AN OVERVIEW OF THE EFFECTS OF CLIMATIC CHANGE AND CLIMATIC VARIABILITY ON FOREST VEGETATION IN WESTERN CANADA

by

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ABSTRACT

Climate warming in the post-glacial periods is known to have produced shifts in the existing boundaries of forest vegetation. This is likely to occur through the doubling of atmospheric CO_2 and the attendant warming trend which is being predicted with increased certainty. The forestry sector, a major component of Canada's economy, would be affected in many ways. Climatic change will impact on forest productivity, wood quality, forest soils, forest insects and diseases, forest logging, natural regeneration, forest hydrology, and forest fires. The frequency and intensity of droughts in a warmer climate need to be explored as these affect the survival and growth of seedlings to replace the areas cut or burned. Research must be undertaken to identify and study all impacts, as these have tremendous implications for the prairie provinces due to significant shifts in agricultural and forestry zones.

The boreal forest is one of the largest remaining tracts of forest land in northern America. It fulfills many important nonmarket functions in addition to being an important source of timber and fibre. According to some economists, the very existence of the boreal forest and its role in the world ecosystem is of greater significance than even its commercial value. Any change in its market and nonmarket functions would, therefore, need to be investigated and assessed thoroughly.

Global CO_2 enrichment will have both direct and indirect effects on plant species of the boreal forest. Enhanced CO_2 will increase productivity through direct effects on photosynthesis and water-use efficiency. Global warming resulting from CO_2 accumulation will be particularly pronounced at boreal latitudes and may increase forest productivity through acceleration of physiological processes and through lengthening of the growing season. The effects of changing patterns of precipitation are less clear.

Ecosystem functioning will be strongly affected; natural succession, nutrient cycling, browsing and grazing, and competitive interactions will all change. The effects of these changes on forest structure and productivity will depend on the relative response of individual species. Economically important tree species could become more, or less, successful depending on how they react to other species. Boundaries of the boreal forest in the prairie

provinces are likely to be pushed northward by as much as 700 km. Areas currently occupied by boreal forest communities may become occupied by grass or brushland or by temperate forests, depending largely on the amounts of precipitation. Long-term studies of responses of important boreal tree species to enhanced CO_2 are needed. Similarly, a modelling effort designed to allow reasonable evaluation of complicated ecosystem functioning is urgently required so that system response to changing climate and atmospheric makeup can be studied.

1. INTRODUCTION

Although many factors may be involved in affecting climatic change, accumulation of greenhouse gases, especially carbon dioxide (CO_2), has large implications. Atmospheric levels of CO_2 have increased from about 283 ppm in 1860 to 340 ppm in 1983 (Gates 1983; Plass 1959); during the past decade, CO_2 concentrations increased at an average rate of 1.5 ppm per year. It is expected that the continued use of fossil fuels, and deforestation especially in the tropics, will produce CO_2 levels as high as 600 ppm within the next century (Bacastow and Keeling 1973). Hengeveld (1987) predicts levels of 1040 ppm under rapid growth/conventional fuel scenarios, or 700 ppm under energy efficient scenarios, by 2100 AD. Because of the infrared absorption qualities of its molecule, an increase in atmospheric CO_2 concentration is predicted to cause global warming, alteration of atmospheric pressure patterns, and changes in precipitation patterns and amounts.

Recent studies indicate that a doubling of CO_2 concentration may increase average summer temperatures of the earth by 3.5 to 4.5^{o}C (Environment Canada 1986). Such a warming is greater than any climatic change experienced during a relatively short period in the past 10 000 years. These studies also suggest that within the next half century, central Canada could experience a mid-summer warming of as much as 9^{o}C with a corresponding 50% reduction in soil moisture. Increased temperatures and aridity will, therefore, affect the growth and quality of forest vegetation in the country.

The temperature effect is expected to be greatest at northern latitudes where long periods of snow cover increase the annual albedo of the land surface (Manabe and Wetherald 1975; Pollard 1985). A large-scale redistribution of global water supplies will be a significant impact of such warming.

Forested areas in western Canada are likely to be affected in several ways. The expected impacts include a direct fertilizer effect of CO_2 on plant growth, CO_2-induced climatic change on physiological and growth processes of forest species, and changes in the structure and function of western Canadian forest ecosystems.

