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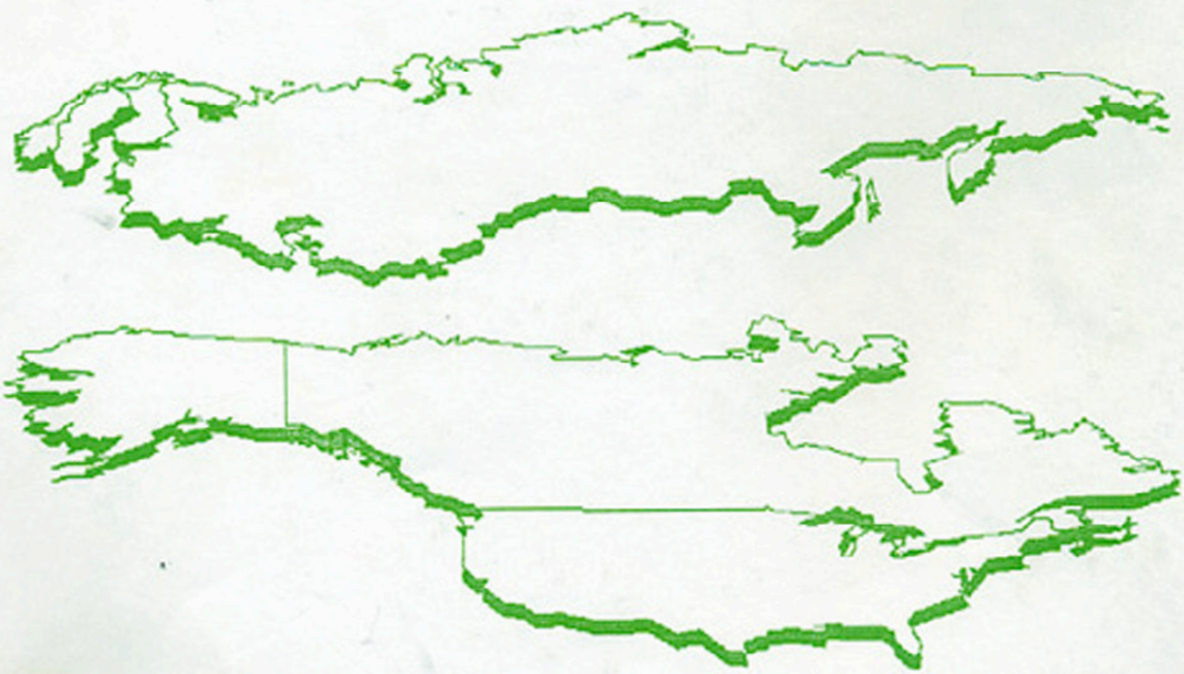

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Proceedings
of the

International Workshop
on

CARBON CYCLING IN BOREAL FOREST AND SUB-ARCTIC ECOSYSTEMS:

Biospheric Responses and Feedbacks to Global Climate Change

Edited by

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FOREWORD

Global climate is projected to change rapidly during the next half century as a result of alterations in the chemical composition of the atmosphere. Further, climate change may be more pronounced in the northern hemisphere. If the projected changes in global climate occur, the impact on terrestrial ecosystem processes is expected to be substantial.

Considerable uncertainty exists regarding responses and feedbacks of tundra, peat lands and boreal forest ecosystems to global climate change. Of particular interest is the role of tundra, peat lands and boreal forests in cycling and sequestering carbon because nearly one-third of the world's terrestrial carbon may be stored in these ecosystems.

An appreciation of the responses and feedbacks of the carbon cycle in boreal forest and sub-arctic ecosystems requires an understanding of the carbon pools and fluxes in these ecosystems. The estimates of current carbon pools and fluxes in the complex of ecosystems that comprise northern regions may be misleading. This is a result of the fact that the estimates are:

- based upon disparate data that were collected, in part, over the past several decades;
- associated with an uncertain estimate of the aerial extent of major vegetation types;
- reflective of mainly North American data and very little data from the former Soviet Union, which has the greatest expanse of boreal forest and sub-arctic ecosystems in the world.

