

SOME EFFECTS OF WIND ON NORTHERN FORESTS IN A CHANGING CLIMATE

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SUMMARY

Of the many aspects of coupling between atmosphere and forest ecosystems, the ecological aspects of wind is, perhaps, least known. The concerns of the greenhouse effect have concentrated primarily on changes in global temperature and precipitation; its effects on forests and vice versa. Within the context of climatic change, however, little attention has been given to the ecological consequences of changes in surface wind patterns. The paper focuses on some of the impacts of wind on northern forests under past, present and future changing climate.

RESUMEN

Aiguos efectos del viento en bosques del norte en cambios climatológicos. De los muchos aspectos relacionados entre atmósfera y ecosistemas forestales, la parte ecológica del viento es, quizás, el menos conocido. Las preocupaciones del efecto invernadero se han concentrado primordialmente en los cambios globales de temperatura y precipitación; así como sus efectos en bosques y vice versa. Sin embargo, en el contexto del cambio climatológico, se ha dado poca atención a las consecuencias ecológicas de los cambios en patrones de vientos. El artículo centra su atención en algunos de los impactos del viento en los bosques del norte (septentrionales), tanto en el pasado, presente como futuro de los cambios climatológicos.

Introduction

As an ecological entity, wind, especially as a disturbance factor, affects every facet of forest ecosystem dynamics including floristic diversity, dispersal, composition, productivity and longevity (WHITE and PICKET, 1985; HYTTBORN *et al.*, 1987). Wind also sets a limit to commercial forestry plantations (CANNELL *et al.*, 1989) and boreal pulpwood stands (SMITH *et al.*, 1987). There is a direct relationship between mean windspeed and mean wind direction and the profile of tree crowns and plantations (ROBERTSON, 1989), forest stands (ROBERTSON, 1987b) and wood properties, such as directionality of compression wood (ROBERTSON, 1990), and density (ROBERTSON, 1991). Changes in regional surface wind patterns concomitant with climatic change may have a profound influence on northern forests and forestry. Unfortunately, the critical wind speeds controlling various ecosystem processes are still largely unknown and the ecological implications of wind needs to be better understood before it is possible to predict rationally how forests may react to climatic change. In the context of climatic change, this paper describes several examples of the effects of wind on natural forest ecosystems, mainly in the boreal forest in eastern North America. Many aspects of the ecological role of wind, e.g., distribution and interaction of forest fires, insects, diseases, wildlife, etc., have been excluded from this review.

GCM Model Simulations of Surface Wind Patterns

Over geological time-scales (*circa* 10 million years) simulation experiments with General Circulation Models (GCM) and geological records show that progressive uplift of plateaus and mountains affect regional and global climate in many ways. Notably, the jet stream is diverted, thus amplifying summer heating and winter cooling. (KUTZBACH, *et al.* 1989; RUDDIMAN and KUTZBACH, in press) with a concomitant change in biota (RUDDIMAN, 1990). For example, because of plateau uplift, the Late Cenozoic climate was characterised by drier summers and winters due to a diversion of westerly winds to a more northerly wind flow. The result was a shift from forest to grassland in central Asia and the American Plains (WOLFE, 1985); while a deep subtropical high pressure zone along the Pacific coast of California caused a shift from an and to a semi-arid vegetation; and woodlands on the Great Plains of North America were transformed to grassland. (Axelrod, 1937).

Spurious causal relationships have been inferred from past climatic events. Prairie droughts in the 1930's led some to believe that global warming would expand the Hadley Cell (BUDYKO, 1974). However, the zonal average Hadley Cell 9,000 years ago was approximately the same as it is at present (KUTZBACH and GUETTER, 1986). Furthermore, the Goddard Institute for Space Studies (GISS) GCM models show that many zonally averaged processes such as the Hadley Cell, Jet Stream, mean precipitation patterns and total atmospheric transport, have very little variation among climate simulations (RIND, 1986).

Of course, there is uncertainty in the ability of GCMs to predict likely changes in surface wind patterns (ROWNTREE, 1990). Nevertheless, GISS GCM models indicate that increased CO₂ concentrations in the atmosphere will result in a warmer troposphere and a cooler stratosphere resulting in an increase in the potential energy of the lower atmosphere (RIND *et al.*, 1990). Apparently, observations suggest a recent increase in the atmospheric energy budget of 10 - 20 Watts per square meter-, with a concomitant increase in surface wind speeds over oceans and severe meteorological events including storm winds, heavy rainfall, hailstorms, prolonged droughts (FLOHN *et al.*, 1990). There has also been an observed increase in dust storms in the Sahara (DRESSEN and VAN DIHN, 1990) which may also reflect an increase in the atmospheric energy budget.