These impacts are of great importance. In 1984, the value of domestic exports of forest products from the prairie provinces was estimated at $708 million (Canadian Forestry Service 1986). Other forest land uses such as hunting, fishing, camping, and picnicing greatly add to the forests' value. The forests are of great importance as sources of municipal and other water supplies. An understanding of the effects of CO_2 enrichment on forest ecosystems is important, therefore, from both a scientific and a practical point of view.

2. DIRECT EFFECTS OF CO_2 ON TREE SPECIES

The direct effects of enriched CO_2 on plants are largely a result of the effects on photosynthesis and water use efficiency (Kramer 1981; Morison 1985). Carbon dioxide is a substrate for photosynthesis; for northern forest species it may limit photosynthetic production even if other necessary factors (e.g., water, nutrients, and light) are not limiting. As a result, most plant species experience a "fertilizer" effect when placed in chronically high levels of CO_2. For most species, high levels of CO_2 also tend to cause partial stomatal closure. This reduces water loss more than it affects photosynthesis. As a result, water use efficiency (photosynthesis/transpiration) is improved.

Direct effects of CO_2 enrichment on boreal forest tree species of the Canadian prairies have not been studied in great detail. Higginbotham et al. (1985) studied growth and photosynthesis of lodgepole pine (<u>Pinus contorta</u> Dougl. var. <u>latifolia</u> Engelm.) seedlings grown at 330, 1000, and 2000 ppm CO_2. Maximum net photosynthetic rates at the three levels were 4.5, 7.2, and 6.5 $mg.dm^{-2}.h^{-1}$. Some fertilization of the photosynthetic process is apparent, even though the highest rates have been observed under normal CO_2 levels in other studies (Dykstra 1974). Kramer (1981) points out that maximum stimulation of photosynthesis occurs shortly after a plant's introduction to a high CO_2 environment. Over long periods, photosynthetic rates tend to drop towards those exhibited at normal levels of CO_2. The plants measured by Higginbotham et al. had been grown under the three CO_2 levels for five months when photosynthesis was measured. Photosynthetic data for other boreal forest tree species are not available.

Impacts of high CO_2 on water use efficiency of northern tree species appear to be quite variable. Brown[1] found that stomatal resistance of trembling aspen (*Populus tremuloides* Michx.) increased about three times when plants were grown at approximately 750 ppm compared to those grown at 340 ppm. Higginbotham et al. (1985) found no difference in stomatal resistance of lodgepole pine grown at 330, 1000, or 2000 ppm CO_2. In both cases, it is likely that water use efficiency is increased because of photosynthetic increases; transpiration will increase only if the relative humidity decreases and/or temperature increases.

Generally, the growth of tree seedlings is positively correlated with exposure to enhanced CO_2 as long as other environmental factors are not growth-limiting. Early increases in photosynthesis are likely channelled into increased leaf production. Although, over time, photosynthetic rates may return to levels similar to those found under ambient levels of CO_2, the increased leaf surface area implies long-term growth enhancement. **Figures 1 and 2** show lodgepole pine and white spruce [*Picea glauca* (Moench) Voss] seedling growth response to enriched CO_2 (Higginbotham et al. 1985; Higginbotham 1983).

Yeatman (1970) found increases of 61% and 40% in shoot dry weight of three-week old seedlings of white spruce and jack pine (*Pinus banksiana* Lamb.) grown at 900 ppm CO_2 and at ambient conditions respectively.

All studies performed to date on the effects of CO_2 enrichment on growth are relatively short-term; no information is available to indicate the long-term effects. In theory, increased growth rates of young plants should be compounded over time, producing mature trees in shorter times than at present. However, early crown closure may create early intra-specific competition, reducing the effect. Other species may respond more readily than trees, causing competitive problems for young trees. While not presently available, such long-term information is clearly needed.

