types: *fir-spruce-birch* forests in Quebec which are similar to forests in northeastern Minnesota; and *pine-maple-oak* forests in northern Wisconsin which are similar to forests in central Minnesota. These types were simulated under the present climate for 800 years, followed by a 100 year transition period to a $2\times\text{CO}_2$ climate and an additional 500 years to allow full adjustment of the forest to the new climate. At the time of the climate change, catastrophic fires were added to the simulation with an annual probability of 1 percent for a given plot, which is equivalent to a 100-year rotation period. A second set of plots was run as a control without this disturbance factor.

The simulations predict that with disturbances, there will be a much shorter lag time for adjustment of vegetation to climate change than without. Instead of waiting for individual trees to die and be replaced by different species adapted to the new climate, disturbances can cause change to occur on a given plot immediately. In the simulation, it takes at least 200 to 250 years for vegetation to achieve equilibrium with the new climate without disturbance, but less than 180 years with disturbance.

The other two stand dynamic models—Pastor and Post (1988) and Solomon (1988)—do not include disturbance as a component. Thus, transitions to future vegetation types modeled by them are probably slower than may actually occur with global warming. An increase in both severe windstorms and fires is likely to occur with global warming, although fire suppression will likely compensate for much of the potential increase in fire frequency.

Overpeck et al. (1990) do not simulate a number of different disturbance regimes, or the possibility that a few unusually hot summers could kill large areas of forest, leading to explosive conditions and burning of large areas within a few years. They simply tested a 100-year fire frequency as an example. The magnitude of increase in fire and windstorm frequency that global warming may cause is not known at the current time. Thus, one cannot predict how much more short rotation forest types, such as jack pine, will occur in the future due to increasing disturbance frequency.

2. Linkages—Pastor and Post (1988).

A number of sites in the northern hardwood-boreal transition zone of eastern North America were simulated, including northeastern Minnesota. Vegetation for each site was simulated for sand and silty-clay loam soils. The model was run for 200 years at each site under the current climate and then changed linearly over a 100-year period to a 2xCO₂ scenario, then run for 200 more years with the new climate.

The simulation shows major differences in response to global warming between a sand and a silty clay loam soil. Predicted biomass in northeastern Minnesota on sand is about 70 percent of the biomass found on silty clay loam under the current climate, because rainfall is sufficient to ameliorate the effects of sandy soils. Under the 2xCO₂ scenario simulated biomass increases 55 percent on silty-clay loam, but decreases 73 percent on sand. The good water retaining capacity of silty-clay loam, combined with a longer growing season, allows more growth, whereas the vegetation on the sandy soil becomes more sparse due to increased evaporation and droughtiness. Under the current climate, the biomass of one acre of forest on sand is simulated to be about 70 percent of that on silty-clay loam, whereas under the 2xCO₂ scenario, the forest biomass on sand would be only 13 percent of that on silty-clay loam.

A major change in species composition is also predicted. The current *birch, spruce and maple* on silty clay loam changes to northern hardwoods—*maple, basswood and birch* under the 2xCO₂ scenario. The forest on sand is predicted to change from *birch, spruce, maple and pine* to *oak, pine and spruce*. Overall, the model predicts that on good soils, northern Minnesota will have more northern hardwood forest. On poor sandy soils, the model predicts that production will go down, under a moderate global warming scenario. No simulation of sandy soils with a hardpan that holds water, which is a common condition in Minnesota, was attempted. Therefore, the predictions for poor sandy soils may overstate changes.

3. Linkages—Cohen and Pastor (1991).

This model is very similar to the one by Pastor and Post (1988), except that serial correlation of temperature—for example, allowing a series of warmer than normal summers to occur—was included. The serial correlations were based on observed temperatures since 1941 in the Lake Superior northern hardwood-boreal forest transition zone.

Generally, the results were similar to Pastor and Post (1988). However, there were two differences in detail. The predicted differences in response between sand and silty-clay loam were exacerbated. This was because on sandy sites, a series of warm years in a row caused higher mortality—resulting in more xeric vegetation becoming established. The transition from boreal conifer-hardwood to northern hardwoods was predicted to occur more

quickly due to episodes of high mortality of spruce caused by series of warm-dry, stressful summers.