There are also large uncertainties in our ability to project changes in carbon pools and fluxes over the next several decades.

In recognition of the need to assess the effect of tundra, peat lands and boreal forests on terrestrial carbon dynamics, an international workshop (with participants from the USA, Canada, the former Soviet Union and other boreal forest and sub-arctic countries) was convened with the following objectives:

- identify available tools and methods that may be used to provide extensive, early evaluation of responses and feedbacks in boreal forest and sub-arctic ecosystems;
- identify available carbon dynamics data and models that may be used to conduct preliminary analyses of carbon cycling and sequestering patterns in boreal forest and sub-arctic ecosystems and establish carbon budgets for boreal and sub-arctic countries;
- identify the necessary elements of a framework to establish the carbon budget for a boreal forest and/or sub-arctic country.

The written contributions to the workshop are presented herein.

Ted S. Vinson Tatyana P. Kolchugina

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SELECTING A MODEL TO ESTIMATE THE EFFECTS OF CLIMATE CHANGE AND MANAGEMENT ACTIVITIES ON CARBON CYCLING IN TEMPERATE FOREST REGIONS

Bob Zybach

ABSTRACT

The use of specific computerized forest models to predict the possible effects of global climate change on the Earth's temperate forest regions is examined. The effects are described in two basic categories: 1) abiotic changes resulting from global warming (i.e., increased temperatures, increased atmospheric CO_2, changed moisture availability and altered solar radiation); and 2) forest management policies that can be developed in response to climate change projections. This report is arranged in three parts: 1) a general description of the historical relationship between human activity, temperate forests, increased CO_2 emissions and climate change; 2) an outline of forest management strategies that are being considered to reduce or eliminate net increases of carbon in the atmosphere; and 3) a brief examination of the types of computer models being developed that are capable of assessing climate and management change impacts upon temperate forests.

INTRODUCTION: FOSSIL FUELS AND GLOBAL WARMING

The possibility of a change in climate caused by human burning of fossil fuels was first brought to the attention of the scientific community in April, 1896, by the Swedish chemist Svante Arrhenius, who characterized the problem as "evaporating our coal mines into the air". Atmospheric increases of carbon dioxide due to fossil fuel consumption dating to the beginning of the industrial revolution were finally proved "scientifically" by Charles Keeling, through research initiated in the early 1950s. Subsequent use of computerized Global Circulation Models (GCMs) by a number of different scientific teams have generally supported Arrhenius's original calculations that a doubling of carbon dioxide in the atmosphere could cause the average temperature of the earth to increase by as much as five or six degrees centigrade. Current projections call for such a doubling to occur sometime within the next century; current estimates are that enough coal and oil remain in the ground to raise the level of carbon dioxide about ten times higher (Weiner, 1991).

Between 1860 and 1960, it has been estimated that humans added 80 billion tons (Gt) of carbon to the atmosphere; from 1960 to 1990, another 80 Gt have been added, and the rate continues to increase (Weiner, 1991). At the present time, it is estimated that world combustion of fossil fuels injects about 5 Gt of carbon into the atmosphere annually. About 2 Gt is removed by the oceans (Rosenfeld and Botkin, 1990). The net annual increase of 3 Gt of carbon is added to the 700 Gt currently estimated to be contained in the atmosphere and is the basis for present concern: human activity may be causing a rapid and pervasive warming of the planet.

The possibility of an increase in the average temperature of the earth by as little as one or two degrees centigrade within the next several decades has given rise to general alarm within the scientific community. Recent projections of resulting discomforts and disasters to the human community have been publicly delivered to influential politicians in several nations and continue to be widely reported in the popular press. One result of this alarm has been the development of a number of strategies for decreasing the use of fossil fuels and/or increasing the rate of sequestering atmospheric carbon (which exists primarily in the form of carbon dioxide) into a variety of biological "sinks" located about the globe. Forest and forest-product management options figure prominently in both strategies.