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[1] Brown, K. 1987. Ph.D. student, Dept. Forest Science, University of Alberta, Edmonton. (Unpublished data)

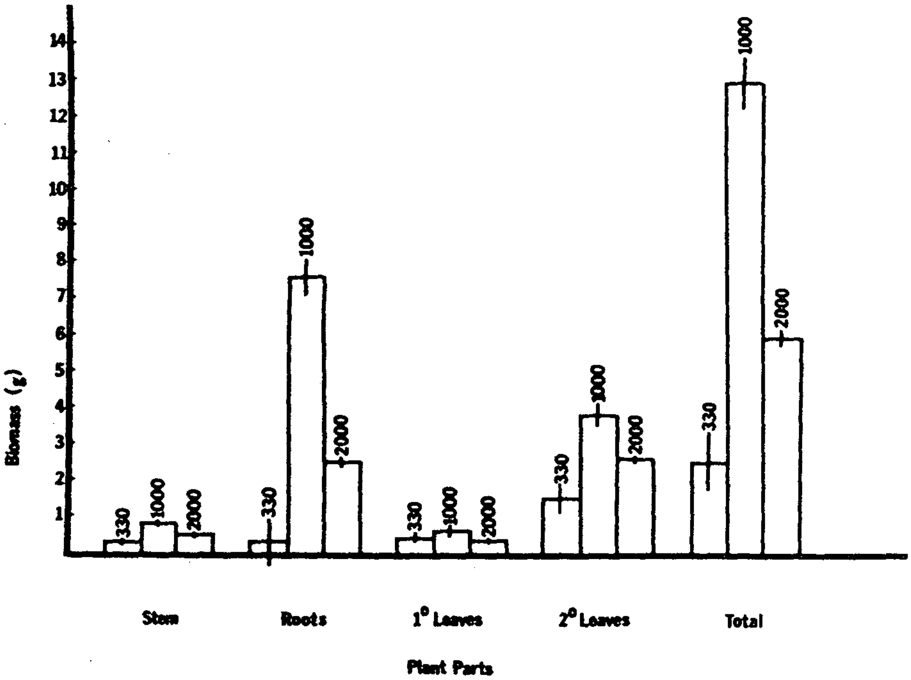

Figure 1. Biomass components of lodgepole pine seedlings grown at 330, 1000, or 2000 ppm CO_2. Lines on bars show ± 1 standard error of the mean. (Higginbotham et al. 1985).

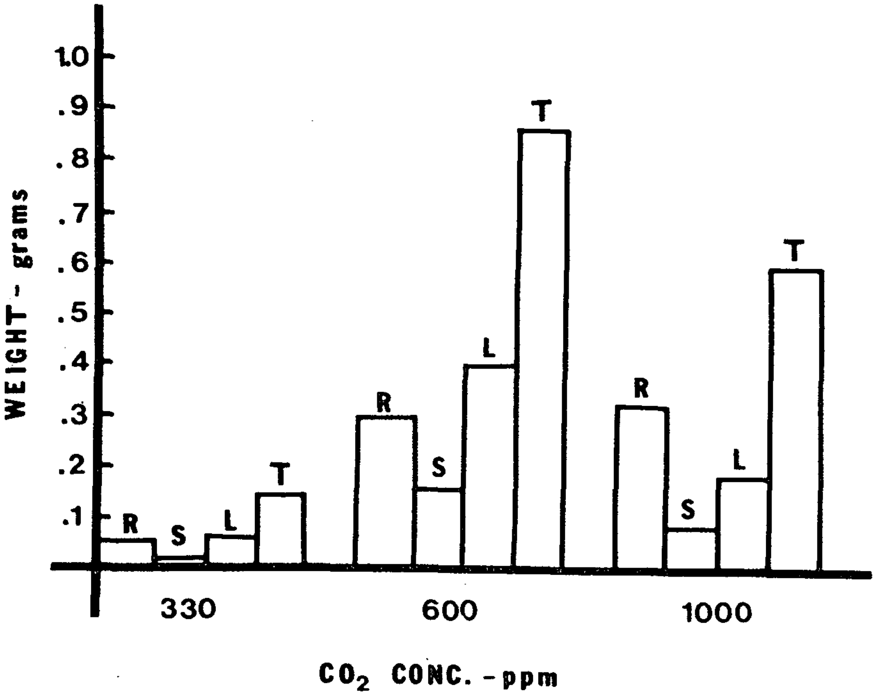

Figure 2. Biomass of roots, stems, leaves, and total plant for white spruce seedlings grown at 330, 600, or 1000 ppm CO_2. (Higginbotham 1983).