4. Forena—Solomon (1988).

This model is very similar to the one used by Overpeck et al. (1990, see above), except that direct effects of CO₂ were simulated by altering tree growth rates in response to drought as indicated by growth chamber experiments with enhanced CO₂ concentrations. Growth of deciduous species was increased by 20 percent and conifers by 11 percent to account for a fertilizer effect during a 2xCO₂ scenario. Response (in terms of biomass production) of coniferous trees to moisture stress was unchanged and deciduous tree response was reduced by 18 percent during a 2xCO₂ scenario. Runs of the model were done for the CO₂ effect doubled and tripled, as well as no direct CO₂ effect. At this point, relatively little is known about response of trees to direct CO₂ effects, and Solomon intended these model runs to show to compare what may happen with various levels of CO₂ effects, not as predictions.

The simulations were run for three sites in central Ontario (boreal forest), northern Michigan (mixed conifer-deciduous forest), and Tennessee (deciduous forest). Runs were done for 400 years under the current climate, then changed to the 2xCO₂ scenario from year 400 to year 500. From year 500 to 700, CO₂ was doubled again, and the model was run 300 more years to allow equilibrium with the 4xCO₂ climate scenario to develop.

Total tree biomass from the simulations indicated that CO₂ effects delay and reduce the amount of dieback that occurs when the climate is warmed. CO₂ fertilization effects increase the total amount of biomass ultimately attained by forests at both the boreal forest and conifer-deciduous sites, although biomass increases somewhat with no CO₂ fertilization effect. At the deciduous forest site, biomass increased temporarily and then decreased for all levels of CO₂ effect. The decrease in biomass was large enough so that only with tripled CO₂ effects was the final biomass as high as simulated under the current climate.

5. Jabowa-Botkin and Nisbet (1992).

The study looked at species composition of forests near Virginia, Minnesota, over a 90-year period (1980 to 2070), during which the climate gradually changed from the current (1951 to 1980) climate to the GISS transient-A 2xCO₂ climate. During the simulation, the forest converted from balsam fir to sugar maple. Balsam fir declines steeply after 1990 and disappears completely by the year 2060. Sugar maple basal area rises steeply after the year 2000 and continues to rise at the end of the scenario.

This study examines the effect of possible errors in input data on output from forest growth models. Only maximum and minimum number of growing

degree days assumed in the model to limit the range of trees was found to have a significant effect, when + and -10 percent analyses were done. For example, if the maximum number of growing degree days that balsam fir can tolerate is increased 10 percent, the simulated decline is not as steep when the climate warms, and if maximum tolerable growing degree days are actually 10 percent less than currently believed the decline is more steep, with virtually no balsam fir left by the year 2010. For sugar maple, which is currently near the northern edge of the range at Virginia, Minnesota, decreasing the assumed minimum number of growing degree days necessary for growth by 10 percent allows the species to increase more rapidly during the warming scenario, while increasing the same variable by 10 percent has the opposite effect. However, the climate change predicted by the GISS scenario is so large, the overall prediction of replacement of balsam fir by sugar maple occurs by 2070, regardless of the input number of growing degree days within a reasonable limit.

Empirical Models

6. *Fossil pollen-based predictions—Overpeck et al. (1991).*

Abundance of a given taxa on the landscape is directly related to the abundance of that taxa's pollen deposition in the region, so that pollen deposition is a proxy for presence of a species. In this study, seven pollen types were considered: sedge, spruce, birch, northern pines (jack, white and red), oak, southern pines, and prairie forbs. A response surface was developed that relates abundance of pollen from each taxa to three climate variables: mean July temperature, mean January temperature, and mean annual rainfall. The future abundance of pollen, as proxies for vegetation type, were then projected using mean values for July temperature, January temperature and rainfall that are predicted by the 2xCO₂ scenarios from the GISS, GFDL, and OSU GCMs.

The projections indicate that spruce would no longer grow in Minnesota, except that the extreme southern edge of spruce range would include the extreme northeastern tip of Minnesota under the GISS scenario. Birch and the northern pines would continue to grow in northern Minnesota, but the region of maximum abundance currently in Minnesota would shift into Ontario. Under all three GCMs, the region with abundant oak (currently in southeastern Minnesota) would shift at least as far north as Duluth. Southern pines would grow in southeastern Minnesota under the GFDL scenario, but would only reach southern Wisconsin under the other two. The region of maximum abundance for southern pines would stay south of the Ohio River. Finally, all three scenarios project the area of medium to high abundance of prairie forbs to shift eastward by from 100 to several hundred miles.

7. *Range Change Model—Davis and Zabinski (1992).*

The modern ranges of four tree species—hemlock, beech, yellow birch, and sugar maple—were characterized in relation to July and January mean

temperatures, and annual rainfall at the margins of their respective ranges. Using GFDL and GISS 2xCO₂ scenarios, the future range was projected by assuming that the same temperature and rainfall combinations along the edge of each species current range will also define each species future range under global warming.