TEMPERATE FOREST HISTORY

Forests began to appear in the Silurian period, about 350 million years before the present (BP). They reached their peak development during the Carboniferous period, 270 to 220 million years BP, at a time when the earth was completely frost free. Widespread glaciation during the ensuing Permian period greatly reduced the area of forest cover and resulted in massive extinctions of both plant and animal species. By the beginning of the Tertiary period, about 50 million BP, modern tree species had come into existence.

Large-scale human manipulation of forests is thought to have started between 7000-5000 years BP, with the development of domesticated plants and animals requiring fields and pasturage. It is estimated that the earth's forests have been reduced by at least one-third since that time, almost entirely due to human activities (Hermann, 1976). James Watt's development of the steam engine in the eighteenth century became the starting point for the systematic mining of the buried Carboniferous forests for fuel. The combination of modern forest clearing and fossil forest consumption by humans is thought to be almost entirely responsible for the increase in atmospheric CO_2 that has occurred over the past several millennia. The rate of increase has accelerated dramatically during the past century and is presumed to be related to expanding human populations and the development of the automobile.

Today there are about 8 billion acres of forests on earth. This figure represents an estimated reduction of 32-35% of temperate forests, 24-25% of subtropical forests and savannahs, and 15-20% of tropical forests since the advent of agriculture (Kauffman et al., 1991). Forests contain about 90% of the carbon in terrestrial vegetation, making forest biomass a major regulator of atmospheric CO_2 (Graham et al., 1990). The purposeful and accidental burning of forests and forest products has been estimated to cause about 40% of the human-based CO_2 that is put into the atmosphere each year (Kauffman et al., 1991).

Temperate forests primarily exist in the northern hemisphere, between 30° to 60° North latitude. They are estimated to contain about 47% of the world's forest biomass and can be characterized as consisting of deciduous, mixed deciduous-coniferous, temperate coniferous and boreal forests. Following tropical forests, they comprise the largest biotic carbon pool on the planet (Amentano and Hett, 1980).

This report focuses on the temperate forest regions of the world for three primary reasons: 1) the Siberian boreal forest of the former Soviet Union contains the largest undisturbed extent of temperate forest on the planet (Table 1); 2) most human-caused atmospheric carbon is the result of industrial development in the northern latitudes; and 3) many of the predictive models discussed in the following pages are species-specific and cannot be used effectively in tropical regions due to the vast amount of unknown and unmeasured species that characterize the forests of those climates.

Table 1. Forest stands of selected European and Asian countries (after Armentano and Hett, 1980).

Country	Land area (million ha)	Forest area (million ha)	Percent Forest area (coniferous)	Total timber resources (billion m³)
Finland	33.70	20.56	81.00	1.50
Sweden	41.10	23.50	82.00	2.36
European Economic Comittee	152.60	30.92	42.00	3.00
Europe (except former Soviet Union)	457.00	169.00	51.00	13.40
Japan	100.00	25.10	42.00	2.09
China	956.00	100.00		
Former Soviet Union	2220.00	765.00	75.00	79.00

MITIGATING STRATEGIES

In an effort to slow or halt net increases of carbon in the atmosphere, a number of strategies have been proposed that involve the management of forests and forest products. A common denominator of such strategies is that they require substantial investments of capital, time and land. Such investments would require major policy commitments on the part of several cooperating forested countries to be effective. For the temperate regions, agreement to manage trees and tree products as carbon sinks would have to be made between the United States, Canada and the former Soviet Union to be effective. In addition, China has the potential for implementing massive afforestation projects on lands that were deforested centuries in the past. European Economic Community (EEC) lands are also a factor, but due to large, affluent populations and a stabilized forest base, these countries are probably better suited for scientific, technological and political contributions toward resolving climate change problems.

Tree Planting

One of the most common strategies considered for sequestering atmospheric carbon is the reforestation and afforestation of lands capable of supporting temperate forests (Amentano and Hett, 1980; Moulton and Richards, 1990; Birdsey, 1991a). Management options typically consider increasing the area of forest lands by planting trees or allowing natural regeneration to occur, thinning overstocked existing stands to encourage more vigorous growth, planting gaps in understocked stands and the manipulation of species to encourage greater carbon sequestering capabilities or to anticipate changed environments.