With respect to the effect of global warming on North America, the GISS GCM model predicts the northern and western regions will become wetter, while the South and east will become drier (RIND, 1988). While mean windspeed and storm frequency will tend to decrease, with much interannual variation (RIND, Personal Communication), there is concern that storm intensity will increase and that the tornado belt will penetrate further north. Since most cyclones track up the eastern seaboard of North America (LEWIS and MORAN, 1984), forests in this region will be most affected by changes in storm frequency and intensity. The GISS GCM model predicts that over eastern North America, under a doubled CO₂ scenario, storm tracks will tend to move eastward and, consequently, may have a more adverse effect on European forests and less of an effect on eastern North American forests.

Storm Damage

Surprisingly, there is little published data on the extent of storm damage in North America. Over the past three centuries there have been at least six major storms that have inflicted major damage on New England forests. The worst of these occurred in 1788, 1815 and 1936; the others date back to 1635, 1869,

and 1944 (SMITH, 1946). Similar storms occurred on the Pacific west coast. In Oregon, since the 1950s, severe storms which devastate forests recur roughly on a 10-year cycle (HARCOMBE, 1986). As an ecological entity, severe storms create large gaps in the old-growth forest, while

moderate storms tend to enlarge the gap: e.g., along the coast from Oregon to Alaska, gaps created and expanded by storms are essential in providing a niche for Sitka spruce (*Picea sitchensis* (Bong.) Carr), (TAYLOR, 1990), one of the World's most valuable timber trees.

Severe storms, lasting only a few hours, can cause vast economic losses and wholesale ecological change. In September 1989, hurricane 'HUGO' destroyed 70 million m³ of timber (worth \$1.4 billion) in South Carolina (WEEDEN, 1990). The scale of the devastation is comparable to the great storms that destroyed northern European forests during January-March, 1990; e.g., on March 1, 1990 in West Germany alone, a storm blew down 50 million m³ (twice the country's annual cut). Intensively managed forests may be more vulnerable to storms damage and endemic wind throw than natural forests if wind resistance is sacrificed for faster growth.

The after-shock of major storm damage, including environmental hazards (with its attendant high risk of forest fire), the cost of clearing up, the loss of investment due to market glut, and the replacement time for wood resources, affects the competitive position of regional, national and even global forest industries.

Forest Migration

Less dramatic than storm damage, but of greater importance, is the influence of windiness on forest ecosystems generally. During the recent paleoclimate, white spruce (*Picea glauca* (Moench.) Voss) spread across 2,000 km from south-central Alberta to the Mackenzie Delta region over a 1,000 year period (RITCHIE and MACDONALD, 1986). This apparently rapid spread correlates with a strong southerly component of surface winds 9,000 years ago simulated by KUTZBACH and GUETTER, (1986).

Many authorities in global warming imply the boreal forest (i.e., the classic spruce/ fir forest) will move northwards up to 700 km within a century or so. This is improbable for many reasons. To begin with, biomes are temporary assemblages initiated and controlled by prevailing environmental conditions at a particular time (HUNTLY and WEBB, 1989) and do not move en masse in response to climatic warming (RITCHIE, 1989). Also, migration rates are only as fast as the rate of development of suitable niches permit. In the past, except in a few exceptional cases, the ability of a subarctic forest ecosystem to track a warming trend is measured in terms of a few hundred metres per century; whereas, on the southern edge of the boreal forest, the northward range extension of a few species, such as beech and oak, is measured in terms of a few hundred metres per year (HUNTLY *et al.*, 1989). Even the replacement of an entire ecosystem, e.g., red spruce by hardwoods, in response to a warming trend, will be delayed by a century or more (DAVIS and BOTKIN, 1985); partly because of slow dispersal, but mainly because of lags in soil development (PENNINGTON, 1986.)

