WORKING PAPER

IMPACTS OF CHANGES IN CLIMATE AND ATMOSPHERIC CHEMISTRY ON NORTHERN FOREST ECOSYSTEMS AND THEIR BOUNDARIES: RESEARCH DIRECTIONS

P.N. Duinker
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PUBLICATION NUMBER 53 of the project:
Ecologically Sustainable Development of the Biosphere

IIASA
International Institute
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FOREWORD

A Task Force meeting was held at IIASA in August 1987 on the subject: *Impacts of changes in climate and atmospheric chemistry on northern forest ecosystems and their boundaries: research directions.* There were 21 participants at the meeting, representing seven of the eight countries having northern forest ecosystems within their boundaries. This topic is important to many national members of IIASA, as well as to the organizers of *Global Change*, a major initiative of the International Council of Scientific Unions.

I am pleased to have an opportunity to thank those who participated in the meeting and in the preparation of this report. The recommendations are timely and ought to be disseminated widely. They represent an important research direction for IIASA and the member countries concerned.

B.O. Döös
Leader, Environment Program

ACKNOWLEDGEMENTS

First we express our deep gratitude to former leader of the Biosphere Project, W.C. (Bill) Clark, and to former head of the Environment Program, R.E. (Ted) Munn, both of whom were critically instrumental in guiding our work in organizing and hosting the workshop and in providing an effective administrative umbrella. M. Brandl of the Biosphere Project superbly handled both pre- and post-workshop secretarial duties.

ABSTRACT

In response to numerous suggestions with the research community that boreal forests should be targeted for analyses of potential ecosystem response to impending major changes in climate and atmospheric composition, a task-force meeting for research-planning purposes was held at the International Institute for Applied Systems Analysis in August 1987. Participants discussed objectives for an international collaborative research program on this subject, what the current state of knowledge is, what the relevant research questions are, and what research approaches should be developed to address these questions. This report summarizes the workshop discussions, and presents synopses of working- group discussions on the following types of investigations: (a) historical responses of boreal-forest stands to changing climate and atmosphere using correlational data analyses; (b) response of boreal ecosystems to warm and enhanced-CO_2 environments using physical field experiments; (c) response of boreal ecosystems to raised or lowered levels of soil moisture using physical field experiments; (d) long-term behaviour of boreal-forest stands in the face of changing atmosphere and climate using measurements from permanent plots; (e) development of comprehensive databases on ecological characteristics of boreal forests and silvical characteristics of boreal-forest tree species based on literature reviews and data syntheses; (f) response and sensitivity of boreal-forest stands and landscapes to changing atmospheric and climatic conditions using simulation models; and (g) response of regional boreal forests to changing climate and atmosphere in the context of forest management using simulation models and policy exercises.

The research themes outlined above cover a wide range of spatial and temporal scales. As well, they cover a wide range of organization, from the organism through populations and communities to ecosystems (indeed, ecosystems including socio-economic subsystems). It is concluded that the various studies can benefit immensely from careful coordination that helps each study anchor its process mechanisms in lower hierarchical levels, and find its significance at higher levels. The coordination would also prevent wasteful duplication of effort in different countries where boreal forests exist, and would assist groups of researchers to benefit from (a) regular contact for exchange of data and information that would not normally be available through regular channels of dissemination, and (b) collaborative research arrangements for expensive, long-term, broad-scale projects that otherwise would probably not be possible.

CONTENTS

SUMMARY OF THE TASK-FORCE MEETING

P.N. Duinker, M.Ya. Antonovski, and A.M. Solomon

INTRODUCTION AND BACKGROUND

Several recent meetings and publications indicate that forests, especially northern forests, deserve research attention in the face of current and expected changes in world climate and atmospheric chemistry. Consider the following examples:

(a) An IIASA workshop on policy-oriented assessment of impacts of climatic variations (Chen and Parry 1987) concluded that, with respect to forests, "efforts are needed primarily to identify the principal sensitivities to climate, characterize their magnitude, and expand the basic data base for further research and assessments", and that boreal forests (including the northern timberline) merit detailed study because they are considered to be temperature-limited with respect to primary productivity, and because atmospheric temperature increases are expected to be largest in high-latitude regions.

(b) A recent NASA workshop on climate-vegetation interactions (Rosenzweig and Dickinson 1986) indicated that "(C)limate, including atmospheric composition, and the distribution and functioning of terrestrial ecosystems, natural and managed, are strongly interactive. Our understanding of the dynamics of both climate and ecosystems have so progressed that it is now important to study the linkages between these systems". Many of the papers presented at that workshop dealt with past or future changes in forested ecosystems.

(c) The Working Group on Terrestrial Ecosystems and Atmospheric Interactions (1986) of the ICSU Ad Hoc Planning Group on Global Change noted that boreal forests were desirable candidate ecosystems for modelling the dynamics of large-scale vegetation changes in response to changing atmospheric chemistry and climate.

(d) A recent book on impacts of climate variability (Parry et al. 1988) contains two chapters addressed specifically to the effects of climatic warming on forest productivity in boreal ecosystems (Binkley 1988, Kauppi and Posch 1988).

The examples given above are just a small portion of the attention now being focussed on the responses of northern forested ecosystems to changes in climate and atmospheric chemistry. But the attention thus far has been much less than satisfactory for many reasons, including the following: (a) many assessments of the effects of climate change and alterations in atmospheric chemistry on northern forest ecosystems have been static, and have not recognized the crucial aspects of the dynamics of ecosystem change (Solomon 1986); (b) most such assessments have not incorporated consideration of changes in soil moisture and other soil characteristics that may attend changes in climate and atmospheric composition (Manabe and Wetherald 1986); and (c) no such assessments have simultaneously examined northern forest ecosystem response to changes in both climate and atmospheric chemistry.

Several small groups of researchers on forest-atmosphere-climate interactions have discussed the collaborative efforts required to study the impacts of changes in climate and atmospheric chemistry on northern forest ecosystems and their boundaries. To develop the topic in a small, specialized and directed working group, we organized and hosted a week-long task-force meeting at IIASA under the aegis of the Project on Ecologically Sustainable Development of the Biosphere (participants are listed in Appendix I). Our objective was to discuss and determine potential collaborators, structure, schedule, funding sources, coordination, and research tasks within an international network of research on the impacts of changes in climate and atmospheric chemistry on northern forest ecosystems and their transition zones into other ecosystems.

No formal papers were presented at the meeting. Rather, we worked in small groups to develop initial ideas on what objectives should be pursued in a collaborative research program on this topic, what the state of current knowledge is related to the objectives, what the relevant research questions are, and what research designs should be developed to address the main open questions. In this report of the meeting, we summarize the discussions and present working-group reports that pose and provide background and rationale for a focussed, circumscribed set of answerable questions.

OBJECTIVES FOR AN INTERNATIONAL COLLABORATIVE RESEARCH PROGRAM

Participants at the workshop were asked to discuss what objectives should be pursued within an international collaborative research program on the theme of responses of boreal forests to a changing climate and atmosphere. The following list is meant to give guidance to the kinds of research that should be undertaken. Thus, the objectives should be:

1. to search for historical patterns in the relationships between changing climate and atmospheric composition, and boreal-forest behaviour;

2. to define the sensitivities of boreal forests to future changes in climate and atmospheric composition;

3. to produce internally consistent and comparable scenarios of possible boreal-forest response in different regions to changing climate and atmospheric composition over the next 100 years;

4. to explore the possible ecological and socio-economic impacts of boreal-forest change in response to changing climate and atmospheric composition; and

5. to explore possible strategic policy options, including technical, institutional, and research/monitoring activities, for managing the consequences of changing climate and atmospheric composition on boreal-forest ecosystems.

RESEARCH THEMES, RATIONALE AND SYNOPSIS OF REQUIRED RESEARCH

With the objectives above as a guide, workshop participants developed research proposals around themes spanning spatial scales from ecosystem microcosms (where responses of individual plants could be gauged) through stand/forest levels to economic regions. The themes are described in summary form below (they are developed more fully in the Appendices), with an indication of what kinds of research participants saw as most useful in addressing the key uncertainties.

1. Historical responses of boreal-forest stands to changing climate and atmosphere - correlational data analyses

Global climate warming over the past 100 years has been well documented by climate researchers. Models of annual variation of temperature strongly suggest that the increase is due to increased concentrations of radiatively active gases, especially CO_2, in the atmosphere. However, studies of the effects of long-term historic and pre-historic climatic change on boreal forests are few. Yet it is precisely these kinds of studies, i.e., studies that illuminate past behaviour of boreal forests under changing climatic conditions, and include searches for the mechanisms linking forest response to the climatic changes, that will help improve the scientific basis and plausibility of scenarios of possible future responses of boreal forests to further climatic change. Thus, the main question in such historical studies becomes: how have boreal forests responded to climatic change and increased atmospheric CO_2 during the past 100-150 years and over millennia, and what mechanisms have controlled the responses?

The approach to historical reconstruction should involve formulation of a new set of perceptions, and new questions and hypotheses, followed by re-interpretation of extant data, followed by gathering of critical new data needed to falsify hypotheses. Thus, one approach would begin by reviewing the relevant concepts, recasting the initial questions, more clearly articulating the main hypotheses, and making more realistic the methods of data collection and analysis. Next, meteorological records could be examined to determine the nature of climate change and variability on a region-by-region basis across the boreal zone. Then, a set of forest growth and depletion studies for a series of north-south boreal-forest transects would be undertaken, using existing data where available and adequate, and launching new field work where existing data are inadequate (likely the majority of cases). The climate and forest data sets would then be analysed for correlations between forest-response variables such as growth, regeneration and depletion, and variables of climatic change and variability. Finally, the mechanisms controlling forest behaviour under conditions of climatic change would be postulated and checked against current understanding as embodied in the literature and in forest-response simulation models.

As in the other studies recommended is this paper, the reconstruction of historical patterns of boreal-forest behaviour under conditions of changing climate should be an international collaborative effort. Since the investigations will likely require new field work on patterns of forest behaviour, a decade at least will be required to complete such a study.

2. Response of boreal ecosystems to warm and enhanced-CO_2 environments - physical experiments

Our ability to predict the response of boreal ecosystems to a changed climate and atmospheric chemistry is limited significantly by the lack of information on individual-tree response at physiological and morphological levels. This is primarily because: (a) studies on boreal forests have been typically at the stand level - there is little information at the organismal level to enable modelling of tree responses; and (b) our knowledge of biotic responses to changing temperature and precipitation is general and qualitative - specific quantitative information on the variability of temperature and precipitation and how trees (and other components such as soil decomposers, insects and diseases) respond to variability and change is lacking. The same is true of CO_2-fertilization responses. The key unknowns at the organism level are tree responses to CO_2 "fertilization" and to altered (i.e., increased) variability and extremes of temperature and precipitation, particularly in the winter months, but also in the fall and spring coinciding with freeze-hardening processes and bud flush, respectively.

There have been no field experiments in which climatic (temperature and precipitation) or CO_2 conditions have been modified for an intact forest microcosm. The boreal forest is recommended as the first forest system to receive such study. Two types of experiments are required at the tree-level, with the overall focus on dominant tree species at 8-12 sites across the boreal forest.

One type of experiment would involve a set of open-top chambers or FACE (Free-Air CO_2 Exchange) apparatus for two age classes, 5-10 and 60-80 years post-fire. For each, the treatments would include at least two levels of each of elevated air temperature and elevated atmospheric CO_2 concentration. Measurements would be made of appropriate variables to answer the following questions:

1. How can a temperature increase or decrease of 1 C to 5-10 C affect boreal forests that normally experience annual temperature amplitudes of 50-80 C?

2. What tree and soil components and processes in boreal forests are most sensitive to extreme climatic events? What kinds and severity of damage occur in "typical" extreme events? Do the trees recover, and if so does recovery require more time than the interval between extreme incidences?

3. What changes do average and extreme climatic shifts induce in nitrogen fixation, soil decomposition and nutrient cycling?

4. Does an enhanced CO_2 level produce a direct and sustained increase in net primary productivity (NPP), or do plants adjust to the new level and resume growth at pre-enhancement levels?

5. How do biological processes other than NPP respond? Does carbon allocation to roots or to reproduction increase? Does tissue quality (e.g., C/N ratio, concentration of N, P, K) change? Is meristematic activity (e.g., cambial growth, budset, lifespan) including fitness (e.g., frost hardiness) and resistance (e.g., to pathogens, pests) altered? What happens to water-use efficiency?

6. Under enhanced CO_2 levels, do shrub competition and moss/lichen growth change relative to trees?

A second type of experiment would examine the genotypic limits of trees to new climates to determine the potential for species acclimation. Here, the genotypic strains of the dominant boreal tree species would be tested for frost hardening and budset/budflush under the altered CO_2 and temperature conditions as above. Several genetic strains (provenances) of each species would be grown for consecutive growing seasons under controlled temperature and photoperiod. The endpoints to be emphasized would be quantitative measures of acclimation limits and rates, growth performance, and freeze-hardening and shoot- and bud-flush in relation to frost, parasites, and herbivores. The main hypotheses to be tested would be that tree species will acclimate to increased CO_2 and temperature, and that different species and provenances will exhibit different rates and limits in their ability to acclimate.