Dramatic range shifts to the northeast are projected for all four species. Sugar maple and yellow birch are the two species of interest in Minnesota. Under the GISS scenario, the southwestern range limit for yellow birch would shift from the Twin Cities to half way between the Twin Cities and Duluth. The western range limit for sugar maple would shift eastward to about the Wisconsin border. Under the GFDL scenario, the southern range limit of both species would shift out of Minnesota, nearly all the way to Hudson's Bay.

Range shifts of this magnitude would require rates of species migration at least 10 times faster than occurred during the retreat of the glaciers from eastern North America between 18,000 years before present and the current time (Davis 1989b). Also, migration of many species may not be as efficient as in the past because of obstacles like cities, open agricultural fields, and because many population outliers on the northern edge of the range have been extirpated by human activities.

Moving Target Problem

Many GCMs provide predictions for 2xCO₂ or 4xCO₂. As a result, the vegetation response models usually show forests changing for a century or two, then reaching a new steady state after the climate change. However, there is no reason to believe that the climate will stop changing once a 2xCO₂ scenario is reached. Human activities may lead to a continuously changing concentration—both up and down—of greenhouse gases in the atmosphere. This could cause climate change so fast that tree species newly established in an area that is outside of their current range would find the climate unsuitable by the time the trees are mature. Such a scenario would lead to continuous species-composition change and high mortality. These changes would have significant implications for natural processes as well as for human uses of forests. Such rates of change would be difficult for forest managers to deal with. These changes would likely accelerate change in the forest products industry, stimulating the development of technologies for using wood fiber produced over short rotations. Rose et al. (1987) point out that while industry can and has moved quickly to adjust geographically and technologically to supply, governments, because of their jurisdiction limits, would encounter considerably more difficulty.

2.4.4

Past Climate Change as an Analog For Global Warming

The period from 9,000 ybp to 4,000 ybp, is thought to have been substantially warmer in summer than at the current time. This period in the middle of the Holocene has been the warmest period of the current interglacial, and is often called the altithermal period. Scientists working on the Climates of Holocene Mapping Project (COHMAP) used GCM to predict the paleo climate, given the distribution of sunlight and CO₂ concentration 6,000 ybp. The results indicate that, during the middle of the Holocene, summers in the Midwest were 2°C warmer than at present. Bartlein et al. (1984), based on pollen-climate response predicted 1 to 2°C increases in summer temperatures in Minnesota during the altithermal, with the greatest warming experienced in the northern part of the state. Thus, the mid-Holocene may provide an analog for future global warming. Reconstructions of the vegetation of 6,000 ybp may be one key to the future.

This analog has limitations, because there are differences in patterns of solar radiation; and in the CO₂ concentration in the atmosphere when comparing conditions during the mid-Holocene with the present conditions, or those predicted to occur in the next century. The summer growing season at the latitude of Minnesota had approximately 8 percent more solar radiation 7,000 ybp than it currently does, due to changes in the earth's orbit and its position relative to the sun (Kutzbach and Otto-Bliesner 1982).

Analysis of fossil pollen deposited during the Holocene in the midwest is summarized by Webb et al. (1983). Their maps show that the prairie peninsula developed by 8,000 ybp. The prairie peninsula is a triangular-shaped area of relatively warm and dry summer climate, more favorable to grasslands than to trees, that has its eastern tip in central Illinois and Indiana. Minnesota is along the northeastern flank of the prairie peninsula, with the edge currently running from Itasca State Park to the Twin Cities metro area. The northeastern flank has shifted position over the last 8,000 years, and 7,000 ybp, at the height of the altithermal period, it was approximately 100 miles east of its current position. Thus, the St. Croix River area in Minnesota would have had summer climate and vegetation similar to central Minnesota cities like Wilmar and Sauk Center today. This analog shows the type of change expected to occur in the next century, given a 2°C warming of summer temperatures.

Paleoecological analysis provides several other insights into the nature of vegetation response to climate change, which were discussed by Davis (1989a). First, species respond differently to climate change. This was seen in the maps of shifts of species range predicted by the range change model (model 7, section 2.4.3), as well as maps of past range changes. Each species will respond to warming with differing rates and areal extent of

changes to range, possibly leading to combinations of species that are rare or absent today. Communities or vegetation types do not shift in response to climate change, but species do. For example, pine forests in Morrison County, MN, from 10,000 to 8,000 ybp did not include white pine. The area was then occupied by prairie and deciduous forest during the warm period from 8,000 to 1,000 ybp. When pine forest reinvaded at 1,000 ybp, the assemblage contained white pine and led to a community type previously unknown in central Minnesota (Jacobson and Grimm 1986).