3. EFFECTS OF CO_2-INDUCED CLIMATIC CHANGE ON TREE SPECIES

Solomon and West (1985) developed a list of variables, data, and ecological responses which must be documented in order to project the effects of CO_2-induced climatic change on forest trees. These include a large range of climatic variables, such as frequency of spring frosts, cumulative degree days, and frequency of heat waves, drought, flooding, and intense wind storms. They also included human variables such as land use practices and pollution (including enrichment of atmospheric CO_2). These factors may influence trees in all life-cycle stages, or only during specific parts of the life-cycle, and may also have both direct and indirect effects on physiology and growth.

A significant weakness exists in that we know little about how even the economically important tree species of the western boreal forest respond to environmental factors under current CO_2 conditions. Extrapolation to the future is impossible without a baseline. Other problems limit our ability to project even on the basis of presently available information. The principal species of the boreal forest have wide natural ranges and occupy many different types of sites. Presumably, significant genetic variation exists among populations; therefore, extrapolation from one population to another is problematic. Acclimation is another problem (Strain et al. 1976). Most species have some potential to maintain physiological processes at or near optimal levels, even though climatic factors may vary. For example, acclimation might allow a seasonal shift in the optimal temperature for photosynthesis such that the optimum will be at or near the seasonal daytime mean temperature. In other words, a single photosynthesis vs. temperature curve does not suffice to define the relationship between these two elements. Since we know nothing about the acclimation potential of the physiological processes of boreal tree species to any environmental factor, we cannot predict what the long-term responses to CO_2-induced climatic change will be.

The scanty data available show that white spruce, black spruce [*Picea mariana* (Mill.) BSP], lodgepole pine, and trembling aspen exhibit peak photosynthesis at temperatures near 20°C (Black 1977; Clark 1961; Dykstra 1974; Lawrence and Oechel 1983; and van Zinderen Bakker 1974). This is common for most C3 plants reported in the literature. Increased growing-season air temperatures could conceivably cause the optimum to be exceeded, but it is likely that acclimation and eventual genetic adaptation could compensate for this.

Cold soils are an important limiting factor in northern ecosystems. Global warming is likely to increase soil temperatures, alleviating respiratory and water uptake problems associated with cold rooting media. How important this may be for northern tree species is unknown. Babalola et al. (1968) found sharp reductions in photosynthesis and transpiration of radiata pine (Pinus radiata D. Dom.) when soil temperatures decreased from 27 to 10°C. Delucia (1986) found no impact on net photosynthesis of Engelmann spruce (Picea engelmannii Engelm.) seedlings for soil temperatures between 10 and 20°C. Similarly, Lawrence and Oechel (1983) found little soil temperature effects on photosynthesis in trembling aspen with rooting zone temperatures ranging from 5 to 25°C.

If warmer growing season temperatures create increased soil moisture stress through increased evapotranspiration, relatively shade tolerant species, such as white and black spruce, will probably experience greater problems than shade intolerant species such as trembling aspen, jack pine, or lodgepole pine. Lopushinsky and Klock (1974) reported that tolerant species tend to have less stomatal control of water loss than intolerant ones. However, this generalization will be influenced by the sensitivity of a particular species to CO_2-induced stomatal closure.

Growth of boreal tree species as it relates to particular environmental factors is poorly documented. Growth results from cell division and subsequent cell enlargement. Cell division involves many enzymatic processes which are strongly temperature dependent. Cell enlargement is temperature-influenced, but also strongly depends on the availability of moisture. Maini (1972) showed that height growth of trembling aspen is reduced in the forest-grassland transition zone in Saskatchewan, as compared to predominately forested areas. This is probably due to a reduction in available soil moisture. A similar reduction is noted in the forest-tundra transition zone, probably as a function of low temperatures.

Development of cold hardiness and true dormancy in northern trees may be delayed by increased annual temperatures. Induction of dormancy normally results from shortened photoperiods, but deep dormancy and extensive cold hardiness develop following the onset of below freezing temperatures (Weiser 1970).