Because of the considerable expense in establishing these kinds of experiments, the work will require the cooperation of several funding agencies in each participating country. Moreover, the funding will have to be secured for as long as a decade, as the timeframe for completing the experiments is about that long.

3. Response of boreal ecosystems to raised or lowered levels of soil moisture - physical experiments

Future responses of boreal-forest ecosystems to changing climate may have as much to do with changing precipitation regimes as with changing temperature conditions. Indeed, changed water conditions will likely influence soil/plant relations more strongly than changed temperature conditions, especially since the influence of changing soil temperature on plants will be significantly modified by the changing moisture regime. Thus, assessments of the sensitivities of forested boreal ecosystems to changing climate will have to take account of anticipated changes in precipitation and thus soil moisture regimes. Yet the current knowledge for doing so is grossly inadequate. Therefore, there is a need to undertake a series of physical experiments throughout the boreal zone in which investigators variously drain or flood replicated plots of trees to test specific hypotheses about ecosystem responses to changing moisture regimes.

For example, in Western Canadian forested bogs under a scenario of reduced moisture, investigators could manipulate ecosystems by draining water from such bogs in summer and removing snow in winter to test such hypotheses as: (a) lower soil-moisture availability will lead to increased peat oxidation, increased CO_2 and methane fluxes to the atmosphere, and increased tree growth and wood quality; (b) smaller accumulations of snow will lead to deeper frost penetration, greater moisture stress in spring, and vegetation decline; (c) lower soil-moisture availability will lead to greater grass dominance, increased probability and intensity of fire, and consequently accelerated rates of peat oxidation; and (d) lower soil-moisture availability will lead to drier organic soils, and deeper fire depths in organic soil layers, resulting in a change from organic-soil systems to mineral-soil systems. Such experimental sites should be located on or near transects used in the permanent-plot monitoring system outlined below.

4. Long-term behaviour of boreal-forest stands in the face of changing atmosphere and climate - monitoring of permanent plots

The most effective check on the performance of simulation models is to compare the behaviour of their response variables with actual behaviour of the systems they represent. Because meaningful simulation work that attempts to define sensitivities of boreal forests to changing atmosphere and climate covers long time horizons, the measurement of actual behaviour of boreal forests also needs to be carried out over protracted time periods. Some such measurement could (and will) be carried out using satellite-based remote sensing; however, as with any remote-sensing application, there is a need for ground-truth measurements to establish the level of reliability of the interpretation of remotely sensed data.

These arguments suggest that a vital part of any assessment of the long-term responses of boreal forests to changes in climate and atmospheric composition will be the establishment and maintenance of a permanent monitoring system composed of a network of forest plots and transects where a suite of ecological measurements are periodically made. In addition to checking the performance of simulation models and remote-sensing programs, the data from such a monitoring network can also be used in preparing ecological characterizations of the boreal forest, and can provide the critical benchmarks for simulation and measurement of future changes presumably caused by changing climate and atmosphere.

Transects along which permanent plots would be located should be laid out consistent with those to be simulated in the work described below on modelling of sensitivities of boreal-forest stand responses. They should be representative of the forests or biomes in which they occur, and should extend well into adjacent biomes. In addition, they should encompass both natural and managed vegetation, and should include existing study sites. The types of data collected at each plot would include forest variables such as composition, tree variables such as bole diameter and total height, and soil variables such as depth to permafrost in late summer and soil porosity. Initial network design would require two years before full field seasons could get underway.

5. Development of comprehensive databases on ecological characteristics of the world's boreal forests, and silvical characteristics of the world's boreal tree species - literature review and data synthesis

An ecological characterization is "a description of the important components and processes comprising an ecosystem and an understanding of their functional relationships" (Hirsch 1980, p. 87). Thus, it is essentially a synthesis of all current ecological information and knowledge about a particular ecosystem or set of ecosystems. Ecological characterizations serve two essential purposes: (a) they provide the basic understanding to build ecosystem-specific models or to parameterize general models; and (b) they indicate the current conditions at which expectations of change must be rooted. In essence, they provide qualitative and quantitative descriptions of the systems to be modelled.

Considering that the system of interest here is the entire circumpolar boreal biome, with a wide range of ecological variability, a collected set of ecological characterizations, one for each "region" of the boreal forest, would be most useful. However, such a set of ecological characterizations is not available in any form. In the literature there are good characterizations of specific boreal forests (e.g., Alaskan boreal-forest ecosystems - Van Cleve and Dyrness (1983), and Van Cleve et al. (1986)), but no comprehensive collection in one language at the disposal of the community of boreal-forest researchers. However, a tremendous amount of descriptive literature, mostly in the form of limited-circulation files and government reports, does already exist that could be used as a basis for preparing synthetic ecological characterizations of the world's boreal forests.

Successful stand- and landscape-level simulations of the impacts of climatic and atmospheric change on boreal forests depend on the availability of life-history and biogeographic information for all the tree species considered. For each species, such information includes the climatic conditions in which the species grows, the soils on which it is found, associated tree species, and its life history (e.g., reproduction, seedling development, growth and yield, reaction to competition, susceptibility to diseases and insects). For tree species in North America, life-history and biogeographic information has been synthesized in two compilations of the silvics of forest trees (Fowells 1965, Harlow et al. 1979). Unfortunately, such information has not been synthesized into such a form in English for non-North-American boreal-forest tree species.

The main objectives here should be to (a) compile comparable ecological characterizations for the major boreal-forest ecosystems of the world, (b) prepare updated descriptions of the silvics of North-American boreal-forest tree species, and (c) make a compilation of the silvics of the tree species found in the boreal forests of Scandinavia, the European part of the USSR, Western and Eastern Siberia, China and Japan. For the ecological characterizations, the boreal biome might be divided regionally as follows: Alaska, Western Canada, Eastern Canada, Sweden/Norway, Finland, European USSR, Western Siberia, Eastern Siberia, China and Japan. As a first effort, the characterizations and silvical descriptions should be based on extant data and literature. All available literature should be collected into one institution for translation and synthesis by a multi-lingual team of boreal ecologists. Both collecting the literature and building the multi-lingual team will require the cooperation and active participation of all the countries named above.

6. Response and sensitivity of boreal-forest stands and landscapes to changing atmospheric and climatic conditions - simulation modelling

The boreal forests, occupying northern latitudes where at least temperature changes over the long-term are expected to be the largest anywhere, are likely to be sensitive to expected changes in atmospheric conditions, especially temperature. So far, assessments of long-term boreal-forest response to changes in climate and atmospheric chemistry have been deficient for the following reasons:

1. They have remained qualitative at a time when scenarios of possible future climates for the world are quantified (even if still very uncertain), and the tools with which to quantify possible future response of forests to changing climate and atmospheric chemical composition are available.

2. If quantified, they have remained static at a time when the tools for gauging responses dynamically are available.

3. They have considered effects of climate without simultaneously looking at atmospheric chemistry, or vice versa, at a time when the tools for undertaking a cumulative assessment of boreal-forest response to both are available or being developed.

Thus, the time is ripe to tackle the question: how might boreal-forest stands (in terms of productivity and stand composition) and the boreal-forest limits (in terms of ecotone locations) around the world respond to long-term (100+ years) changes in climate and atmospheric chemical composition?

In pursuing such a question, the approach should be based on dynamic simulation that projects boreal-stand response from the present time through several hundred years of continuous change in climate and atmospheric chemical composition. Scenarios of possible environmental change and forest response should be constructed for north-south transects that stretch well beyond the current limits of the boreal forest (to take account of possible shifts of boreal-zone limits). Transects through Alaska, Western Canada, Eastern Canada, Norway/Sweden, Finland, West Soviet Union, West and East Siberia, and Japan are initially proposed. Points (stands) along each transect would be suitably located, and the projection of stand response to changes in climate and atmospheric chemistry would be used to construct transect responses. Boreal-forest responses should be simulated against long time series of temperature (monthly means), precipitation (monthly totals) and atmospheric chemical composition. Boreal-forest response should be represented by such variables as biomass, productivity, and growing stock. The initial work by Solomon (1986) in carrying out such simulations in Canadian tundra, boreal forests, and transition forests provides an example of how these studies could be organized.

The degree of biotic unity of the vegetation of the boreal zone and the relatively low forest-tree diversity in boreal forests invites a unified modelling approach across all the boreal forests of the world. The establishment of a unified boreal-forest simulation modelling exercise should be the beginning of a continuing (computer-assisted and function-oriented) dialogue on factors controlling pattern, process, and response to environmental change in the boreal forest. Because the network of investigations using the Jabowa-Foret type of models (Shugart 1984) is probably the broadest and furthest advanced at this time, and because of their applicability to our questions, this family of simulators seems most appropriate for initial efforts. The results of the unified boreal simulators should regularly be compared with other models parameterized for some of the same sites, and should be compared at every opportunity with field data. A set of forest-stand parameters that are required for such comparisons should be defined as an aid to field workers who wish to contribute to these comparative studies.

To undertake such a project, a set of collaborators throughout the boreal zone is needed (and indeed, is already being formed). Regional teams would be responsible for much of the basic scientific work, with a central team responsible for coordination of the modelling work and for drawing collaborators together periodically for meetings to discuss progress and results. The project would probably require 3-4 years to complete. The main product would be a first-of-its-kind assessment, in quantitative terms, of possible long-term change in the world's boreal forests due to possible changes in climate and atmospheric chemistry. Findings would be summarized in a series of sequential maps of the boreal zone, showing changes over time along the transects for the key response variables. The results should be usable in at least the following ways:

1. Since they would show to what climatic and atmospheric chemical conditions and changes boreal forests seem to be sensitive, they will permit efficient and effective identification of factors requiring highest priority for further research in pursuit of understanding of such responses.

2. They can serve as the biophysical input into assessments of economic and social responses to changes in the boreal-forest zone as a consequence of climatic and atmospheric change.

7. Response of regional boreal forests to changing climate and atmosphere in the context of forest management - simulation modelling and policy exercises

While efforts to explore the sensitivities of boreal-forest stands to changes in climate and atmospheric composition are vital, the stand level (e.g., 10^0-10^2 ha) is not generally the spatial unit of interest for either forest-management decisions or considerations of public policy. Typically, the unit of interest for forest-management considerations lies at a spatial scale of about 10^3-10^6 ha, and for considerations of public forest policy, the spatial unit of interest is usually a political domain such as an American state, Canadian province, or a European country or republic. To begin to understand the implications and significance of changes in climate and atmospheric composition on forests at a policy-meaningful level, it is necessary to build upon stand-level understanding to determine possible biophysical responses, and then to aggregate the responses up to the scale of management/policy units with a view to compare the magnitude of those responses with forest response to typical kinds of management interventions.

The basic question here is: to what degree are region-scale forests sensitive to anticipated changes in climate and atmospheric composition, compared with their sensitivity to management interventions (within limits defined by technical, economic and social constraints)? Task-force participants identified the need for a set of carefully designed, regional case studies to address this question. The case-study regions should be chosen from throughout the boreal zone with due regard for their assumed sensitivity to climatic and atmospheric change, levels of forest management, kinds of institutions involved in setting forest policy, and availability of basic forest-resources information. The case studies should all draw on a common pool of analytical support in building environmental scenarios and modelling forest responses, and should follow a common structure including: (a) definition of environmental scenarios, (b) simulation and aggregation of stand-level responses, (c) specification of forest-management regimes, (d) generation of regional forest-response scenarios, and (e) policy analyses of the constraints on and opportunities for forest management in the face of climatic and atmospheric change. Such an integrated system of case studies would require the cooperation of teams in each country where a case-study region were located, and would require several years to complete.

CONCLUSIONS

The research themes outlined above on the effects of climatic and atmospheric change on boreal-forest ecosystems cover a wide range of spatial and temporal scales. As well, they cover a wide range of organization, from the organism through populations and communities to ecosystems (indeed, ecosystems including socio-economic subsystems). Clearly, the various studies can benefit immensely from careful coordination that helps each study anchor its process mechanisms in lower hierarchical levels, and find its significance at higher levels. The coordination would also prevent wasteful duplication of effort in different countries where boreal forests exist, and would assist groups of researchers to benefit from (a) regular contact for exchange of data and information that would not normally be available through regular channels of dissemination, and (b) collaborative research arrangements for expensive, long-term, broad-scale projects that otherwise would probably not be possible.

REFERENCES

Binkley, C.S. 1988. A case study of the effects of CO_2-induced climatic warming on forest growth and the forest sector: B. Economic effects on the world's forest sector. In: The Impact of Climatic Variations on Agriculture. Volume 1. Assessments in Cool Temperate and Cold Regions (M. Parry, T.R. Carter, and N.T. Konijn, editors), pp. 197-218. Reidel, Dordrecht, the Netherlands.