A second insight from paleoecology listed by Davis (1989a) is that there are lag times between climate change and vegetation response. Unless the climate changes so dramatically that adult trees are killed, there could be two or three centuries of lag time before forest dominated by long-lived species such as white pine or sugar maple are completely replaced by different species. The forests may appear unchanged during this time, but different species would be replacing individual trees as they die. On the other hand, if disturbances are frequent, large areas may be converted to new species almost instantly, and lag times may be only a few decades. The likelihood of more fires in Minnesota if the climate warms substantially suggest that lag times will be relatively short if fires cannot be controlled, but long if fires can be controlled.

3

OZONE DEPLETION

3.1

Cause of Ozone Depletion

Ozone depletion refers to the reduction of ozone concentrations in the earth's stratosphere, which is caused by CFCs (freons) used in air conditioners, refrigerators, as solvents, and as propellants in aerosol cans. Stratospheric ozone depletion is a separate problem from excess ozone near the ground, which can affect tree growth and is explained in section 4. Unlike CO₂ and methane, CFCs are totally artificial compounds. Under natural conditions in the upper atmosphere, ozone (O₃) is constantly formed from ordinary oxygen (O₂) in a chemical reaction catalyzed by ultraviolet light (Graedel and Crutzen 1989). Ozone is also constantly broken down, at a rate equal to its formation, so that a natural balance is attained in which a constant concentration of ozone is maintained. Chlorine atoms from CFCs upset this natural balance by reacting with ozone to produce ordinary O₂ and a chlorine oxide. Thus, in the presence of chlorine atoms, breakdown of ozone is faster than the rate of formation (Graedel and Crutzen 1989).

CFCs have a residence time in the atmosphere of 60 to 100 years (Graedel and Crutzen 1989), so that even if the recent agreements among nations to limit CFC use is effective, ozone depletion will continue for many decades.

The current concentration of chlorine atoms in the atmosphere is 3 ppb, and this concentration is predicted to be between 2.4 and 6 ppb by the year 2030, depending on how fast people reduce emission of CFCs into the atmosphere. The amount of ozone depletion for a given level of CFCs has yet to be determined (Rowland 1989). However, it is known that the current level of CFCs has produced a 4.7 percent loss of ozone during winter for the 40 to 50° north latitude belt (Rowland 1989). What is not known is how much more ozone may be destroyed by CFCs already in the atmosphere, and the exact rate of increase/decrease of atmospheric CFCs in the future. Estimates of average stratospheric ozone depletion worldwide ranging from 4 to 31 percent are cited by Rowland (1989).

3.2

Potential Effects on Forests

The ozone layer absorbs much incoming ultraviolet radiation, shielding the earth's surface. Thus, the major problem for forests caused by thinning of the stratospheric ozone layer would be injury to trees by ultraviolet light.

Several studies have looked at the effect of levels of ultraviolet light equivalent to those that would occur with a 20 to 40 percent reduction in stratospheric ozone on crop plant and tree seedlings grown in a greenhouse environment. Stunting, reduction in leaf area and biomass, and changes in allocation, such as the root to shoot ratio are well-documented, although there is less sensitivity to high ultraviolet levels among plants that are shaded (Teramura 1983, Gold and Caldwell 1983, Teramura and Sullivan 1987, Berenbaum 1988, Sullivan and Teramura 1988). In both crop plants and tree seedlings, there are species that are resistant to the effects of enhanced levels of ultraviolet, and other species that are sensitive. Tree species that grow in high elevations seem to be most resistant among those species studied so far (Sullivan and Teramura 1988), possibly because they experience relatively high levels of ultraviolet radiation compared to low elevation species, and have evolved resistance to effects of high ultraviolet light levels. However, there are differences in sensitivity to ultraviolet light among low elevation species. In addition, there is much variation in sensitivity to ultraviolet light among individuals within species.

One consequence of differences in sensitivity of plant species to ultraviolet light may be changes in the competitive relationship among species (Gold and Caldwell 1983). The proportion of each species with natural forest regeneration may be different with more ultraviolet radiation than it currently is, even if the overall biomass is not changed. For example, Sullivan and Teramura (1988) found that red pine seedlings are stunted by a level of ultraviolet light that would be experienced at 39° N Latitude, if stratospheric ozone was reduced by 20 or 40 percent, but that white pine and white spruce seedlings were not. This suggests that white spruce seedlings may have an

advantage in competition with red pine under enhanced ultraviolet light levels, while at the current time red pine seedlings grow faster than white spruce seedlings under most open conditions.