Anticipated costs of such a strategy are extremely high. Moulton and Richards (1990) estimate that a tree-planting program expected to reduce net emissions of CO_2 by only 10% for the United States would require 71 million acres and cost 0.7 billion dollars a year. The average cost for each ton of sequestered carbon rises from $9.72 at this level, to $17.91 (7.7 billion dollars per year) for a strategy designed to reduce net emissions by 30%. The marginal cost of a strategy to reduce net emissions by 56% rises to an average of $43.30. Rosenfeld and Botkin (1990) estimate that to offset 100% of current global fossil fuel consumption, we would have to double the size of the world's forests, an area that would be about five times as large as the entire area of the United States.

There are other problems as well; we do not understand how specific species of trees will respond to climate change, or even know how individuals or families within a population will respond. McCreary et al. (1986) suggest that Douglas-fir viability is significantly altered by a few degrees of change in winter chilling temperatures when the trees are dormant. Squillace and Silen (1962) document the great amount of growth and survival variation between different races of ponderosa pine planted in experimental plots throughout their range in 1926.

Aspects of large-scale tree planting projects that were not discussed in detail within the reviewed literature include potential extinctions and extirpations of wildlife populations, and differences in net CO_2 emissions caused by plantation locations (trees planted in urban environments can reduce fuel uses related to seasonal heating and cooling requirements of local human populations, while those located near industrial developments may experience poorer health and greater mortality).

Prescribed Fire/Fire Suppression

A significant body of literature exists detailing the use of prescribed fire in reducing the occurrence of periodic stand replacement fires (Olson, 1981; Reid and Oechel, 1984, Bergeron and Brisson, 1990). By removing dead materials at periodic intervals and suppressing the development of ladder fuels, the intensity, range and frequency of wildfires can be reduced. Such strategies may become critical if, as projected by several researchers, the occurrence of global warming may cause an increase in catastrophic fires (Graham et al., 1990).

Although prescribed fire is not usually defined in terms of wildfire control or suppression, that would prove to be its primary function as a carbon-sequestering strategy. Auclair (1990) relates government fire suppression policies to the capacity of North American forests to function as an effective carbon sink over the past several decades. Some of his conclusions may be debated because the relatively short time that he analyzes does not take into account the fuel-clearing catastrophic fires of the mid-1800s, the large-scale clear cutting that took place following World War II, or the relationship between climate trends and forest fires that have developed over the past three centuries.

Wood Product Substitutes

The substitution of wood products as a carbon sequestering strategy is bilateral. By substituting biomass fuels for fossil fuels, the primary source of human-caused carbon additions to the atmosphere is eliminated. By substituting non-carbon-based products for wood products, forest harvesting can be reduced. For instance, the replacement of newsprint by electronic mail eliminates the use of one of the fastest decomposing forest products. Conservation of existing products by careful storage, reduced use, or re-cycling is another form of substitution that is aligned with this strategy.

Wood Preservation Technologies

A basic limitation with most models developed to track carbon cycling is that they don't adequately assess the "shelf life" of carbon contained in wood products derived from forests. Often products are simply divided into two or three basic categories such as paper products and construction materials, and arbitrary values are then assigned. A slightly more sophisticated approach to this problem is provided by Kurz et al. (1990).

Little information exists regarding the life of wood products after they are processed and distributed. Preservation can be accomplished by a number of methods, including distribution patterns, manufacturing specifications (including species selection) and chemical treatment. Hermann (1976) quotes William Wright when he states that "the Comstock Lode can in truth be called the tomb of the forests of the Sierra." It would be interesting to see how much these mining timbers have decomposed since Wrights work first appeared in 1876. Pioneer settlers in the Pacific Northwest were known to prefer "yellow" (old-growth) Douglas-fir shakes for home and barn construction because they "lasted longer than cedar."

A primary problem in determining wood product life, one shared with chemically-treated products as well, is the great amount of variabilities encountered following sale and use. Fire history, local climates and micro-climates, maintenance schedules and methods, etc., all profoundly affect the length of time in which carbon is stored in construction materials, telephone poles, pilings and other long-term uses of wood.