Chen, R. and M. Parry (editors). 1987. Policy-Oriented Impact Assessment of Climate Impacts. Research Report RR-87-7, International Institute for Applied Systems Analysis, Laxenburg, Austria. 54 pp.

Fowells, H.A. 1965. Silvics of Forest Trees of the United States. United States Department of Agriculture Forest Service, Agriculture Handbook Number 271. U.S. Government Printing Office, Washington, D.C. 762 pp.

Harlow, W.M., E.S. Harrar, and F.M. White. 1979. Textbook of Dendrology. McGraw-Hill, New York. 510 pp.

Hirsch, A. 1980. The baseline study as a tool in environmental impact assessment. In: Biological Evaluation of Environmental Impacts, pp. 84-93. FWS/OBS-80-26, Fish and Wildlife Service, U.S. Department of the Interior, Washington, D.C.

ICSU Ad Hoc Planning Group on Global Change (IGBP). 1986. Terrestrial Ecosystems and Atmospheric Interactions. Report of the Working Group on Terrestrial Ecosystems and Atmospheric Interactions. International Geosphere-Biosphere Programme, International Council of Scientific Unions, Paris, France.

Kauppi, P. and M. Posch. 1988. A case study of the effects of CO_2-induced climatic warming on forest growth and the forest sector: A. Productivity reactions of northern boreal forests. In: The Impact of Climatic Variations on Agriculture. Volume 1. Assessments in Cool Temperate and Cold Regions (M. Parry, T.R. Carter, and N.T. Konijn, editors), pp. 183-195. Reidel, Dordrecht, the Netherlands.

Manabe, S. and R.T. Wetherald. 1986. Reduction in summer soil wetness induced by an increase in atmospheric carbon dioxide. Science 232:626-628.

Parry, M., T.R. Carter, and N.T. Konijn (editors). 1988. The Impact of Climatic Variations on Agriculture. Volume 1. Assessments in Cool Temperate and Cold Regions. Reidel, Dordrecht, the Netherlands. 876 pp.

Rosenzweig, C. and R. Dickinson (editors). 1986. Climate-Vegetation Interactions. Workshop Proceedings, Report OIES-2, Office of Interdisciplinary Earth Studies, University Corporation for Atmospheric Research, Boulder, Colorado. 156 pp.

Solomon, A.M. 1986. Linking GCM climate data with data from static and dynamic vegetation models. In: Climate-Vegetation Interactions (C. Rosenzweig and R. Dickinson, editors), pp. 95-98. Workshop Proceedings, Report OIES-2, Office of Interdisciplinary Earth Studies, University Corporation for Atmospheric Research, Boulder, Colorado.

Shugart, H.H. 1984. A Theory of Forest Dynamics: The Ecological Implications of Forest Succession Models. Springer-Verlag, New York. 278 pp.

Van Cleve, K. and C.T. Dyrness (editors). 1983. The structure and function of a black spruce forest in relation to other fire-affected taiga ecosystems. Canadian Journal of Forest Research 13:695-916.

Van Cleve, K., F.S. Chapin, P.W. Flanagan, L.A. Viereck, and C.T. Dyrness. 1986. Forest Ecosystems in the Alaskan Taiga. Springer-Verlag, New York. 230 pp.

APPENDIX I

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APPENDIX II

HISTORICAL PATTERNS OF CHANGE IN CLIMATE, ATMOSPHERE AND FOREST RESPONSE

Rapporteur - Allan Auclair

INTRODUCTION AND RATIONALE

Global climate warming over the past 100 years has been well-documented by climate researchers. The change of annual mean temperature in the northern hemisphere is estimated to be 0.6 C over the 1880-1985 period (Jones et al. 1985). Models of annual variation in temperature strongly suggest the increase is due largely to the enhanced greenhouse effect (Hansen et al. 1983). The rise in atmospheric CO_2 since 1958 has been approximately 10% (315 to 340 ppm) and as much as 26% (270 to 340 ppm from 1850 to 1983) over the life of most mature boreal forests.

Studies of effects of long-term climate changes on boreal forests are few. The most notable topics of inquiry have been the effects on the tree line, and on tree growth as evidenced in tree rings. A comprehensive synthesis is lacking.

There are sound reasons for an emphasis on historical reconstructions in a research program on forest response to changing climate and atmosphere:

(a) there is ready access to a plethora of databases, many of them automated, and including survey and monitoring information, literature, dendrochronology, and pollen stratigraphy;

(b) the approach is relatively inexpensive (emphasizing synthesis rather than acquisition of new data) and would result in high returns within a short timeframe;

(c) existing data are rich in biological and biophysical observations that are more likely to yield realistic insight into the mechanisms of climate-forest interactions than other approaches, especially at an inception stage;

(d) the historical approach has a high potential to identify clear signals in the biosphere that CO_2 warming (and concentration changes) has had or is having an effect; it is improbable that other approaches than careful reconstruction can provide an effective substitute; and

(e) rapid progress in assembling concrete, factual evidence of the impacts of warming is likely to be convincing and saleable to funding agencies, governments, industry and the public.

The principal research questions that need to be addressed in historical-reconstruction work are:

(1) What have been the climate and CO_2 changes within the major regions of boreal forest?

(2) Have significant biological effects already occurred?

(3) What are the mechanisms of interaction? How can an increase of 0.6 C in annual mean temperature have a marked impact on an ecosystem experiencing annual variations of 50-100 C?

(4) What data exist to enable an historical evaluation of atmospheric changes and biological responses?

LITERATURE REVIEW

Question 1: What have been the climate and CO_2 changes within the major regions of boreal forest?

Climatologists have recently succeeded in removing the bias and errors that have typically been part of long-term global meteorological datasets. The corrections have included data-punching errors, and errors arising from changes in instrument design and collection criteria, relocation of recording stations, the "urbanization effect", and unequal spatial distribution of stations. Two datasets that have achieved these corrections for the northern hemisphere stand out, viz. Jones et al. (1985) and Hansen and Lebedeff (1987). Since these are stratified by zones, regional maps, or grids, it is possible to identify specific regions of interest such as the boreal forest. The trend in annual mean temperature in the zone north of 64.2°N from Hansen et al. (1983) indicates warming since the 1880s with sharp increases in the 1920s, 1930s and early 1980s. This variability contrasted with the gradual, consistent temperature increase in the southern hemisphere. In a recent analysis, Hansen and Lebedeff (1987) indicated that 1980 and 1981 were the warmest years on instrumental record and the recent warming (1965 to 1985) has been evident at all latitudes; this contrasted to the decades of the 1930s and 1940s in which warming was primarily at the poles. Wigley et al. (1980) analyzed one-hundred year records and showed large regional discrepancies in temperature and precipitation changes over boreal areas. Historical evidence indicates warming has occurred primarily in the winter months (von Rudloff 1967). There is tentative evidence that periods of rapid climate change may be accompanied by extreme events (Karl et al. 1984).

Data on changes in atmospheric chemistry are recent, although some histories have been compiled for CO_2, CH_4, SO_2, NO_x emission rates, and in some cases estimates of atmospheric concentrations have been made (Keeling 1986, Husar 1986). These gases are not uniform regionally and vary seasonally. Atmospheric CO_2 levels, for example, were found to be low in the southern hemisphere and increase from the equator toward the North Pole; seasonal differences are more pronounced at high northern latitudes (Keeling 1986).

Question 2: Have significant biological effects already occurred?

A brief review was made of climate-related forest changes in Quebec. Black spruce (Picea mariana (Mill.) B.S.P.) at treeline in northern Quebec showed very slow growth between 1400 and 1880. A marked increase occurred after 1880, reaching a peak in the 1930s decade, corresponding to a general global warming trend over the last century (Payette et al. 1985). White spruce (Picea glauca (Moench) Voss) at its forest limits expanded significantly during the last 100 years as evidenced in population age profiles. Expansion began around 1880 but was more important between 1920 and 1965. Although the latitudinal treeline did not change, seed regeneration increased 100 meters above the pre-1880 altitudinal limit and increased within existing stands, resulting in high tree densities within a population of young cohorts (Payette and Filion 1985). Associated with these changes, some mammals also expanded their northern limit; a dendrochronological analysis of feeding scars indicated that the porcupine population (Erethizon dorsatum) expanded significantly during the 20th century and especially over the last 25 years. This corresponded to climate change with a time lag of several decades (Payette 1987). On the southern periphery of boreal forests in Quebec, successive diebacks on black ash (Fraxinus nigra Marsh.), white and yellow birch (Betula papyrifera Marsh, B. alleghaniensis Britton) and sugar maple (Acer saccharum Marsh.) each corresponded to marked temperature increases in the 1920s, 1930s and 1980s respectively (Auclair 1987). The overall pattern suggested by these data is forest expansion at the northern limits of the boreal zone concurrent with forest decline in transitional forest on the southern margin.

A change in fire frequency is suggested by increased frequency of red pine (Pinus resinosa Ait.) at its northern limit in Quebec over the 1815-1855 and 1925-1985 periods (Bergeron and Gagnon 1987). The high fire frequency in 1961, 1979 and 1980 over boreal areas suggests a link to the generally warm, dry conditions in those three years (Harrington 1982).

Surveys on insects and diseases have been systematically made in Canada since 1936, but long-term trends have been assembled only in exceptional cases; rhythms in spruce-budworm (Choristoneura fumiferana Clem.) populations, for example, have been reconstructed in detail (Kettela 1983, Royama 1984). Links between insect levels and long-term climate change have not been attempted and are complicated by an evolution of forest management and insect control practices.

A review of CO_2-induced effects on boreal forests was not attempted. The most frequently cited tree studies are those of Lamarche et al. (1984), Sionit et al. (1985) and Tolley and Strain (1984a, 1984b, 1984c). Their reports suggest the following responses may have occurred historically: increased (radial) growth rate, plant height, leaf area and number of leaves; increased water-use efficiency; altered root/shoot ratio; and increased tissue C/element ratios. Individual tree species responded differently suggesting shifts in the competitive balance between species; tree species also acclimatized to the higher CO_2 at different rates. Other effects may include increased flower and seed production, vegetative sprouting, and altered phenology and senescence, nutrient availability and herbivory (Oechel and Strain 1985).

Question 3: What are the mechanisms of interaction?

A review of forest dieback in northern hardwoods indicated that climate extremes such as the lack of snow cover, exceptionally warm winter weather, or extremes of summer soil temperature and/or drought was likely the source of damage on root systems. Root damage and mortality preceded symptoms of crown dieback (Auclair 1987). There was some evidence that fine roots may be more sensitive to stresses than other tree tissues. In an historical analysis, this possibility needs further consideration as does the likelihood that periods of climate change were accompanied by extreme climatic events affecting the soil microclimate.

Question 4: What data exist to enable an historical evaluation of atmospheric changes and biological responses?

Appendix IIa enumerates parameters on which data should be sought. There is undoubtedly a great deal of systematic information on boreal forests within government survey and monitoring programs that has not yet been published. Some recent attempts to compile historical information have been made, for example, by the Carbon Dioxide Information Analysis Center (1987) at Oak Ridge, USA.

REQUIRED STUDIES

The principal question that arises is whether recent warming and increased CO_2 have already had a general impact on the boreal forest ecosystem. If so, what have these impacts been? It is suggested that the following hypotheses be tested:

Hypothesis I: Climate warming due to the enhanced greenhouse effect already has occurred and has had a measurable impact on boreal-forest ecosystems.

Positive effects include increased tree growth and increased tree colonization; negative effects include increased depletions due directly to physical stress (drought, frost, ice and wind damage) and indirectly due to increased insects, diseases, fire and dieback.

Hypothesis II: The primary mechanism of growth depletion due to climate warming consists of extreme climatic events associated with the onset of rapid warming or cooling episodes.

Extreme climatic events included severe cold, heat episodes, drought and flooding.

Hypothesis III: Under climate warming, net tree production has exceeded losses to depletions on the northern limits of boreal forest; depletions have exceeded net tree-production gains in southern boreal forest and in transitional mixed hardwoods.

Hypothesis IV: The effect of increased carbon dioxide on boreal-forest ecosystems has been to increase net carbon assimilation in trees as well as other plants.

Other changes include increased shrub growth relative to tree growth, altered shoot/root ratio, and increased C/element ratios in plant tissues.

The approach to historical reconstruction should not be a conventional literature review or a systematization of existing data. A very important step will involve formulating a set of new perceptions, questions and hypotheses before approaching the data. The basic premise of the work is to re-interpret existing information in a new light and in a synthetic fashion. Until now this has been done only in a very limited way.

Step 1: The first step recommended is an analysis of the problem, specifically a formal problem analysis with the aim of exploring more broadly the four hypotheses around a specific geographic area and set of data. The objective is to test, elaborate and otherwise modify the hypotheses and methods to ensure the concepts and initial questions are realistic.