Another factor that may alter forest productivity and competitive relationships among species is interaction among insect pests, tree species, and ultraviolet light. Berenbaum (1988) reviewed the effects of ultraviolet light on plant chemistry, and found that several chemicals—for example certain alkaloids and flavonoids—are produced in greater amounts in plants exposed to higher than normal levels of ultraviolet light. These secondary plant chemicals reduce the palatability of plant parts to many insects. These effects have been studied only in herbaceous plants so far.

Unfortunately, the effects of long-term exposure to relatively high levels of ultraviolet light in mature forests have not yet been studied. At this time no predictions can be made of the potential changes in species composition and productivity that may occur over the next century if large reductions in stratospheric ozone concentration continue to occur.

4 AIR POLLUTION

Research on the effects and mechanisms of acidic deposition and associated atmospheric pollutants on forest ecosystems has reached the end of an initial exploratory stage, which is summarized in Balogh et al. (unpubl.). This intensive short-term effort has not necessarily supported the initial concerns that North American forests are suffering widespread damage caused by acid deposition. Most forests in Minnesota are apparently healthy. Known forest health problems are in most instances related to natural stresses and/or past land use practices. Ozone may have detrimental effects on certain sensitive species such as white pine. However, experimental evidence from tree seedlings indicates highly variable responses to acid deposition and ozone. Ozone responses are frequently adverse, while growth response to acid deposition can often be positive. The combination of the negative and positive response provides some insight into why neither of these pollutants is consistently associated with widespread forest change in the eastern United States. It is possible that the nature of tree response to the combination of ozone and acid precipitation, in the absence of other stresses, is offsetting. This would lead to a no effect conclusion when attempting to interpret uncontrolled, observational studies.

Based on this research review and the assessment of NAPAP review papers (Barnard et al. 1990; Shriner et al. 1990), conclusions on the potential effects of atmospheric pollutants on Minnesota's forests include:

1. Most forests in the Lake States and adjacent Canadian Provinces are currently considered relatively healthy. The majority of forests in this region, including Minnesota, are *not* affected by observed symptoms of decline directly related to the effects of atmospheric pollutants.
2. Ozone is the pollutant of greatest current concern regarding regional scale impacts on Minnesota's forests. White pine, possibly certain hardwood species, and some seedlings are especially susceptible to ozone damage. However due to compensatory genetic and physiological mechanisms within plants, the extent of ozone effects in relation to changes in forest productivity and diversity remains to be determined.
3. There is a consistent spatial and temporal association of visible ozone injury and the occurrence of known phytotoxic levels of ozone throughout eastern North America for sensitive species such as white pine. This level of injury has not been extensively documented in Minnesota's forests. There is no consistent evidence of a relationship of ozone exposure in the field and damage or reduced growth for other forest trees. Under controlled greenhouse and other experimental conditions, other possibly sensitive tree species (e.g., trembling aspen, green and white ash, hybrid aspen, jack pine) have exhibited visible injury consistent with that observed in the field. Seedlings of sensitive species may be at higher risk to potential injury. However, the observed growth response of sensitive species to ozone exposure is highly variable.
4. Despite some localized point source problems, there is no documented evidence or indication of a general decline of forests in Minnesota, the United States, and Canada due to acidic deposition, other acidifying atmospheric pollutants, or other environmental stress factors. There is experimental evidence that acid deposition and associated pollutants (nitrates) can alter the resistance of red spruce to high levels of atmospheric pollutants at high elevations in the northern Appalachian Mountains. These conditions are not related to growth conditions of black or white spruce in Minnesota.
5. Most exposure effects studies suggest that direct effects to forest vegetation by acidic air pollutants occurs at pH values at or less than 3.0.
6. Ambient SO₂ concentrations are not responsible for regional scale forest growth reductions. Growth reduction of forest trees resulting from SO₂ exposure is primarily a point source problem.
7. Although not extensively documented, NO₂ at ambient conditions is not a direct source of regional growth reduction.