W.K. Ferrell (Professor Emeritus, OSU College of Forestry) is currently engaged in research that attempts to track the life of forest products in the Douglas-fir region (Harmon, personal communication, 1991). Such research should reveal sources of information and develop a methodology that will be of use to other regions.

Log Banks

One strategy for sequestering carbon that might be considered is the creation of "log banks," essentially the purposeful storage of harvested wood products in environments that inhibit decomposition. Biomass could be stored underwater, underground, or in an arctic climate for decades or centuries. There are two basic advantages to this strategy. First, dead trees or underproductive forestlands could be harvested, allowing for reforestation with a more efficient cover. Second, future generations could draw directly from these banks, reducing their need for harvesting green trees.

USING MODELS TO ANALYZE PREDICTIONS AND STRATEGIES

Climate changes have effects at a variety of spatial and temporal scales (Figure 1). Available models are generally capable of addressing problems at only one given scale. An

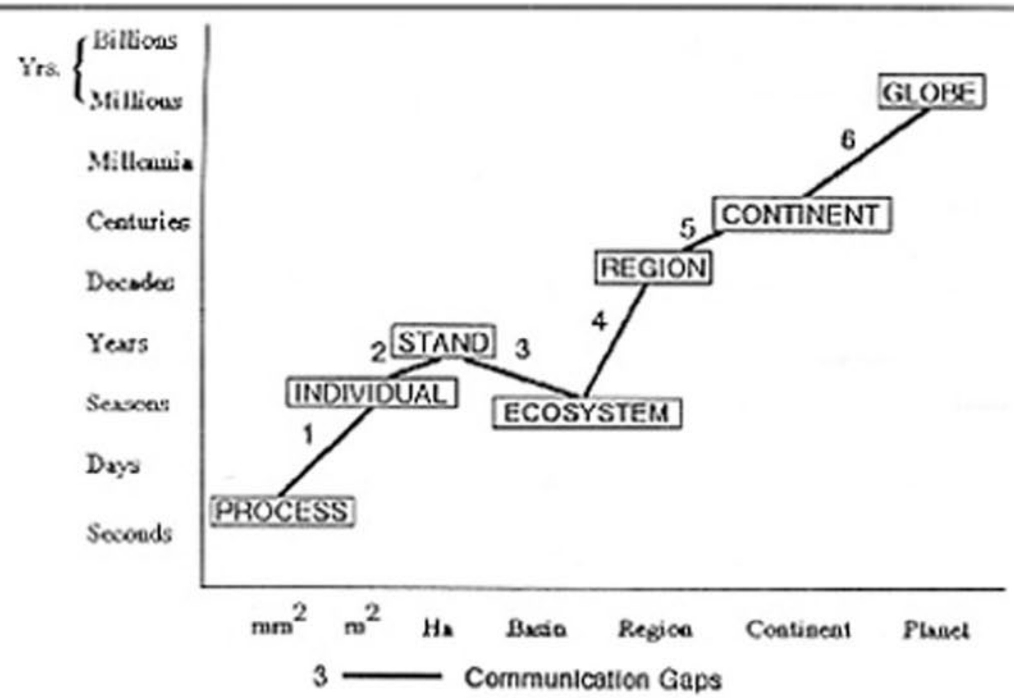

Figure 1. Ecological scales of time and space (after Pastor and Post, 1986).

additional problem is the gap that exists between each of the different scales. Existing models are incapable of bridging these gaps.

The development of computerized forest predictive models is in its infancy. At the present time, there are no models that can accurately reflect the present or reasonably predict the future on a regional basis. There are three primary reasons for this condition: 1) scientists have only recently started to unravel and understand the complex interdependencies that exist between the living and non-living components of the biosphere; 2) computers are technologically incapable of storing or processing the vast amount of data necessary to present those interdependencies; and 3) the future is unpredictable.