Step 2: Analysis of meteorological records for regions of boreal forest (and transition zones to forest-tundra and mixed hardwoods). The emphasis will be on using existing, enhanced, gridded hemispheric datasets such as those compiled by the Norwich (Jones et al. 1985) and NASA (Hansen and Lebedeff 1987) groups.

Step 3: Growth/depletion studies across north-south boreal-forest transects. The goal is to test Hypotheses I, III and IV using existing data and if essential, acquire data or define the data gaps on population age structure, tree growth by stem analysis, and losses to fire and other depletions.

Step 4: Test Hypothesis II. Relate growth and depletion patterns to climatic characteristics derived in Step 2. Emphasis will be given to deducing mechanisms that explain the enhanced growth and/or depletion levels.

Step 5: Incorporate mechanisms into existing simulation models or those under development.

LITERATURE CITED

Auclair, A.N. 1987. Climate change theory of forest declines. Unpublished manuscript. Atmospheric Environment Service, Canada Department of Environment, Downsview, Ontario, Canada. 25 pp.

Bergeron, Y. and D. Gagnon. 1987. Age structure of red pine (Pinus resinosa Ait.) at its northern limit in Quebec. Canadian Journal of Forest Research 17:129-137.

Carbon Dioxide Information Analysis Center. 1987. Publications and other documents. CDIAC, Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

Hansen, J.E. and S. Lebedeff. 1987. Global trends of measured surface air temperature. Manuscript submitted to GJB. 35 pp.

Hansen, J., D. Johnson, A. Lacis, S. Lebedeff, P. Lee, D. Rind, and G. Russell. 1983. Climatic effects of atmospheric carbon dioxide. Science 220:874-875.

Harrington, J.B. 1982. A statistical study area burned by wildfire in Canada. Canadian Forestry Service, Department of the Environment, Information Report PI-X-16, Ottawa, Canada. 32 pp.

Husar, R.B. 1986. Emission of sulfur dioxide and nitrogen oxides and trends for eastern North America. In: Acid Deposition: Long-Term Trends, pp. 48-92. National Academy Press, Washington, D.C., USA.

Jones, P.D., S.C.B. Raper, R.S. Bradley, H.F. Diaz, P.M. Kelly, and T.M.L. Wigley. 1985. Northern hemisphere surface air temperature variations: 1851-1984. Journal of Climatology and Applied Meteorology 25:161-179.

Karl, T.R., R.E. Livezez, and E.S. Epstein. 1984. Recent unusual mean winter temperature across the contiguous United States. Bulletin of the American Meteorological Society 65:1302-1309.

Keeling, C.D. 1986. Atmospheric CO_2 concentrations - Mauna Loa Observatory, Hawaii 1958-1986. Report NDP-001/R1. CDIC Numeric Data Collection, Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

Kettela, E.G. 1983. A cartographic history of spruce budworm defoliation 1967 to 1981 in eastern North America. Canadian Forestry Service, Canada Department of Environment, Information Report DPC-X-14, Ottawa, Canada.

Lamarche, V.C., D.A. Graybill, H.C. Fritts, and M.R. Rose. 1984. Increasing atmospheric carbon dioxide: tree ring evidence for growth enhancement in natural vegetation. Science 225:1019-1021.

Oechel, W.C. and B.R. Strain. 1985. Native species responses to increased carbon dioxide. In: Direct Effects of Increasing Carbon Dioxide on Vegetation (B.R. Strain and J.D. Cure, editors), pp. 117-154. United States Department of Energy, Office of Energy Research, Report DOE/ER-0238, Washington, D.C., USA.

Payette, S. 1987. Recent expansion at tree line: a dendroecological analysis. Canadian Journal of Zoology 65:551-557.

Payette, S. and L. Filion. 1985. White spruce expansion at the tree line and recent climatic change. Canadian Journal of Forest Research 15:241-251.

Payette, S., L. Filion, L. Gauthier, and Y. Boutin. 1985. Secular climate change in old-growth tree-line vegetation of northern Quebec. Nature 315:135-138.

Royama, T. 1984. Population dynamics of the spruce budworm Choristoneura fumiferana. Ecological Monographs 54(4):429-462.

von Rudloff, H. 1967. Die Schwankungen und Pendelungen des Klimas in Europa seit dem Beginn der regelmässigen Instrumenten-Beobachtungen (1670). Veiweg, Braunschweig, FRG.

Soinit, N., B.R. Strain, H. Hellmers, G.H. Reichers, and C.H. Jaeger. 1985. Long-term atmospheric CO_2 enrichment effects and the growth and development of Liquidambar styraciflua and Pinus taeda seedlings. Canadian Journal of Forest Research 15:468-471.

Tolley, L.C. and B.R. Strain. 1984a. Effects of CO_2 enrichment on growth of Liquidambar styraciflua and Pinus taeda seedlings under different irradiance levels. Canadian Journal of Forest Research 14:343-350.

Tolley, L.C. and B.R. Strain. 1984b. Effects of CO_2 enrichment and water stress on growth of Liquidambar styraciflua and Pinus taeda seedlings. Canadian Journal of Botany 62:2135-2139.

Tolley, L.C. and B.R. Strain. 1984c. Effects of CO_2 enrichment and water stress on gas exchange of Liquidambar styraciflua and Pinus taeda seedlings grown under different irradiance levels. Oecologia 65:166-172.

Wigley, T.M.L., P.D. Jones, and P.M. Kelly. 1980. Scenario for a warm, high-CO_2 world. Nature 283:17-21.

APPENDIX IIa

LIST OF FOREST COMPONENTS MOST LIKELY AFFECTED BY CLIMATE CHANGE

A change in climate is expected to affect a wide spectrum of forest processes and forest-management operations. To date, most attention on the issue of climate warming has focussed on forest boundaries, and on growth enhancement due to CO_2 fertilization and to temperature/precipitation changes. This is a small fraction (2 of 17 topics identified below) of the total range of forest responses suggesting the need to examine other effects, particularly where these result in economic loss to the forest sector.

I. FOREST PRODUCTION

1.	Regeneration	Incidence of NSR (non-sufficiently restocked) Land Seedling Production in the Nursery Species Selection Site Preparation Planting Seedling Establishment and Survival
2.	Growth*	CO_2 Enhancement Temperature/Precipitation Relations Soil Organic Matter and Nutrient Dynamics Soil Water
3.	Wood Quality	Tree species (e.g., number of rings/inch)
4.	Forest Boundaries*	Tree-line Grassland/Wetland Borders Agricultural Displacement

II. FOREST DEPLETION

5. Fire
6. Insects
7. Diseases
8. Decline and Diebacks
9. Windthrow
10. Icing/Winterkill/Frost Damage
11. Flooding/Landslides

III. FOREST HARVESTING/TRANSPORTATION/STORAGE

12. Trafficability of Harvesting Machines
13. Landslides/Flooding
14. Fire Hazard
15. Road/Water Transportation
16. Wood Storage

IV. FOREST ECONOMICS AND POLICY

* focus of recent research

APPENDIX III

RESPONSE OF BOREAL ECOSYSTEMS TO WARM AND ENHANCED-CO_2 ENVIRONMENTS - PHYSICAL EXPERIMENTS

Rapporteur - Allan Auclair

BACKGROUND

Our ability to predict the response of boreal ecosystems to a changed climate and atmospheric chemistry is limited by the lack of specific information on what the climatic changes will be and on how individual tree species will respond at a physiological and morphological level. Two reasons for this are: (a) studies on boreal forests have been typically at the stand level: there is little information at the tree level to enable simulations of tree responses; and (b) our knowledge of temperature and precipitation responses is general - specific information on the variability of temperature and precipitation and how trees (and other components, e.g., soil decomposers, insects and diseases) respond to variability is lacking. The same is true of CO_2-fertilization responses.

The largest unknowns at the tree level are tree responses to CO_2-"fertilization" and to altered (i.e. increased) variability and extremes of temperature and precipitation, particularly in the winter months, but also in the fall and spring coinciding with freeze-hardening processes and bud flush, respectively.

JUSTIFICATION

One of the principal reasons for interest in the boreal forests is their large potential contribution to the global carbon balance. In addition they contribute in a major way to the national economies of the countries they occupy. The boreal forests occupy about one-fifth of the terrestrial land area, and are rich in carbon storage both in above-ground biomass and in soil organic matter. Moreover, they experience the largest annual amplitudes of temperature and CO_2 of any forest system; they are expected to contribute greatly to methane injection into the atmosphere and to undergo the largest temperature increases. The results are expected to include changes in species composition, forest boundaries, ecosystem primary production, and carbon storage. With the information currently available, it is not possible to predict with confidence the effect of altered temperature and elevated CO_2 regimes on these indicators.

There has been no field experiment which has modified the climatic (temperature and precipitation) or the CO_2 environment of any intact forest ecosystem. The boreal forest is recommended as the first forest system to receive such a study. The reasons for this are several-fold:

(a) the boreal forest can be studied through the cooperation of a relatively small number of countries;

(b) good communication exists among scientists working in the various nations of this region;

(c) knowledge of the response to altered climate and to elevated CO_2 of less than 6 genera and 20 species will include the major dominant trees of the boreal zone; and

(d) there is strong economic interest in forestry and other natural resources that are likely to be strongly affected.

REQUIRED STUDIES

Two types of experiments are required at the tree level. The overall focus should be on dominant tree species at 8-12 sites across the boreal forest.

Warming and CO_2-Fertilization Experiments

The establishment of a coordinated circumboreal field warming and CO_2 fumigation experiment is proposed. Field studies at selected sites are recommended in the dominant forest types across the major regions of boreal forest (Table III-1).

Table III-1. Proposed main species of interest and locations for a coordinated set of field warming and CO2-fumigation experiments in the boreal forest.

COUNTRY	SPECIES	PROPOSED LOCATION
USA	*Picea mariana*	Fairbanks
	Abies balsamea	Northeast USA
CANADA	*Picea glauca*	British Columbia Interior
	Picea mariana	Ontario/Quebec
SCANDINAVIA	*Picea abies*	Sweden/Finland
	Pinus silvestris	Finland/Sweden
USSR	*Picea abovata*	West Siberia
	Abies siberica	West Siberia
	Larix siberica	East Siberia
CHINA	to be determined	northern China
JAPAN	*Abies sachalimensis*	Hokkaido Island
	Picea glehnii	Hokkaido Island
	Picea jezoensis	Hokkaido Island

Note: further consideration of key deciduous species such as *Betula* spp. and *Populus* spp. is required.

Hypotheses and Research Questions

Hypothesis I: Climatic warming is associated with extreme climatic variability of temperature and precipitation; the extreme temperature precipitation events ultimately have the largest detrimental impact on trees and other ecosystem components and incites damage and mortality either directly or through the secondary action of pathogens and fire.

Research Questions:

I-1. How can a temperature increase or decrease of 1 C to 5-10 C have a strong impact on a boreal forest that normally experiences annual temperature amplitudes of 50-180 C?

I-2. What tree and soil components and processes in boreal forest are most sensitive to extreme climatic events? What kinds and severity of damage occur in "typical" events? Does the tree recover, and if so does recovery require longer than the average frequency of extreme incidences?

I-3. What changes occur in meristematic activity, fitness, resistance to pathogens, N-fixation, soil decomposition and nutrient cycling?

Hypothesis II: Enhanced CO_2 levels result in an initial positive NP response followed by acclimation of growth processes to pre-enhanced levels; acclimation time is inversely proportional to the magnitude of the step-increment of CO_2 level.

Research Questions:

II-1. Is an enhanced CO_2 level followed by sustained increased NPP or does the plant adjust to the new level and resume growth at pre-enhancement levels?

II-2. How do biological processes other than NPP respond? Does carbon allocation to roots or to reproduction increase? Does tissue quality (e.g., C/N, N, P, K, etc., concentration) change? Is meristematic activity (e.g., cambial growth, budset, lifespan) including fitness (frost hardiness) and resistance (to pathogenes, pests) altered? What happens to water-use efficiency?

II-3. Under enhanced CO_2 levels, do shrub competition and moss/lichen growth increase relative to trees?

II-4. What changes occur in soil processes such as decomposition, N-fixation, nutrient cycling?

Study Design

A set of open-top chambers or FACE (Free-Air CO_2 Exchange) apparatus is recommended for two age classes, 5-10 and 60-80 years postfire. On each, chambers should be replicated 2 or 3 times for the following treatments:

(a) control;
(b) CO_2 345 ppm;
(c) CO_2 680 ppm;
(d) +5 C warming; and
(e) +10 C warming.

The endpoints to be emphasized on each site are:

(a) productivity;
(b) species composition;

(c) water status;
(d) wood quality; and
(e) susceptibility to frost and drought.

The processes to be studied at the level of individual trees include:

(a) soil: nutrient cycling, temperature and moisture status;
(b) competition: among plant species including shrubs, cryptograms;
(c) growth: Net C flux (net primary production, or NPP), C allocation, meristematic activity (shoots, buds, cambium, fine roots), biomass accumulation, reproduction; losses (litter, leachate, exudation);
(d) depletions: losses to insects, diseases, herbivores, frost, drought, fire;
(e) water use efficiency;
(f) morphology: shoot/root ratios, cell/morphology, wood quality; and
(g) fitness: susceptibility/resistance to pests, frost, drought.