8. Compared to ozone and many nonpollutant stress factors, acid deposition appears to be a minor factor affecting the current health and productivity of most forests in the United States and Canada. Most forests in Minnesota, the United States, and Canada are exposed to levels of acid deposition that do *not* have serious impacts on long-term health and productivity. The possibility of long term (several decades) adverse effects on some soils may be realistic. Nutrient loss coupled with accelerated harvest may reduce the fertility of soils with low buffering capacity or low rates of mineral weathering.
9. Attempts to distinguish adverse impacts resulting directly from atmospheric pollutants are likely to be confounded by interactions with other forest health and management relationships.
10. **Available information does not rule out the subtle effects of ozone and acid deposition which might predispose trees subject to damage from other natural and harvesting stresses.**

5

SUMMARY AND SYNTHESIS

Significant warming of the earth's climate, caused by anthropogenic changes in atmospheric chemistry, is likely over the next century. All global circulation models (GCMs)—although not all scientists—predict that substantial warming is the most likely scenario. GCMs can simulate the changes in earth's temperature during the annual seasonal cycle. However, this does not guarantee accurate simulation over longer time periods. Therefore, long-term GCM predictions should be considered speculative at this time. Five different GCMs predict worldwide temperature increases ranging from 1.5 to 4.51 °C. Interior continental areas such as Minnesota are likely to warm more than the global average, due to their relative remoteness from oceans which act to buffer temperature extremes. However, nothing is currently known about how the Great Lakes might modify warming in the Upper Midwest, nor of the geographic extent of any such modifying effects.

If warming occurs, increasing summer temperatures would have the greatest impact on Minnesota forests by causing greater evaporation and drier soils. Three of the five GCMs surveyed for this report predict decreased summer soil moisture in Minnesota, one predicts a decrease only in western Minnesota, and one predicts increased summer soil moisture. Four of five GCMs predict that Minnesota would have greater precipitation and soil moisture during winter, which could compensate for drier summers by allowing dormant season recharge of subsoil moisture.

Using the altithermal period 6,000 years before present as an analog for warm summers, a shift to the northeast of about 100 miles in the geographic range of important Minnesota tree species is expected if summer temperatures increase by 2°C; which is the median of the range in predicted changes. Various scenarios projected by the GCMs could lead to range shifts for species that would vary from only a few tens of miles to as much as several hundred miles. These shifts in range represent a potential loss in Minnesota forest area, because the area with climate suitable for grasslands would expand at the expense of forests. Use of drought resistant tree varieties, fire control, and tree planting could mitigate these factors and therefore reduce the potential loss of forest area.

If warming occurs, productivity of individual sites may increase on deep loamy soils in northern Minnesota as the growing season lengthened. However, sandy soils may experience a large decrease in productivity due to intensified summer drought. No simulations have been done that predict the future productivity of Minnesota forests given the current spatial distribution of species and stand ages across the landscape. Given the uncertainty in GCM predictions, the range of potential scenarios generated, the current poor understanding of future range shifts, lack of information on adaptability of trees to environmental stress, and failure of growth models to take into account the currently existing conditions in Minnesota, no prediction can be made for overall future productivity of the Minnesota forest base under global change.

Stratospheric ozone depletion is definitely occurring, allowing more ultraviolet light to penetrate the lower portions of the earth's atmosphere. This depletion will continue for several decades, even if use of all CFCs is discontinued at this time. The ultimate level of depletion that will occur and the effects of the resulting ultraviolet light on forest health is not known. However, it could add, either synergistically or additively, with global warming to produce multiple effects on Minnesota forests. Air pollution such as lower level ozone and acid rain is not likely to add much to multiple impacts on Minnesota forests, except very locally near point sources of air pollution.

Using the altithermal period 6,000 years before present as an analog for warm summers, a shift to the northeast of about 100 miles in the geographic range of important Minnesota tree species is expected if summer temperatures increase by 2°C; which is the median of the range in predicted changes. Various scenarios projected by the GCMs could lead to range shifts for species that would vary from only a few tens of miles to as much as several hundred miles. These shifts in range represent a potential loss in Minnesota forest area, because the area with climate suitable for grasslands would expand at the expense of forests. Use of drought resistant tree varieties, fire control, and tree planting could mitigate these factors and therefore reduce the potential loss of forest area.

If warming occurs, productivity of individual sites may increase on deep loamy soils in northern Minnesota as the growing season lengthened. However, sandy soils may experience a large decrease in productivity due to intensified summer drought. No simulations have been done that predict the future productivity of Minnesota forests given the current spatial distribution of species and stand ages across the landscape. Given the uncertainty in GCM predictions, the range of potential scenarios generated, the current poor understanding of future range shifts, lack of information on adaptability of trees to environmental stress, and failure of growth models to take into account the currently existing conditions in Minnesota, no prediction can be made for overall future productivity of the Minnesota forest base under global change.