4. IMPACTS OF EXPECTED CLIMATIC CHANGE ON STRUCTURE AND FUNCTION OF BOREAL ECOSYSTEMS

A fundamental principle of ecosystem function is that all components (plant species, animal species, and the various components of the physical environment) interact with each other. These interactions may take several forms but, because they exist, it can be said that an ecosystem has functional relationships such as for an individual organism (Odum 1969). The structure of an ecosystem is dependent on the size, age, number, and type of interactions which occur between living organisms and the physical environment. Several factors and processes in an ecosystem are likely to be affected by CO_2-induced climatic change and by the direct effects of increasing atmospheric CO_2. These include competitive relationships, life cycles, natural succession, nutrient cycling, energy flow, and system hydrology.

Competition occurs when different species or different individuals of the same species require the same or similar resource bases, and where some or all of those resources are potentially in short supply. Light, nutrients, and moisture constitute examples of resources commonly competed for by plants. Keen competition between plant species is common in the boreal forest under current conditions. This competition is understood reasonably well and various forest management practices exist for dealing with the problem, where it has a negative effect on economically important tree species. In general, the problem is most significant during the regeneration and establishment phases of the tree life cycle.

All plant species will not react similarly to an enhanced CO_2 environment. If, for example, marsh reed grass [*Calamagrostis canadensis* (Michx.)] responds more to CO_2 enrichment than white spruce, competition between the two species will result in a greater advantage to the grass than presently exists. If the tree responds more positively, a currently serious competitive situation may be alleviated.

Kramer (1981) and others have indicated that life-cycle stages (at least in plants) will likely be accelerated in a high CO_2 environment. Both vegetative and reproductive maturation will probably occur sooner than under current conditions. This will likely cause the process of natural succession to accelerate. The various seral stages of a succession may remain intact but, their persistence will be reduced. This will have significant, mostly positive, benefits for traditional timber management, but may have negative impacts on game management and some forms of recreation.

Nutrient cycling is typically slow and often limiting in the boreal forest. Much of the nutrient capital is tied up in organic matter on the forest floor. Release of these nutrients is restricted by slow rates of decomposition. Global warming would improve this situation as long as adequate moisture is available. On the other hand, litter quality (C/N and C/P ratios) may be reduced under conditions of higher system productivity which could yield reduced rates of decomposition. If the nutrient cycle is not constrained as suggested above, forest sites will probably be more fertile (a greater percentage of the nutrient pool will be available annually) and the importance of mycorrhizal associations could decrease. Shortened life cycles should increase the rate at which nutrients tied up in living organisms are returned to the forest floor and, ultimately, to the soil, causing further acceleration of nutrient cycling.

5. EFFECT ON FOREST GROWTH AND PRODUCTIVITY

Net productivity is known to depend on temperature and precipitation (Lieth 1975), with temperature being the more important control in cool climates and precipitation in hot climates (Bazilevich et al. 1971; Drozdov 1971). The effect of increased temperature on photosynthesis and rate of growth will influence forest productivity and the quality of timber produced from the boreal forest region under CO_2-induced climatic change. Productivity models based on the summation of growing season temperature (Kauppi and Posch 1985) may be useful in estimating changes in forest production due to impending climatic change.

With climatic change, much of the existing forest-grassland transition and the southern forest subregions of the boreal forest region may become suitable for agriculture. A study of forest areas with climate similar to that expected from the CO_2-induced change will help identify tree species suited to the modified climate scenario. Climate-productivity models may help to update forestry yield tables from existing sites and species.

6. EFFECT ON RISK FACTORS

Forestry risk factors such as fire, insects, and diseases will be affected by CO_2-induced climatic change. Because of available combustible material, increases in temperature will increase the risk of fire, both in frequency and intensity. These fires will impact the microclimate of boreal subregions. Rouse (1976) reported increases in mean soil temperatures of 60 to 70% after burning of lichen woodland in the Northwest Territories. Such fires also affect the seasonal dynamics of thawing and the soil energy balance.

Temperature and precipitation are factors controlling the incidence and prevalence of forest insects and diseases. Ives (1981) reported weather to be the overriding factor in determining the abundance of 21 forest insects in Manitoba and Saskatchewan. A change in weather patterns under increased CO_2 will bring changes in the composition and abundance of insect populations and disease organisms. These changes would impact the present health of our forests and the quality of forestry related resources. As stress develops due to higher temperatures and possibly lower precipitation, trees will be reduced in vigour and become prone to damage by insects and diseases. These changes could affect future timber supplies from the boreal forest.