Genotypic Limits to Acclimation

It is recommended that genotypic strains of the dominant tree species be tested for frost hardening and budset/budflush under the altered CO_2 and climatic conditions of the warming and CO_2-enhancement experiments.

The hypothesis to be tested would be:

Hypothesis III: Tree species will acclimate to increased CO_2 and temperature; different species and provenances will exhibit different rates and limits in their ability to acclimate.

Five genetic strains (provenances) of each species should be grown for three consecutive growing seasons under controlled temperature and photoperiod in growth chambers under the following treatments:

(a) control;
(b) 345, 525, 680 ppm CO_2;
(c) 0, +5, +10 C temperature above ambient; and
(d) CO_2 x temperature factorial of above.

The indicators to be emphasized are quantitative measures of:

(a) acclimation limits and rates;
(b) growth performance;
(c) freeze-hardening in relation to frost, parasites, herbivores; and
(d) shoot, bud-fish in relation to frost, parasites, herbivores.

APPENDIX IV

RESPONSE OF BOREAL ECOSYSTEMS TO RAISED OR LOWERED LEVELS OF SOIL MOISTURE - PHYSICAL EXPERIMENTS

Rapporteur - Ross Wein

INTRODUCTION AND RATIONALE

There is now considerable support for the hypothesis that of all the world's ecosystems, the boreal forest could change the most dramatically with climatic warming resulting from enhanced carbon-dioxide levels in the atmosphere (Emanuel et al. 1985). Observational evidence of the past one hundred years (Jones et al. 1986), as well as global climatic models, provide supporting evidence.

With increased carbon-dioxide levels, the major two physical factors of temperature and moisture will change and boreal-forest ecosystems must respond to the new climatic regime. For example, air and soil temperatures will be higher in winter and will result in earlier melting of the snow cover. Lower reflectivity of the land surface will lead to warmer air and soils and a longer growing period. Permafrost degradation will result in high societal costs where ice-rich soils are common (see reviews in McBeath et al. 1984).

The moisture regimes of the boreal zone range from marine to continental around the circumpolar area. Global climatic models do not predict clearly the patterns of precipitation, but climate warming will likely lead to higher evaporation rates and more drought stress in some regions, whereas increased moisture is predicted in other regions.

Both low temperature and low moisture probably limit productivity in the boreal forest, though the literature tends to favour low temperature as the primary controlling force (e.g., Kauppi and Posch 1985). This is likely because most studies of plant productivity have been conducted in areas of higher rainfall. It is recognized that the large continental areas of the circumpolar forest, such as Northwest Canada and the Yakutian A.S.S.R., are drought- and cold-dominated, while other areas are low-temperature dominated.

If the time dimension for climatic change is in the vicinity of five decades, and boreal trees have ages that represent centuries, individual trees must obviously tolerate the new climate or die. Only then could a new population with a different genetic base have an opportunity to establish. Because there are relatively few tree species in the boreal forest, it may be possible to predict the effects of increases in temperature and changes in moisture. Synergistic factors that may severely modify the long-term succession patterns include forest fires, insects, diseases and human activities.

It is proposed that extensive experimental field studies concerning soil and vegetation responses be conducted on a number of forest types along several biome-sector permanent transects. Short-term changes on these experimental plots will be used as climatic-change indicators. It will also be important to measure rates of change of soil and vegetation processes because of important feedback mechanisms (e.g., methane and carbon-dioxide production from bogs contribute to further climatic warming).

REQUIRED STUDIES

Since climatic-change scenarios suggest that some areas within the boreal biome will receive more precipitation in summer and winter, whereas other areas will receive a reduction in moisture, a range of studies are proposed. Although there is inertia in an ecosystem, it is hypothesized that a reduction or increase in moisture stress will cause certain elements of the ecosystem to become unstable and therefore respond in a dramatic manner on a short-term basis.

The proposed research approach here is experimental, utilizing replicated plots up to 1 ha in size. Experiments should be located in forest types that are particularly important economically or that may dramatically change with climatic warming.

Examples of Hypotheses Related to Moisture-Change Scenarios

Forest-Grassland Ecosystem (Reduced-Moisture Scenario)

It is suggested that there should be a moisture-reduction experiment on forested organic terrain and another in high-production forest where the mineral soil is covered by thin organic layers. A small amount of literature provides background for this research (e.g., Peterson et al. 1983, Singh and Powell 1986). The hypotheses which stimulated this research revolve around increased organic soil oxidation, increased carbon dioxide and methane flux to the atmosphere, and increased tree growth and wood quality. Additional hypotheses will likely involve vegetation (fuel) changes that will influence the probability of forest-fire occurrence and severity.

Since it is recognized from paleoecological work that grassland-forest boundaries have shifted strongly in the past, it is hypothesized that elements of the grassland in the forest vegetation will become more dominant with climatic warming. The proposed experimental work should identify those elements of the vegetation that will show the initial change. Since it is difficult to restrict rainfall and snowfall on plots experimentally, the general approach should be to remove snow where possible and to enhance early spring melting through applications of charcoal to the snow surface in the spring. Surface and internal drainage should be enhanced to ensure that drought conditions are simulated. There will be an increased probability of fire subsequent to such a treatment. Since it is recognized that some areas do not burn simply because an ignition source is not available, fire should be excluded from some of the drained plots.

Tundra-Forest Ecotone (Increased-Moisture Scenario)

In northern Quebec, Canada, the climate-change scenarios suggest an increase in summer and winter precipitation. The hypotheses that should be tested centre on an increase in snow quantity and in summer precipitation. Tree seedlings should be transplanted into non-forested areas of the ecosystem and protected by deep snow (wind barriers should be used to accumulate snow) to determine if survival is possible. Since it is recognized that wind and snow control tree form and development, experimental deep-snow modifications could determine if krumholtz can be stimulated to develop an erect-tree growth form. Bud and needle demography as well as growth form analysis and tree ring growth trends should be examined.

INTERNATIONAL COLLABORATION REQUIRED

Communication among international scientists will stimulate the exchange of information on moisture-stress experiments. Although standardized experimental approaches are not essential, the testing of similar hypotheses is important. The importance of similar experiments in representative areas of the major vegetation types is recognized and the link between these experimental approaches and the monitoring of climatic change on the transects is essential.

LITERATURE CITED

Emanuel, W.R., H.H. Shugart, and M.P. Stevenson. 1985. Climate change and the broad-scale distribution of terrestrial ecosystem complexes. Climate Change 7:29-43.

Jones, P.D., T.M.L. Wigley, and P.B. Wright. 1986. Global temperature variations between 1891 and 1984. Nature 322:430-434.

Kauppi, P. and M. Posch. 1985. Sensitivity of boreal forests to possible climatic warming. Climatic Change 7:45-54.

McBeath, J.H., G.P. Juday, G. Weller, and M. Murray. 1984. The potential effects of carbon dioxide-induced climatic changes in Alaska. Miscellaneous Publication 83-1, School of Agriculture and Land Resource Management, University of Alaska, Fairbanks, Alaska. 208 pp.

Peterson, E.B., M.M. Peterson, and R.B. Kabzems. 1983. Impact of climatic variation on biomass accumulation in the boreal zone: selected references. Information Report NOR-X-254, Northern Forest Research Centre, Canadian Forestry Service, Edmonton, Alberta. 355 pp.

Singh, T. and J.M. Powell. 1986. Climatic variation and trends in the boreal forest region of Western Canada. Climatic Change 8:267-278.

APPENDIX V

LONG-TERM BEHAVIOUR OF BOREAL-FOREST STANDS IN THE FACE OF CHANGING ATMOSPHERE AND CLIMATE - MONITORING OF PERMANENT PLOTS

Rapporteur - Ross Wein

INTRODUCTION AND RATIONALE

Readily available literature on the boreal-forest biome tends to be regional in focus because of the large areal extent of the biome, and the few researchers and research organizations. There are major difficulties in extrapolating regional information to larger areas and in making extrapolations to other circumpolar regions.

The boundary for the monitoring study proposed here is the complete circumpolar biome. At the most inclusive level, a framework to capture the regional variability through techniques such as satellite imagery should be provided. For more detailed research, the study sites should be located along north-south transects that span the biome and include representative ecosystems.

In identifying transect locations, maximum use of existing data sets, current research, and proposed research should be made so that researchers can be attracted to specific areas and data can be better integrated to test climatic-change hypotheses. The transect focus will foster easier upscaling of data collected on intensively studied field plots and will provide bench-mark areas for monitoring indicators of climatic change.

REQUIRED STUDIES

It is presently proposed that ten transects (two in Canada, one in Fenno-Scandia/four in USSR/one in China, one in Japan and one in Alaska) be located in the major sectors of the boreal forest. In practical terms, the transects must span the range of conditions through the boreal sector into adjacent biomes. The transects may be oriented latitudinally or altitudinally through the boreal forest from temperate forest or possibly grassland into the alpine or tundra zone.

A transect may consist of a broad belt running through a range of ecosystems or it may consist of segments of intensively studied ecosystems because resources required for a full-length transect are not available. It is imperative that previous or existing study sites, government stations, protected areas and environmental monitoring stations be included because climate-change field studies will be long-term. The transect may include ecosystems that are managed to a minor degree as in conservation areas, or that are heavily managed such as plantations. These ranges of conditions are to be included because over the time span of the predicted climatic changes, intensive management of the boreal forest will continue and accelerate.

Boreal-forest researchers already recognize spatial variability within their regions of study, but in some cases, remotely-sensed data from satellite imagery may be used to locate transects.

Within a transect, it is envisaged that there will be a range of intensity of field data collection. For landscape-scale studies such as the validation of remotely sensed data or the development of forest- disturbance histories, the transects should be considered as a belt and will extend over great distances. In some cases, many semi-permanent plots will be established, for example, to check performance of stand-growth models; in this use, sufficient plots must be sampled to represent the important successional sequences. Experimental manipulative plots should be located in one or more representative vegetation types along the transect. Permanent plots for monitoring indices of climatic change should be concentrated near ecotones because this is where ecosystem components will first register the climatic-change stress.

EXAMPLES OF TRANSECTS

Western Canada

This transect would stretch from the tundra near the mouth of the Mackenzie River, south through the forest-tundra zone and the heavily forested zone, into the deciduous woodland-grasslands near the Peace River. The southern end of the transect has commercial forestry operations and the forests throughout the transect have been heavily influenced by fires. Current research programs that can be incorporated into the program include fire history mapping, use of satellite imagery, and use of forest-dynamics models in a fire-management study in Wood Buffalo National Park. Drainage experiments on forested organic soils are currently being studied in the bog-dominated areas near the southern end of the transect.

Eastern Canada

This transect would stretch 1 200 km from the arctic tundra east of Hudson Bay, through the boreal forest to the deciduous forests in the St. Lawrence River Valley. The geological formation of Precambrian Shield and the associated soils are poorly developed with low nutrient levels. Three bioclimatic zones (arctic, boreal and temperate) are recognized and the major ecological gradients include an increase in temperature and humidity from the north to the south; associated with this is a decreased fire-disturbance gradient from south to north. Logging activities and disturbance from defoliating insects are more important in the south.

Northern Japan

A 50-km transect on Hokkaido Island would stretch over the 1 500-m altitudinal gradient from the pine-dominated zone at higher elevations, through the fir-dominated zone, to the maple-dominated zone at lower elevations. Clearcutting and selective logging operations are intensive in this boreal zone, occasional storms cause major natural disturbances (wind fall), and there is periodic volcanic-ash deposition. The volcanic geology of the transect is complex. Seven to ten forest types are recognized on the steep mountainous topography.

INTERNATIONAL COLLABORATION REQUIRED

Collaboration will be required throughout the program but especially as the transect locations are established. During field-data collection, collaboration will be required to ensure uniform methods. Toward the end of the program, cooperation is needed to synthesize the data.

APPENDIX VI

DEVELOPMENT OF COMPREHENSIVE DATABASES ON ECOLOGICAL CHARACTERISTICS OF THE WORLD'S BOREAL FORESTS, AND SILVICAL CHARACTERISTICS OF THE WORLD'S BOREAL TREE SPECIES - LITERATURE REVIEW AND SYNTHESIS

Rapporteur - Peter Duinker

INTRODUCTION

Ecological Characterization of Boreal Forests

Research on the theme of impacts of changes in climate and atmospheric composition on northern forest ecosystems can be considered as a form of environmental impact assessment. In undertaking such assessment work, Hirsch (1980, p.87) has argued that "as an early step . . . , efforts must be made to understand the most salient features of the ecosystem involved". Hirsch is referring to an ecological characterization, which he defined as "a description of the important components and processes comprising an ecosystem and an understanding of their functional relationships" (p. 87). Hirsch (1980) went on to list the kinds of information that should be part of an ecological characterization:

> "The characterization should address such major elements as physiography and geology; climate; and physical transport mechanisms such as hydrology, sediment flux, . . . and atmospheric transport. It should describe the important species, communities and populations in the study area, with particular emphasis on those organisms perceived as being of importance to man or critical to the functioning of the ecosystem. Population estimates can be approximate but they should, where feasible, attempt to address the extent and causes of natural variability. The characterization should describe ecological processes, such as trophic relationships, food chains, and energy flows, particularly those considered to be or known to be controlling. It should describe social and economic features of the area (e.g., population distribution, land use, industrial development), and address significant man-induced or natural influences on the ecosystem such as successional processes, existing man-made modifications and extent of pollution."