Stratospheric ozone depletion is definitely occurring, allowing more ultraviolet light to penetrate the lower portions of the earth's atmosphere. This depletion will continue for several decades, even if use of all CFCs is discontinued at this time. The ultimate level of depletion that will occur and the effects of the resulting ultraviolet light on forest health is not known. However, it could add, either synergistically or additively, with global warming to produce multiple effects on Minnesota forests. Air pollution such as lower level ozone and acid rain is not likely to add much to multiple impacts on Minnesota forests, except very locally near point sources of air pollution.

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LITERATURE CITED

- Balogh, J. C., R. M. Tietge, and T. A. Leppala. 1992. Impacts of timber harvesting and management in Minnesota on forest health—air pollution. Duluth, MN: Spectrum Research, Inc. Unpublished.
- Barnard, J. E., A. A. Lucier, R. T. Brooks, A. H. Johnson, P. H. Dunn, and D. F. Karnosky. 1990. Changes in forest health and productivity in the United States. In *Acidic deposition: State of science and technology*. National Acid Precipitation Assessment Program Report no. 16. Washington, D.C.
- Bartlein, P. J., T. Webb III, and E. Fleri. 1984. Holocene climatic change in the northern Midwest: Pollen-derived estimates. *Quaternary Research* 22:361-74.
- Berenbaum, M. 1988. Effects of electromagnetic radiation on insect-plant interactions. In *Plant stress-insect interactions*, 167-85, ed. E. A. Heinrichs. New York: Wiley-Interscience.
- Botkin, D. B., and R. A. Nisbet. 1992. Forest response to climatic change: Effects of parameter estimation and choice of weather patterns on the reliability of projections. *Climatic Change* 20:87-111.
- Brown, K., and K. O. Higginbotham. 1986. Effects of carbon dioxide enrichment and nitrogen supply on growth of boreal tree seedlings. *Tree Physiology* 2:223-32.
- Clark, J. S. 1988. Effect of climate change on fire regimes in northwestern Minnesota. *Nature* 334:233-35.
- Cohen, Y., and J. Pastor. 1991. The responses of a forest model to serial correlations of global warming. *Ecology* 72:1161-65.
- Davis, M. B. 1989a. Insights from paleoecology on global change. *Ecological Society of America Bulletin* 70:222-28.
- Davis, M. B. 1989b. Lags in vegetation response to greenhouse warming. *Climate Change* 15:75-82.
- Davis, M. B., and C. Zabinski. 1992. Changes in geographical range resulting from greenhouse warming—effects on biodiversity in forests. In *Consequences of greenhouse warming to biodiversity*, eds. Peters and Lovejoy. New Haven, CT: Yale University Press.

- Farrar, J. F., and M. L. Williams. 1991. The effects of increased atmospheric carbon dioxide and temperature on carbon partitioning, source-sink relations and respiration. *Plant, Cell and Environment* 14:819-30.
- Fifield, R. 1988. Frozen assets of the ice cores. *New Scientist* 118:28-29.
- Flannigan, M. D., and C. E. Van Wagner. 1991. Climate change and wildfire in Canada. *Canadian Journal of Forest Research* 21:66-72.
- Frelich, L. E., and C. G. Lorimer. 1991. A simulation of landscape-level stand dynamics in the northern hardwood region. *Journal of Ecology* 79:223-33.
- Gold, W. G., and M. M. Caldwell. 1983. The effects of ultraviolet-B radiation on plant competition in terrestrial ecosystems. *Physiological Plantarum* 58:435-44.
- Graedel, T. E., and P. J. Crutzen. 1989. The changing atmosphere. *Scientific American* 261:58-68.
- Hansen, J., G. Russell, D. Rind, P. Stone, A. Lacis, S. Lebedeff, R. Ruedy, and L. Travis. 1983. Efficient three-dimensional global models for climatic studies: Models I and II. *Monthly Weather Review* 111:609-62.
- Jacobson, G. L., and E. C. Grimm. 1986. A numerical analysis of Holocene forest and prairie vegetation in central Minnesota. *Ecology* 67:958-66.
- Kellogg, W. W., and Z-C. Zhao. 1988. Sensitivity of soil moisture to doubling of carbon dioxide in climate model experiments. Part I: North America. *Journal of Climate* 1(4):348-66.
- Kramer, P. J., and N. Sionit. 1987. Effect of increasing carbon dioxide concentration on the physiology and growth of forest trees. In *The greenhouse effect, climate change, and U.S. Forests*, eds. W. E. Shands and J. S. Hoffman, 219-46. Washington, D.C.: The Conservation Foundation.
- Kutzbach, J. E., and B. L. Otto-Bliesner. 1982. The sensitivity of the African-Asian monsoonal climate to orbital parameter changes for 9000 years B.P. in a low-resolution General Circulation Model. *Journal of Atmospheric Sciences* 39:1177-88.