The usefulness of forest predictive models, so far as climate change is concerned, lies in their ability to provide a range of possible consequences. Such models can be grouped into two basic categories: stochastic and non-stochastic. Stochastic models are those that can accommodate random or conjectural events, and thus will produce a number of theoretically possible alternatives. It is up to the analyst to then choose an alternative that most closely resembles a desired result, or else simply average the total of a number of computer runs to moderate projections of the more variable factors. Non-stochastic models tend to apply a set of given empirical equations to a specifically defined inventory of values. They are most often used to determine such things as timber cutting schedules and anticipated growth rates for stands of trees, rather than successional responses to possible or unanticipated changes to the environment. Non-stochastic models can also be made to respond to conjectural changes in temperature, available moisture, or atmospheric CO_2 but this process usually involves the introduction of an entirely new set of equations.

Stochastic models are most often used to predict changes in forest range, structure, or carbon-sequestering capabilities in response to alterations in the climate, but are limited by a lack of information as to how these processes work. For instance, very little is known as to how organic carbon in forest soils has changed over time (Pastor and Post, 1986). Similarly, it is impossible to predict how changes in average global temperature will affect planetary cloud formations; lower elevation clouds will tend to cool the earths surface, while higher elevation clouds will likely exacerbate warming trends (Weiner, 1991).

Predictive models can be used to measure the impact of climate change by considering the individual variables most likely to affect forest growth: CO_2, temperature, precipitation and radiation. Again, a primary problem is our lack of information. For instance, commercial greenhouse operators will sometimes increase the growth of plants by subjecting them to greater levels of CO_2, but it is not known whether mature trees will also respond in a like manner, whether plants can become acclimated to such changes over time, or if available nutrients would eventually become depleted through increased levels of plant growth.

The problem becomes more complicated the more these processes are generalized, particularly over time and space. For instance, a single temperature event, a region-wide cold snap occurring over a few hours time in November, 1955, had a severe impact on the viability and volume of a number of races of 30-year-old ponderosa pine that had been planted in separate plots throughout the region. The results of this single event were still noticeable during research measurements taken in 1986 (Silen, personal communication, 1991). Other problems include incomplete data regarding stand fire histories, the impacts of industrial pollutants upon localized tree populations, a lack of knowledge regarding intra-species genetics and a lack of sophistication regarding the modelling of biomass decay rates (standing snags vs. downed logs, north slopes vs. south slopes, etc.).

Despite the limitations posed by predictive models, they remain our best tool for projecting the potential impacts upon global forests caused by climate change. They are also our best tool for measuring the potential results of implementing strategies designed to mitigate such change.

CURRENT MODELS

There are a number of predictive models being developed that are capable of measuring possible impacts of climate change on temperate forests. A recent technical review classified several such models according to "levels of resolution" (Ågren et al., 1991).

Physiologically-Based Models

The greatest level of resolution is provided by models in which plant processes can be described in biochemical terms. Predictions of individual plant responses to environmental changes can be modelled through an understanding of such processes as carbon uptake through photosynthesis and water-vapor exchanges through transpiration and respiration. The objectives of this approach are to explain and predict the functioning of plant communities from a micro-environmental level. Several forest models exist in this category, including BACROS, FORGRO, MAESTRO, BIOMASS and FOREST-BGC. A primary problem with these models is how to scale them from a plant physiology level to an ecosystem, regional, or global level (Figure 1).

Population Models

This level of resolution simulates tree growth as it is affected by competition between individuals and population dynamics. These models apply to stands of single species and multiple species, describing volumes spatially, individually (by tree) through time, or by summarizing variables (total number of trees, etc.). All models in this category consider recruitment (new seedlings), individual growth, factors limiting such growth, mortality, stand structure and spacing. Most models in this classification are limited by the assumption that climate is assumed to be the same for an entire region.

Ecosystem Models

At this level of modelling, whole plants or major plant components are integrated interactively with the environment, particularly with the soil. Typically, all green plant biomass is included in a single compartment. Objectives of these models include the ability to simulate ecosystem responses to such abiotic drivers as light intensity, soil water and soil temperature. Different management option impacts are able to be measured at the ecosystem level. Ecosystem models can be divided into short (one day or less) and long (one month to one year) time steps. Short-time step models require the input of driving variables on a daily basis and generally simulate ecosystem dynamics for 2-10 year time periods, while long-time step models are designed to predict ecosystem dynamics over periods of time that can be measured in decades. Short-time step models have been used largely to predict crop and grassland responses to such climatic changes as CO_2 enhancement, supersonic-transport-induced weather and hail suppression. Long-time step models, such as GEM and CENTURY have been designed to simulate long-term (10-100 year) responses of grasslands and forests to differing management practices and possible climate changes.