An ecological characterization is essentially a synthesis of all current ecological information and knowledge about a particular ecosystem or set of ecosystems. For environmental-impact-assessment work, which is future-oriented and relies heavily on simulation modelling, ecological characterizations serve two essential purposes: (a) they provide the basic understanding to build ecosystem-specific models or the parameterize general models; and (b) they indicate the current conditions at which expectations of change must be rooted.

Considering that the system of interest here is the entire circumpolar boreal biome, with a wide range of ecological variability, a collected set of ecological characterizations, one for each "region" of the boreal forest, would seem to be what researchers should find most useful. However, such a set of ecological characterizations is not available in any form. There are good characterizations in the literature of specific boreal forests (e.g., Van Cleve and Dyrness 1983, Van Cleve et al. 1986), but no comprehensive collection in one language at the disposal of the community of boreal-forest researchers. However, a tremendous amount of descriptive literature, mostly in the form of limited-circulation files and government reports, does already exist that could be used as a basis for preparing synthetic ecological characterizations of the world's boreal forests.

Silvics of Boreal-Forest Tree Species

Successful stand- and landscape-level simulations of the impacts of climatic and atmospheric change on boreal forests depend on the availability of life-history and biogeographic information for all the tree species considered. For each species, such information includes the climatic conditions in which the species grows, the soils on which it is found, associated tree species, and its life history (e.g., reproduction, seedling development, growth and yield, reaction to competition, susceptibility to diseases and insects; see Figure 1.) For tree species in North America, life-history and biogeographic information has been synthesized in two compilations of the silvics of forest trees (Fowells 1965, Harlow et al. 1979). Unfortunately, such information has not been synthesized into such a form in English for non-North-American boreal-forest tree species.

REQUIRED STUDIES

The main objectives here should be to (a) compile comparable ecological characterizations for the major boreal-forest ecosystems of the world, (b) prepare updated descriptions of the silvics of North-American boreal-forest tree species, and (c) make a compilation of the silvics of the tree species found in the boreal forests of Nordic Europe, the European part of the USSR, Western and Eastern Siberia, China, and Japan. For the ecological characterizations, the boreal biome might be divided regionally as follows: Alaska, Western Canada, Eastern Canada, Sweden/Norway, Finland, European USSR, Western Siberia, Eastern Siberia, China, and Japan. As a first effort, the characterizations and silvical descriptions should be based on extant data and literature. All available literature should be collected into one institution for translation and synthesis by a multi-lingual team of boreal ecologists. Both collecting the literature and building the multi-lingual team will require the cooperation and active participation of all the countries named above.

REFERENCES

Fowells, H.A. 1965. Silvics of Forest Trees of the United States. United States Department of Agriculture Forest Service, Agriculture Handbook Number 271. U.S. Government Printing Office, Washington, D.C. 762 pp.

Harlow, W.M., E.S. Harrar, and F.M. White. 1979. Textbook of Dendrology. McGraw-Hill, New York. 510 pp.

Hirsch, A. 1980. The baseline study as a tool in environmental impact assessment. In: Biological Evaluation of Environmental Impacts, pp. 84-93. FWS/OBS-80-26, Fish and Wildlife Service, U.S. Department of the Interior, Washington, D.C.

Van Cleve, K. and C.T. Dyrness (editors). 1983. The structure and function of a black spruce forest in relation to other fire-affected taiga ecosystems. Canadian Journal of Forest Research 13:695-916.

Van Cleve, K., F.S. Chapin, P.W. Flanagan, L.A. Viereck, and C.T. Dyrness. 1986. Forest Ecosystems in the Alaskan Taiga. Springer-Verlag, New York. 230 pp.

Figure 1. Example life-history characteristics to be included in a description of the silvics of boreal-forest tree species.

Average maximum age on a good site (yr)

Average maximum diameter on a good site (cm)

Average maximum height on a good site (m)

Maximum annual diameter increment on a good site (cm)

Tolerance of shade (tolerant, intolerant)

Soil moisture preference (dry, moist, wet)

Tendency to root- or stump-sprout (none, moderate, prolific)

Tolerance of the heat generated by fire (tolerant, moderate, intolerant)

Reproduction:

- is seedling germination triggered by fire (e.g., serotinous cones)?
- is seedling germination enhanced after fire?
- can trees reproduce by layering?
- is mineral soil required for seedling establishment?

Ability to grow on sites with permafrost (good, intermediate, poor)

Ability to grow on nutrient-poor sites

Minimum and maximum growing degree days (5 C base) at the northern and southern boundaries of the geographic range of the species

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APPENDIX VII

RESPONSE AND SENSITIVITY OF BOREAL-FOREST STANDS AND LANDSCAPES TO CHANGING ATMOSPHERIC AND CLIMATIC CONDITIONS - SIMULATION MODELLING

Rapporteur - Hank Shugart

BACKGROUND AND RATIONALE

Relatively large changes in regional-global patterns of climate and atmospheric composition are expected to take place over the next several decades to centuries. Atmospheric chemistry affects trees indirectly through changes in air temperature and light quantity and quality but also directly (e.g., toxins). The boreal forests, occupying northern latitudes where temperature changes over the long-term are expected to be the largest anywhere, are likely to be sensitive to these expected changes in atmospheric conditions. In addition, it is thought that the boreal-forest zone is a major reservoir of the world's terrestrial carbon, and that it may be contributing significant amounts of methane, a radiatively active trace gas, to the atmosphere. So far, assessments of long-term boreal-forest response to changes in climate and atmospheric chemistry have been deficient for the following reasons:

(a) They have remained qualitative at a time when scenarios of possible future climates for the world are quantified (even if still very uncertain), and the tools with which to quantify possible future response of forests to changing climate and atmospheric chemical composition are available.

(b) If quantified, they have remained static at a time when the tools for gauging responses dynamically are available.

(c) They have looked at climate without simultaneously looking at atmospheric chemistry, or vice versa, at a time when the tools for undertaking a cumulative assessment of boreal-forest response to both are available or being developed.

With the call from the international research and policy communities for better understanding of the possible long-term responses of major ecosystems to expected changes in global patterns of climate and atmospheric chemical composition, and with the tools available for undertaking such assessments quantitatively, the time is ripe for an international collaborative research effort aimed at the following question.

THE BASIC RESEARCH QUESTION

How might boreal-forest stands (in terms of productivity and stand composition) and the boreal-forest limits (in terms of ecotone locations) around the world respond to long-term (100+ years) changes in climate and atmospheric chemical composition?

BOUNDS AND APPROACH

Time

The projection and scenario building proposed here would be based on dynamic simulation that projects boreal-stand response from the present time through several hundred years of continuous (whether smooth or abrupt) change in climate and atmospheric chemical composition. Thus, this is not an equilibrium, static exercise, but a dynamic one that results in time-series of possible response.

Space

Scenarios of possible response should be constructed for north-south transects that stretch well beyond the current limits of the boreal forest (to take account of possible shifts of boreal-zone limits). Transects through Alaska, Western Canada, Eastern Canada, Norway, Sweden, Finland, West Soviet Union, West and East Siberia, and Japan are initially proposed. Points (stands) along each transect should be suitably located, and the projections of stand response to changes in climate and atmospheric chemistry used to construct transect responses. Several transects involving point representations are chosen because they are the most efficient way to assess boreal-forest response over large areas - continuous transects, and particularly area-based simulations involving GIS-computing, would require exorbitant resources for inventorying current conditions and doing the computational work.

Driving Variables

Boreal-forest responses should be simulated against:

(a) temperature - monthly means (with due regard for within-month variance and extremes);
(b) precipitation - monthly totals (as above); and
(c) atmospheric chemical composition.

Time-series over tens of decades for these driving variables should be obtained from appropriate sources.

Response Variables

Boreal-forest response should be represented by:

(a)	biomass	- total (kg/ha);
		- woody (kg/ha);
(b)	productivity	- total (kg/ha/yr);
		- woody (kg/ha/yr);
		- merchantable volume (m^3/ha/yr); and
(c)	growing stock	- total merchantable volume (m^3/ha).

Simulation Tool for Projection

The most well-developed simulation tool for this purpose is of the "Jabowa-Foret" type (Shugart 1984). Versions of this "gap" model, which accounts for tree-level processes of birth, growth, reproduction, and death, have already been adapted for use in ecological assessments for many of the world's boreal forests in North America and Europe. This has been part of an effort already underway to develop a unified forest simulation model for the boreal zone. The plan here would be to build on this work in establishing a common model structure for all the simulations, and have regional teams install transect-specific functions and parameters as required/desired.

The degree of biotic unity of the vegetation of the boreal zone (e.g., many of the mosses, trees and shrubs differ only at the genus level across continents) and the relatively low tree-species diversity in boreal forests invites a unified modelling approach across all the boreal forests of the world. In addition, a unified simulation modelling exercise has many benefits. For example, the development of a community GCM (general circulation model) at the NCAR facility in the USA has provided the atmospheric modelling community with considerable ability to compare results for different simulated world climates and serves as a standard on which discussions about which functions should be added to or deleted from the evolving model could be based. In a similar vein, the establishment of a unified boreal-forest simulation modelling exercise should be the beginning of a continuing (computer-assisted and function-oriented) dialogue on factors controlling pattern, process, and assisted and function-oriented) dialogue on factors controlling pattern, process, and response to environmental change in the boreal forest. However, the model should not be considered as an end in itself. Other general modelling approaches could certainly add to the spirit of the exercise, although at this time the network of investigators using the Jabowa-Foret type of models is probably the broadest and furthest advanced. The results of the unified boreal simulators should regularly be compared with other models parameterized for some of the same sites, and should be compared at every opportunity with field data. The use of this particular modelling approach in paleo-ecological reconstructions of forests at a time in the past when climates were quite different from those of today provides a motivation to use the models of this form to project future forest response to changes in climate and atmospheric chemistry. And finally, the common underlying model structure will enhance comparability of the scenarios for all the transects.

RESULTS

The main product would be a first-of-its-kind assessment, in quantitative terms, of possible long-term change in the world's boreal forests due to possible changes in climate and atmospheric chemistry. Findings should be summarized in a series of sequential maps of the boreal zone, showing changes over time along the transects for the key response variables. Publication would likely require a book-length monograph. The results would be usable in at least the following ways:

1. Since they would show to what climatic and atmospheric chemical conditions and changes boreal forests seem to be sensitive, they would permit efficient and effective identification of factors requiring highest priority for further research in pursuit of understanding of such responses.

2. They can serve as the biophysical input into assessments of economic and social responses to changes in the boreal-forest zone as a consequence of climatic and atmospheric change.

REFERENCE

Shugart, H.H. 1984. A Theory of Forest Dynamics: The Ecological Implications of Forest Succession Models. Springer-Verlag, New York. 278 pp.

APPENDIX VIII

RESPONSE OF REGIONAL BOREAL FORESTS TO CHANGING CLIMATE AND ATMOSPHERE IN THE CONTEXT OF FOREST MANAGEMENT - SIMULATION MODELLING AND POLICY EXERCISES

Rapporteur - Clark Binkley

HYPOTHESIS

At the regional level, the most pernicious effects of the anticipated changes in climate and atmospheric composition can be offset by management and policy intervention. A forest region refers to the unit of area, typically 10^6 to 10^8 hectares in size, where markets for products or labour are formed. It is comprised of several ownerships or forest-management units, each of which is comprised of many forest stands. The region is usually the smallest forested unit recognized in public policy, and is therefore an interesting and important unit of analysis.

RATIONALE

Efforts are now underway to explore the sensitivity of boreal-forest stands to changes in climate and atmospheric composition through the use of dynamic stand-level simulation models (e.g., Shugart 1984). But the stand level (e.g., 10^0-10^2 ha) is not generally the spatial unit of interest for either forest-management decisions or considerations of government and private policy. The unit of interest for forest-management considerations lies at a spatial scale of about 10^3-10^6 ha, coinciding with, for example, ownership boundaries of commercial forest land, or tracts of public land over which annual allowable cuts are calculated. To consider public policy for forests, the most appropriate spatial unit is usually a political domain such as a USA state, Canadian province, or a European country or republic.