Energy flow in ecosystems results from feeding by herbivores and carnivores and by decomposition. Strain and Bazzaz (1983) indicated that carbon/nitrogen and carbon/phosphorous ratios in plants are likely to increase in a high CO_2 environment. This will probably lead to more herbivory. Defoliating insects may have to eat more to obtain necessary nutrients (Lincoln et al. 1984). Problems such as defoliation by tent caterpillar and spruce budworm, and browsing by snowshoe hares and ungulates, may increase.

7. EFFECTS ON FOREST HYDROLOGY

Temperature and precipitation are important factors which influence water yield. A change in either of these factors will determine the amount and regimen of water originating from forest watersheds. Another likely impact will be on the frequency and intensity of drought occurrence due to modified precipitation patterns, and changes in snow accumulation and snowmelt over source areas. However, regional patterns of changes in temperature, precipitation, and soil moisture will determine what impact the Greenhouse Effect will have on local ecosystems, water supplies, and agriculture (Schneider 1987).

System hydrology will be affected by CO_2-induced impacts on precipitation. If annual or growing season precipitation decreases or stays the same as at present, and temperatures increase, evapotranspiration demand may become excessive. If precipitation increases, groundwater levels may rise, causing anaerobic conditions in the rooting zone of soils that are now mesic. Such changes would influence plant growth and forest yield.

8. FOREST ZONATION AND SHIFT IN BOUNDARIES

All of the processes and factors discussed above will be important throughout the period of climatic change and beyond. In addition, climatic change and impacts will probably cause a northward movement of the boreal forest. A simplified view of the factors controlling current forest boundaries suggests that, in the prairie provinces, the boundary between the predominantly forested area and the forest-grassland transition zone lies parallel to the $2^{o}C$ mean annual temperature isotherm. The northern boundary of the predominantly forested area lies along the $-4^{o}C$ isotherm (Munro 1956; Rowe 1972). Based on predictions of the general circulation model of the Goddard Institute for Space Studies (GISS) for mean annual temperature following a doubling of current CO_2 levels, the forest-grassland predominantly forest boundary may shift northward by as much as 700 km. Similarly, the northern boundary of the predominantly forested area will also shift northward. Clearly precipitation, and perhaps other factors, should also be considered, but it appears to be likely that the existing boreal forest will be replaced by grassland, brushland, or temperate forest, and the boreal forest will make significant incursions into the forest-tundra transition zone. After examining the late-Quaternary trends of vegetation history in the Western Interior of Canada, Ritchie (1976) reports that such shifts have occurred in the past.

9. FOREST ECONOMIC EFFECTS

The boreal forest is of great importance to the economy of the prairie provinces. Dependence on the boreal forest for commercial and non-commercial amenities will be significantly affected by the impending climatic change. Possible replacement of the southern boreal forest by grassland and a general shift of the forest to the north has economic consequences which need to be studied at length.

Economic impacts within Canada will be related to changes in forestry supplies from other regions of the world as these are also likely to be influenced by future climatic change. An international, econometric model will be needed to study the consequent elasticities of supply and demand, and to determine the net economic benefit/loss of the change.

In addition to changes in commercial timber production, the anticipated climatic change will impact non-market benefits (such as recreational, scenic, and waste receptor) of the boreal forest. As discussed in previous sections, climate warming will also increase the risk and uncertainty associated with growing forestry crops over long periods.

10. POLICY IMPLICATIONS OF CLIMATIC CHANGE

Shifts in forestry and agricultural zones will have other important implications for the prairie provinces. The impacts involve many aspects of forestry practices in Canada such as net productivity, species composition and structure of plant communities, forest fires, insect and disease infestations, water supplies, drought, and natural regeneration and restocking. Established forestry industries will also be impacted due to likely shifts in the resource base related to their specific interests.

In order to resolve inherent conflicts, these and many related considerations need to be examined well ahead of the anticipated changes. It is only through timely and careful planning that the impacts of long-term climatic change can be managed so that beneficial effects may be maximized and adverse effects minimized. This planning and assessment will require interdisciplinary cooperation among scientists and resource managers. Fortunately, the change is not sudden but is spread over a number of years, thus giving us enough time to carefully and diligently examine policy alternatives.

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