Regional Models

This group of models operates at the lowest level of resolution, with plant populations combined into biomes. At the present time, there are no reliable models that have been developed at this level, although the FOREST-BGC model is being modified to accommodate regional applications. It is expected that this model will be validated for general use in about two years (Running and Gower, 1990).

Brief Description of Select Models

The effects of climate change take place at the molecular level of individual organisms. However, it is the cumulative effect, on a regional or global basis, with which we are most concerned. The following models were selected for further description based upon their degree of development, their general availability and the fact that they can be arranged in a hierarchical fashion from physiological processes to population dynamics to ecosystem responses. Theoretically, such responses may then be analyzed in a cumulative and interactive manner to determine regional and global results.

FOREST-BGC (Running)

This is a physiologically based model that is currently being updated. The newer model was being withheld from general use at the time of this report and unavailable for further description. Particular attention is paid to water availability, with descriptions of rainfall, interception by canopies, soil evaporation, etc. Required inputs include daily weather data (temperature, precipitation and light) and such soil physical characteristics as rooting depth and water retention functions. The model allows the examination of temperature and precipitation, with carbon outputs allocated between three vegetation pools, a detrital pool and a nondetrital soil pool. The ecosystem objective is to measure forest growth and water balance, as evidenced by leaf area production (LEA) and retention. Photosynthetic rates and transpiration are dependent upon radiation, but this model doesn't have a mechanism to account for increased cloudiness. Prediction times are limited to months and years; there is no current method of generalizing predictions to a regional basis. The earlier version of this model is described by Running and Coughlin (1988); the current model is being modified and tested as outlined in Running and Gower (1990).

JABOWA II (Botkin)

This is a population model with stochastically simulated processes. Predictions are usually based upon the mean of several (30-40, or more) model runs. Simulation is based upon the birth, growth and death of individual trees in representative plots. A weakness associated with averaging runs is that extreme events, which may significantly affect forested areas, are averaged out of existence (Graham et al., 1990). This model is being marketed for $250 in a version that operates on IBM personal computers (Inouye, 1991). It is of particular value to studies of temperate forests, both because of its availability and because of the principal author's familiarity with forest modelling, boreal forests and remote sensing (Botkin et al., 1972; Botkin et al., 1984; Botkin and Simpson, 1990). Jabowa II is specifically described in Botkin and Nisbet (1991).

CENTURY (Parton)

This is a long-time step ecosystem model that has been developed to simulate carbon, nitrogen, phosphorous and sulphur dynamics for the plant-soil system in response to climate changes and management practices. Monthly time steps are used to predict regional trends regarding ecosystem processes and responses over time periods that vary from 10-500 years. Driving variables are daily temperature records, precipitation and light. Outputs include five carbon pools, two allocated to soil and three allocated to vegetation. It features a complex soil process model with feedback between nitrogen availability and production.

U.S. Carbon Budget Model (Birdsey)

This is a collection of five USDA Forest Service models: TAMM, ATLAS, FORCARB, HARVCARB and BICARB. It is essentially an inventory series that would require the introduction of an entirely new set of equations to accommodate environmental changes (Birdsey, 1991b). A secondary weakness is that these models are entirely dependent upon Forest Service data and are nearly useless for applications regarding temperate forests outside of the United States.

CONCLUSIONS

Based on the information presented herein, the following conclusions are appropriate:

- Selection of a model is dependent upon the temporal and spatial scale of the question that is being asked;

- None of the models in current use has demonstrated an ability to make accurate or reliable projections;

- Information gaps exist that need to be addressed to increase model projection accuracy;

- Communication gaps exist between models that operate at differing scales; and

- The need for predictive models that can provide insights to biospheric responses to climate change and to large-scale conifer forest disturbances is critical.

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