To understand the policy implications and significance of changes in climate and atmospheric composition on forests, three steps are necessary. The first step builds on stand-level understanding to determine possible biophysical responses. The second step aggregates the responses to the scale of management/policy units. The third step uses the regional forest-response measures to assess economic, environmental and social effects, including (a) forest industry and associated economic responses (e.g., harvest levels, employment, prices), (b) environmental responses (e.g., hydraulic regimes, wildlife populations), and (c) social responses (e.g., community and settlement opportunities). With this basic analytical approach, investigators can elucidate management and policy alternatives for mitigating the impacts of climatic change and address the fundamental question of this research: can management and policy intervention in boreal forests overcome the deleterious effects of climatic change?

METHODS

We propose that this question be examined through a series of coordinated case studies located throughout the boreal regions of the world. The case-study approach is ideally suited to (a) illuminate the effects of different social and policy systems on likely response, and (b) provide information which will be useful to national or regional decision-makers in dealing with questions of climate change. Coordination of the case studies would permit drawing out common themes and provide investigative economies of scale. Finally, global coverage would enable initial estimates of likely adaptations of social systems to climatic change, and the consequent effects on the biosphere.

STUDY STRUCTURE AND COORDINATION

The study should be directed overall by a core team that would coordinate communications among the case-study teams, documentation of the work, common analytical support for the case studies, and other similar functions. It should likely meet twice a year, once alone and once in connection with a workshop engaging all case-study investigators.

Each case study should be organized and staffed as local conditions permit and require. Each should be structured so that it can stand alone as a scientific investigation on its own merits, but has sufficiently parallel structure with the others that comparability of results is ensured.

COMMON ANALYTICAL SUPPORT

For reasons of investigative scale economy and comparability of case-study results, it seems desirable to have all case-study teams draw upon a pool of common analytical support, at least for the following components of the scenario building:

1. Climate-atmosphere scenarios - the detailed data for these scenarios should be case-specific, but the means by which the data were generated, and what phenomena they represent, should be consistent across case studies. The climate scenarios should be developed both from historical records and from model-based projections.

2. Growth-response scenarios - it seems desirable to build upon the work of stand-level growth-response studies, both current and planned, in applying the same family of climate-sensitive stand simulators, with appropriate modifications to adapt the models to specific case-study forest conditions.

3. Economic scenarios - common economic models, such as the IIASA global forest-products trade model, could be used to gauge economic repercussions of changes in wood supply.

4. Water- and wildlife-related response models - water and wildlife impacts are likely to be case-specific. For example, in boreal Canada it would be interesting to explore the effects of climatic change on the breeding grounds of the endangered whooping-crane population. A linked marsh-population model would be appropriate here. In other places, other systems will be important. However, we are concerned that insofar as possible, a comparable set of water and wildlife impact analyses be undertaken.

MAIN STEPS IN A CASE STUDY

The following steps are proposed to guide the completion of each case study.

1. Define the scenarios for change in climate and atmospheric composition.

2. Simulate stand-level responses to the climate-atmosphere scenarios, and aggregate the responses appropriately up to the forest-management-unit level.

3. Specify and simulate management regimes for each management unit.

4. Generate region-level responses from aggregated management-unit responses.

5. Present first-approximation results to the management and policy communities in the region of interest.

6. Undertake detailed policy analysis to explore the constraints on and opportunities for forest-management and policy interventions in the face of climatic and atmospheric change.

CASE-STUDY POSSIBILITIES

Case studies should be chosen with due consideration for several dimensions such as: (a) sensitivity of forests to temperature change vs. precipitation change; (b) degree of forest-management interventions; (c) kinds of forest-management and public-policy institutions; (d) availability of basic forest information for the biophysical simulations, or (e) issues related to large-scale forest land-use. On the basis of initial investigations into possible biophysical response, availability of data, and interest by local researchers, seven possible case-study areas are identified:

(a) Soviet Union;
(b) Northern China;
(c) Japan;
(d) U.S.A.
   - Alaska;
   - Rocky Mountains;
   - Maine;
(e) Canada
   - Yukon (perhaps jointly with Alaska);
   - Northern Saskatchewan and Alberta;
   - New Brunswick (perhaps jointly with Maine);
   - Rocky Mountains (perhaps jointly with USA Rockies);
   - insular Newfoundland;
(f) Sweden/Norway; and
(g) Finland.

REFERENCE

Shugart, H.H. 1984. A Theory of Forest Dynamics: The Ecological Implications of Forest Succession Models. Springer-Verlag, New York. 278 pp.

APPENDIX IX

THE ROLE OF FIRE, INSECTS AND DISEASES IN THE IMPACT OF CHANGES IN CLIMATE AND ATMOSPHERIC CHEMISTRY ON BOREAL FORESTS

Roger Street

INTRODUCTION AND RATIONALE

Forest consumers (fire, insects and diseases) play a predominant role in defining the characteristics of northern forest ecosystems. They are an integral part of the natural histories of these ecosystems and dictate to some degree their relative viability in terms of economic and social productivity. In addition, fire, insects and diseases are sensitive to their environment. Therefore, any attempt to understand the responses and sensitivities of northern forest ecosystems to changes in climate and atmospheric chemistry must include an examination of the responses of these consumers and the ensuing response of the forest ecosystems.

FIRE

The overwhelming impact of wildfires on ecosystem development and forest composition in northern forest regions is readily apparent upon even casual observation. Large tracts of even-aged stands (e.g., jack pine and black spruce) dominate the landscape in an irregular patchwork mosaic, the result of periodic severe wildfires. The temporal and spatial variability of these wildfires is closely linked to climate, particularly the coincidence of an abundance of available fuel (dry periods) and an ignition agent (lightning). Changes in climate and the associated changes in weather patterns could significantly affect the spatial and temporal nature of wildfires and thereby affect these ecosystems.

The expected changes in climate and atmospheric chemistry associated with enhanced levels of CO_2 and other "greenhouse" gases include changes which will significantly affect wildfires. The climate-change scenarios suggest increases in the severity of forest-fire seasons in the boreal-forest region (Street, unpublished report). The suggested changes in both temperature and precipitation will have a direct impact on the length of the fire season as well as the relative severity of the fire season as a whole. The enhanced evaporation rates under the climate-change scenarios would promote fuel drying, thereby increasing available fuel loads. In addition, the changes in weather patterns that would be associated with changes in temperature and precipitation would result in changes in lightning (ignition agent) and wind regimes which would alter the fire climates of northern forests.

Fuel availability would also change due to the direct impacts of CO_2 enhancement. The expected increases in leaf biomass will result in significant increases in aboveground fuels. In addition, the increased branching postulated to occur within enhanced CO_2 environments will not only increase the fuel loads but may have an impact on the severity of individual wildfires, increasing the potential for more severe burns and crown fires.

INSECTS AND DISEASES

The close relationships between the dynamics (temporal and spatial) of insect and disease populations and their physical and chemical environment suggests that changes in their environment would lead to changes in population dynamics. Possible impacts include:

- modification of geographic limits as temperature and precipitation regimes change;

- changes in the frequency of outbreaks of pests and diseases as a result of the modification of weather patterns which may or may not be favourable for their development;

- host-population susceptibility to infestation may be altered as a result of changes in the stress on particular species; and

- changes in the chemical makeup of the host species (e.g., C/N ratio of leaves) may alter the feeding habits of insects resulting in an altered impact on the forest.

The relationships between climate and atmospheric chemistry and forest insects and diseases have not been examined to the extent required for these types of analyses. Some information exists for a limited number of species as the mountain pine beetle and the spruce budworm.

REQUIRED STUDIES

Fire

The main research questions that need to be addressed under this sub-theme component are:

- what changes in fire severity can be expected to result from a changing climate and chemical environment?

- what effect will these changes have on forest-ecosystem structure (including species composition and distribution), function and productivity?

It is suggested that addressing these questions will require an examination of the response and sensitivity of fire in changes in its physical environment, both directly (climate induced) and indirectly (changes in available fuel). In addition, the linkage between the two questions (i.e., the first question suggests changes to forest structure which will affect fire severity) requires that the analyses be dynamic in nature and should be integrated with stand-modelling efforts.

It is suggested that this research make use of existing data bases and modelling systems such as the Canadian Forest Fire Danger Rating System or the U.S. Fire Danger Rating System. Extensive data bases relating basic fuel and weather information exist and could be exploited to develop the required simulation(s). The results of these analyses should be applied at the stand level but also should address the problem at the forest-management/policy-setting scale.

Insects and Diseases

The research questions that should be addressed under this sub-theme component are:

- what changes in the activities of insect and disease populations can be expected under a changing climate and chemical environment?

- what are the impacts of these changes on the structure (including species composition and distribution), function and productivity of forest ecosystems?

As was the case for forest fires, the nature of the questions suggest the need for analyses which are dynamic in nature. Developed simulations must address the problem at the stand level but be capable of aggregation to the forest-management/policy-setting level. The most effective approach would be to concentrate research efforts on one or two economically significant (or environmentally sensitive) insects and diseases.

APPENDIX X

NOTES FROM P. KOLOSOV

In the following notes I will address the sub-themes in which my participation at the workshop was planned:

1. Moisture-regime manipulations.
2. Sensitivity of regional forests to climate.
3. Sensitivity tests throughout the boreal zone.

MOISTURE-REGIME MANIPULATIONS

We have formed an algorithm for estimating spatial soil-moisture conditions, based on both satellite and terrestrial data. This algorithm uses the daily information from meteorological satellites on cloud cover with a spatial resolution of 111 x 111 km (or 1° x 1°). The cloud types are determined as "frontal" and "unfrontal". The terrestrial information is taken from the network of meteorological and actinometrical observations (such as atmospheric temperature, precipitation, wind-flow speed, radiation balance). Some kinds of initial values and critical parameters needed to begin are: soil-moisture (in mm) contents to the end of spring; and parameters estimating the potential soil-moisture contents (so-called "hydro-physical constants"). From a theoretical point of view, our algorithm is based on the equations of heat and water balance considered "in corpore".

The equation of heat balance of the earth's surface is:

$$R = LE + P + B \ , \tag{1}$$

where R is radiation balance, LE is heat loss due to evaporation, P is turbulent flux of real (explicit) heat, and B is heat flux of the soil.

For estimating the evaporation from land surfaces, we used the Penman-Budagovsky empirical equation:

$$E = E_0(\text{th } S) \ . \tag{2}$$

Here,
$$S = \frac{X-DW}{E_0} \ , \tag{3}$$

where X is precipitation, E_0 - maximum potential evaporation (or evaporation from water surface), DW is the change of soil-moisture contents for the month (in layer 0-100 cm).

An investigation of the index S allowed us to determine its critical values and intervals:

(a) when $S < 0$, the water flow is directed upwards to the soil surface;

(b) when $0 < S \leq 0.5$, the water balance takes place in the soil layer 0-100 cm;

(c) when $0.5 < S \leq 2$, the water flow is directed downward to the layers below 100 cm;

(d) when $S > 2$, the surface water flux begins.

Using equation (2) for equation (1), we receive:

$$\frac{R}{LE_0 ths} - \frac{P}{LE_0 ths} = D$$

$$D = 1 + \frac{B}{LE_0 ths}; \quad \frac{R}{LE_0} - \frac{P}{LE_0} = D_0 .$$

Therefore $\frac{1}{ths} = \frac{D}{D_0}$. (4)

The index D is connected with the cloud-parameter N, determined from satellite data, and the "hydro-physical constant" V.

$$D = f(N_{satell.}, V) .$$

The index D_0 may be determined from initial data on soil-moisture contents and the index D:

$$D_0 = a(D) * W^b ,$$

where "a" and "b" are the empirical parameters, changing from 0 to 1. Parameter W estimates "the moisture memory" of the soil system. It is formed from the precipitation of the current month, and soil moisture contents of the preceding month.

Therefore, we can estimate the change of soil-moisture content during any month (i) =

$$DW_i = X_i - E_{0i}, S_i ,$$

where S_i is from equation (4), not from (3)! There is a satellite estimation of the value of s.

We propose to apply this algorithm for estimating the total humidification and its dynamic for a territory of regional scale (10^4 km^2). In addition, we are able to get maps of index S, which has a predictive meaning.

SENSITIVITY OF REGIONAL FORESTS TO CLIMATE

In this aspect we propose two directions of investigation. Initially, we would investigate a new index estimating the transformation of the "climate signal" in different ecosystems. Precipitation is considered as "input" and evaporation as "output". The vegetation season is considered.

The index is formed in this way:

$$JWR_{p\%} = \frac{X_p - X_{100-p}}{E_p - E_{100-p}}$$, (JWR - Index of water exchange regulation)

where X_p and X_{100-p} and E_p and E_{100-p} are amounts of precipitation (X) and evaporation (E) for any frequency (p and 100-p) (more correctly, -p is probability).

This index shows the ecosystem's ability to regulate water exchange between atmosphere and earth surface as follows:

When $JWR_p > 1$, the ecosystem attenuates input signal.

When $JWR_p < 1$, the ecosystem intensifies input signal.

When $JWR_p \approx 1$, signal is not transformed by the ecosystem.