- Manabe, S., and R. T. Wetherald. 1987. Large scale changes of soil wetness induced by an increase of CO₂ concentration in the atmosphere. *Journal of Atmospheric Science* 44:1211-35.
- Mitchell, J. F. B., and G. Lupton. 1984. A 4xCO₂ experiment with prescribed sea temperatures. *Progress in Biometeorology* 3:353-74.
- Norby, R. J., E. G. O'Neill, and R. J. Luxmoore. 1986. Effects of atmospheric CO₂ enrichment on the growth and mineral nutrition of *Quercus alba* seedlings in nutrient-poor soil. *Plant Physiology* 82:83-89.
- Overpeck, J. T., P. J. Bartlein, and T. Webb III. 1991. Potential magnitude of future vegetation change in eastern North America: Comparisons with the past. *Science* 254:692-95.
- Overpeck, J. T., D. Rind, and R. Goldberg. 1990. Climate-induced changes in forest disturbance and vegetation. *Nature* 343:51-53.
- Pastor, J., and W. M. Post. 1988. Response of northern forests to CO₂-induced climate change. *Nature* 334:55-58.
- Pastor, J., and W. M. Post. 1985. *Development of a linked forest productivity-soil process model*. Publ. no. 2455. Oak Ridge, TN: Oak Ridge National Laboratory, Environmental Sciences Division.
- Rose, D. M., A. R. Ek, and K. L. Belli. 1987. A conceptual framework for assessing impacts of carbon dioxide change on forest industries. In *The greenhouse effect, climate change, and U.S. forests*, eds. Shands, W. E. and J. S. Hoffman, 259-75. Washington, D.C.: The Conservation Foundation.
- Rowland, F. S. 1989. Chloroflourocarbons and the depletion of stratospheric ozone. *American Scientist* 77:36-45.
- Schlesinger, M. E., and J. F. B. Mitchell. 1987. Climate model simulations of the equilibrium climatic response to increased carbon dioxide. *Reviews of Geophysics* 25:760-98.
- Schlesinger, M. E., and Z-C. Zhao. 1989. Seasonal climatic changes induced by doubled CO₂ as simulated by the OSU atmospheric GCM/mixed ocean layer model. *Journal of Climate* 2:459-95.
- Schneider, S. H. 1989. *Global warming—are we entering the greenhouse century?* San Francisco, CA: Sierra Club Books.

- Shriner, D. S., W. W. Heck, S. B. McLaughlin, D. W. Johnson, P. M. Irving, J. D. Joslin, and C. E. Peterson. 1990. Response of vegetation to atmospheric deposition and air pollution. In *Acidic deposition: State of science and technology*. National Acid Precipitation Assessment Program Report no. 18. Washington, D.C.
- Solomon, A. M. 1988. Ecosystem theory required to identify future forest responses to changing CO₂ and climate. In *Ecodynamics: contributions to theoretical ecology*, eds. W. Wolf, C. J. Soeder, and F. R. Drepper, 258-74. New York, NY: Springer-Verlag.
- Sullivan, J. H., and A. H. Teramura. 1988. Effects of ultraviolet-B radiation on seedling growth in the Pinaceae. *American Journal of Botany* 75:225-30.
- Teramura, A. H. 1983. Effects of ultraviolet-B radiation on the growth and yield of crop plants. *Physiological Plantarum* 58:415-27.
- Teramura, A. H., and J. H. Sullivan. 1987. Soybean growth responses to enhanced levels of ultraviolet-B radiation under greenhouse conditions. *American Journal of Botany* 74:975-79.
- Tolley, L. C., and B. R. Strain. 1984. Effects of CO₂ enrichment on growth of Liquidambar styraciflua and Pinus taeda seedlings under different irradiance levels. *Canadian Journal of Forest Research* 14:343-50.
- Washington, W. M., and G. A. Meehl. 1989. Climate sensitivity due to increased CO₂: Experiments with a coupled atmosphere and ocean general circulation model. *Climate Dynamics* 4:1-38.
- Webb, T., III, E. J. Cushing, and H. E. Wright, Jr. 1983. Holocene changes in the vegetation of the midwest. In *Late-Quaternary environments of the United States. Vol. 2. The Holocene*, ed. H. E. Wright, Jr., 142-65. Minneapolis, MN: University of Minnesota Press.
- Winkler, J. A., R. H. Skaggs, and D. G. Baker. 1981. Effects of temperature adjustments on the Minneapolis-St. Paul urban heat island. *Journal of Applied Meteorology* 20:1295-1300.