Investigation of the JWR-index at the local level (based on direct measurement) shows that regulation ability depends on:

(a) the type of ecosystem (forest, grass, agricultural);

(b) the vegetational phase (the beginning, the point of maximum vegetation, the end of the vegetation period);

(c) the degree of anomaly of the climate conditions; and

(d) human activity.

We investigated the behavior of this index during the vegetation season for the European territory of the Soviet Union and West Siberia. Our investigation was based on network climatological data, i.e., precipitation and total evaporation observed during the whole observation period. Space resolution was 2° x 2°. The probability curves approximating time-series of meteorological observations were determined by the methods of probability papers, which straighten Pearson's 3rd type curves. The values X_p,...,E_p,..., were taken from these theoretical curves.

Both regional and local investigations of the proposed index show that northern forest ecosystems have the maximum ability for regulation (2-3, mean value ≈ 2.5). The spatial gradient of index JWR in the forest zone is minimum (only 0.1-0.2 per 100 km). The same value of spatial gradient of JWR is in the steppe-zone, but the steppe's ability for regulation water exchange is less than that for the forest zone: $JWR_p = 1.5$. Agricultural ecosystems show minimum values of the index ($JWR_p = 1.1$ to 1.5, and even less than 1).

On the European territory of the USSR, maximum values of index (2.5 to 3) situated in the taiga (56°-64° latitude). Since the taiga forest attenuates climate changes to a high degree, the same picture was obtained for West Siberia, but there the motion of the maximum was to the north (62°-66° latitude) in cedar and bog regions.

The strongest spatial gradient of index JWR_p, i.e., 1.0 per 100 km, was found for forest-steppe and zones. We have mapped the spatial distribution of JWRp for probability p = 20%. The variation of probability allows us to determine the conditions of maximum regulation ability for each ecosystem. Thus, forest ecosystems (taiga and mixed forest) show their maximum regulation ability especially in extreme moisture conditions (dry or wet anomalies). On the whole, the JWR map shows the distribution of potential ability for regulation of water exchange by natural and agricultural ecosystems. We also computed the change of landscape regulation ability during the last 100 years, based on published data of the square of human activity. Our index of water-exchange regulation was diminished during the 100-year period by deforestation, urbanization, agricultural activities and other kinds of human activities from mean value of 2.2 to 1.6 for the Northern Hemisphere.

It seems to me that these investigations ought to be called "premodeling" or studies before modeling. By these studies we try to determine the structure of meteorological fields and their potential connections with vegetation distribution.

Our index $S = \dfrac{X - DW}{E_0}$ is our second direction of investigation.

We are able to investigate the sensitivity of this index to the change of climatic values such as precipitation (X), evaporation (E, E_0) and soil-moisture content (W, DW). Now we begin this work based the meteorological data for the last 100 years. We hope to receive maps of the frequency S-value in I, II, III, IV critical intervals for European steppe and forest zone.

SENSITIVITY TESTS THROUGHOUT THE BOREAL ZONE

We found the actual boundary of the northern forest by investigation of time-space variability of spring floods on the territory of the USSR. I think that stream-flow (or spring snow-flood) is a good indicator of the boundary of the northern forests' influence on runoff forming processes. A comparison of two boundaries, i.e., that computed from stream-flow data and the geographical forest boundary, shows us that northern forests have been moving further north during the last ca. 100 years. I consider it is not connected only with climatic changes but also with human activities, especially in the western and central regions of the European part of the Soviet Union. But in the territory situated east of the Volga, the climate during the last 100 years became drier. This "new boundary" of northern forests ought to be proven and corrected by satellite information. We saw this boundary on our statistical maps, where the greatest space gradient of flood variation takes place.

By monitoring the stream-flow and its variability, we can do the forest's monitoring. The amount of stream-flow, its variability, its space-time distribution, reveal not only deforested area, but also the areas of forest degradation where forests lose their water-exchange regulation role (or capability).

APPENDIX XI

NOTES FROM M. KORSUCHIN

I. STAND MODELLING

The main open questions are as follows:

I.1. The role of adaptive reactions of a tree in stand dynamics. Almost all of today's models are "mechanical" ones, they do not include adaptive elements. This inclusion is a necessary next step in the development of stand modelling. I see at least three types of adaptations that may be introduced now, with a real chance of success:

(a) adaptive changes in photosynthesis after long-term (weeks or more) changes in light intensities;
(b) stomatal regulation; and, with somewhat less success,
(c) the inclusion of adaptive shifts in assimilation distributions and resulting morphological reaction of a tree.

It is quite probable that the addition of these adaptive reactions in today's stand models will not markedly change the reactions of the whole stand to climatic changes. But this is a question requiring investigation.

I.2. It is desirable to extend step-by-step a physiological tree model (submodel) for use in stand-dynamics models. Perhaps the most important case, the introduction of stomatal regulations, will aid in the connection of stand dynamics to geophysical (climatic) variables.

I.3. It is desirable to continue to develop a theory of intra-tree competition. For example, models now existing (particularly gap models) may be improved markedly by the addition of vertically distributed crowns and by a more accurate description of root competition (the latter is badly described in all existing models). Root competition is a very important factor in boreal forests, especially in wet-lands and nutrient-poor lands.

As for points I.1 and I.2, we are trying to formulate a simple submodel of tree water balance and stomatal regulation which may be used in stand models. We hope to obtain the working variant of this submodel during this winter-spring. During the next two years we hope to introduce a photosynthesis-light adaptation. Regarding I.3, we already have a vertical crown-competition submodel and root-competition submodel. They may be used in stand models of any form, including dynamic equations and gap-models. Our research approaches are obvious - formulation of models and their testing by means of attempts to describe real forest data.

I.4. Bearing in mind the problems of modelling landscapes (listed below), it is desirable to improve gap models by adding moss and grass variables to the tree variables now present in gap-models.

II. LANDSCAPE MODELLING

As already mentioned above, the problem of forest-moss, forest-grass (plus forest-bog) interactions and their model embodiment arises from a wish to evaluate possible shifts between the forest, tundra, bog, and steppe landscapes when the climate is changing. The development and testing of landscape models are much more difficult than for stand models, for the reason of data rarity and poorly known ecological mechanisms, especially for large-scale interactions (e.g., dispersal, fire and insert propagation). I am not sure that large-scale difficulties may be overcome during the next three years, in order to lead us to the working model tool, a gap model at the stand level. On the other hand, small-scale interactions and their mechanisms (e.g., forest-moss) are sufficiently well-known to develop a real working tool soon.

APPENDIX XII

NOTES FROM A. ISAEV

STATUS OF OUR KNOWLEDGE ON THE PROBLEM

Investigations carried out in the last 20 years (e.g., studies by Yu.G. Puzachenko and others on the vegetation structure of the USSR forest zone; a team of scientific workers from the Institute of Geography of Siberia under the leadership of V.B. Sochava; scientific workers from the Institute of Forest and Wood) indicate that the discovery of relations among forest composition, structure, productivity and other features, and climate should be of a regional nature. Comprehensive universal schemes for forest dependence on climate are not sufficiently informative, in spite of the fact that they reveal some global regularities (the schemes by Budyko, Ryabchikov and others). A new stage of forest-climate investigations relies upon quantitative parameters of climate, obtained with the help of methods of climate-parameter calculation based on data from the Soviet Reference Book on Climate.

A lot has been made in parallel in investigations of forest geography in Siberia. Results of the investigations of forest-climate relations are given in the monograph "Climate and Mountain Forests of Southern Siberia" by N.P. Policarpov, N.M. Chebakova, and D.I. Nazimova. Using comparative-geographical analysis, different methods of mathematical analysis, two-dimensional and multi-dimensional ordinations, and relying upon concepts of system organization of forest cover in mountains, the authors evaluated quantitatively the role of heat and water supply in the differentiation of forest cover into altitudinal (zonal) belts (BC). It is shown that under a wide range of natural conditions, general regularities of a climatic nature of these categories and their classes remain for the mountains of South Siberia; each class has its place within a multi-dimensional space of climate features. Thus, their interpretation of the ecosystems of a zonal range with specific peculiarities of the vegetation, soils, and seasonal rhythms of the biotic component of the natural complexes is confirmed. Their climatic ranges are characterized by a great number of indices of heat and water supply and continentality that varies greatly within the region.

The comparison of multi-dimensional and two-dimensional ordination schemes shows a high degree of informativity of the two-dimensional schemes, where humidity index and energy supply are the coordinate axes. The stability of humidity indices at some important altitude-belt borders should be noted. Thus, in different natural regions the border of a forest and steppe under combination with different composition of forests and steppes is estimated by Budyko to have a humidity index of 1.2, and a border (ecotone) of light- and dark-needle zonal formations of 0.65. The upper boundary of the forest is characterized by a very large range of humidity index (0.35-1.2) under a rather stable value of radiation balance (23 $kcal/m^2/yr$). These data are obtained by means of calculation methods using our own climate investigations over the mountains.

Existing methods of calculating climate parameters allow one to catch differences within an altitudinal belt caused by exposure and steepness which are especially significant within the continental sector of Eurasia. Thus, calculation values already now can be used in the analysis of relations to ecosystems of a rank of geomorphological complexes (e.g., slopes, watersheds, valleys) with an aim of simulating and forecasting the parameters of potential forests. First attempts at modelling and mapping the mountain forests in Zapadny Sayan - a representative mountain region of South Siberia - are being undertaken.

EVALUATION OF THE SUGGESTION

Investigations on this problem would be highly effective if they would be systematically undertaken by a complex of specialists: forest ecologists, climatologists, geobotanists, soil investigators, and plant breeders. Methods of comparative ecology and geography, and mathematical analysis for the determination of the role of climate in the formation of contemporary forest cover and potential forests, should be used as widely as possible. The systems approach must be a necessary condition.

The system "boreal forests and climate" has many levels, each of them characterized by a specific time frame (a minimal period of functioning). At the space-time scheme suggested, we are interested in large-scale systems - forests, zonal complexes, altitudinal-belt complexes, regions, subcontinents. Their functioning period has an order of 10^{2-3} years; however, in future much is determined by rates and scales of climate changes and anthropogenic pressures.

The stability and steadiness of forest ecosystems depend more on their ecological parameters than on their dimensions. For example, an altitudinal zone (belt) for mountain boreal forests is measured by a few hundreds of meters while over the plain their analogs are 1,000 and more kilometers long! The altitudinal zonal complexes can be shown only at maps of medium and larger scale. Gradients of climate parameters in mountains are 2-3 orders of magnitude higher than those in a plain. In the continental sector of Eurasia, they are expressed especially clearly and allow one to observe a distinct dependence between climate and such features of the forests as composition, structure, productivity, forest regeneration, and lower-layer formation.

The spatial interrelation of forest and climate can be used for constructing an ecological ordination and then developing a model in time. Our strategy of scientific research is from geography to ecology, and then from ecology to a geographic prognosis, which means making a scenario of future forests under different changes in the climate and anthropogenic pressures.

FURTHER INVESTIGATIONS

Plans for further investigations include the following points:

1. Analogical schemes of ordination of the boreal forests into climate-parameter coordinates is reasonable to have for other regions as well: perhaps a rank of the subcontinent (a sector of the continent) would be optimal. For climax and subclimax forests, basic models show a stable state of the forests that had fixed contemporary definite anthropogenic and pyrogenic modification over the last dozens and hundreds of years. The principle of ergodichnosty is the most applicable in this case.

2. Parallel with climax and subclimax forest ecosystems, anthropogenic modifications and their separate features can be recorded in the same schemes. It is quite possible that a convergence of forest associations is exposed in the course of anthropogenic succession - at the expense of impoverishment with those populations that are already now endemic and weakly stable to external influence. In particular, populations of large ferns, species of a nemorose complex in a "chern taiga" of Altai and Sayans flourishing under the forest crown cover degrade easily under repeated anthropogenic pressure and clear-cutting of the forest. Conifer species are replaced by broad-leaved species. Relations with climate peculiarities of the altitudinal zones are also noted here. This trend towards broad-leaved species (birch, aspen, and to a lesser extent other species) will make its own corrections into the schemes of future forests.

3. The known restrictions of methods of comparative geography should be taken into account. The relations between climate and features of forest ecosystems - composition, productivity and so on - are not purely ecological; as a matter of fact, they are integral reflections of the effect of other factors also - phytoceonotic, anthropogenic, cataclysms, historical - the result of which is the present-day distribution of forests. Nevertheless, heat and water regimes act in a leading role for zonal ecosystems, and even their internal subdivisions that are connected with the slopes - their orientation and form - are important. At this level, the heat and water regimes should be recognized as leading factors.

4. Consideration of reverse relations in the climate-vegetation system was not our task. Still, the important climate-regulating role of the forests, especially in mountain countries of the boreal zone, should not be neglected. The disturbance of the balance of mountain ecosystems is fraught with especially large-scale consequences, and this must always be borne in mind when forecasting the state of forests in regions of intensive development.