Tree genera with light, wind-dispersed seeds do not necessarily migrate faster than genera with heavy, animal-dispersed seeds (JOHNSON and WEBB, 1989); for example, blue jays were responsible for the northward spread of oak and beech in postglacial times at rates as rapid as those of eastern hemlock (DAVIS, 1989).

Large-scale human disturbances of the northern forest and its soils, notably wood harvesting, hydro developments and agriculture, will tend to over-ride any normal response of natural forest ecosystem adaptations to climatic change. Perhaps nowhere else on earth is the fragility of northern forests to human disturbance better demonstrated than in Iceland. At the time of settlement in A.D. 874, 65 per cent of Iceland was vegetated and at least 25 per cent (roughly 25,000 km²) was covered with birch forest. Presently, because of overgrazing and forest removal (RUNOLFSSON,

1987), less than 25 per cent of Iceland is vegetated and only 1 per cent of the original forest remains (ARNALDS, 1987).

The boreal forest, indeed any forest, is particularly sensitive to large scale human disruption, because clearcutting of slow growing tree species, which characterise the old-growth forest, coupled with a warming trend, will tend to favour pioneer, light demanding species (SEDJO and SOLOMON, 1988). There is also concern that human disturbance of the northern forest, aggravated by increased wind exposure, will halt range extensions by eradicating advanced disjunct colonies of species which have less efficient dispersal mechanisms; consequently, some species will be in danger of extinction. Eastern hemlock (*Tsuga canadensis* (L.) Carr) is an example of a species that was once abundant, but which, because it regenerates poorly following logging and its seedlings are destroyed by browsing, is now considered a rare species throughout most of its range (DAVIS, 1989).

Wind as a Vector of Forest Decline

Winds associated with shifts in the relative position of a climatic divide (often inappropriately referred to as an 'Arctic Front') affects the forest tundra ecotone. The summer position of this climatic divide, which imposes alternating periods of cold and warmth on many time scales, is reflected in tree growth as a distinctive ebb and flow of species migration and also, the capacity of countries like Iceland to produce crops (MALMSTROM, 1960).

In north-central USSR the growth and distribution of larch (*Larix* spp.) indicates 140 - 160 year cycles of the tree-line fluctuation in response to climatic change, compared to 60-80 year cycles in the expansion of the boreal forest zone (GORCHAKOVSKY and SHIYATOV, 1978). In Lapland, winds associated with outbreaks of Arctic air, have a more direct effect on the growth variation in Scots pine than precipitation and temperature (POHTILA, 1980) patterns of tree growth at Churchill, Manitoba, reveal intermittent periods of arctic and temperature conditions depending on the position of the 'Arctic Front' (SCOTT *et al.*, 1988).

The climatic divide is reversed somewhat in Newfoundland, inasmuch that cricaceous heath dominates the southern part of the island, while productive forest dominates the northern part. Cool, moist southwesterly on-shore winds blowing over the cold Labrador current, which depresses growth, is primarily responsible for this reverse gradient. Palynological evidence indicates shifts in the relative position of winter and summer storm tracks is one of the main factors influencing the movement and species composition of the forest-tundra ecotone in Labrador (MACPHERSON, 1985). With the passing of the oceanic climatic optimum, there has been a general deterioration of the climate as a consequence of cooler ocean temperatures during the past 3,000 years (MACPHERSON, 1981), which tends to perpetuate the coastal tundra in southern Labrador and Newfoundland (MACPHERSON, 1981).

In the Scandes Mountains, the alpine tree-line has decreased 200 m, as a result of a cooling trend of about 2°C during the past 8,000 years (KULLMAN, 1988). Despite tree-line advances elsewhere, such as in the Labrador-Ungava region, in response to a warming trend during most of this century

(PAYETTE *et al.*, 1985), temperatures have actually been falling in Scandes Mountains since the 1950s. This observed cooling trend is sufficient to cause a retrogression of the birch forest/alpine tundra ecotone (KULLMAN, 1989). Because the forest decline is most pronounced on windswept crests, it is suggested that lack of resistance to mechanical damage by wind, glaze and snow loading contributes much more to decline rather growth limiting effects of cooler temperatures (SVEINBJORNSSON, 1983). Such is the case in a recent drop in the tree-

line on the Avalon Peninsula, Newfoundland; which resulted in increased wind exposure due to opening of the landscape by clearing and extensive fires in the post- European settlement period (MEADES, 1989). There is no evidence linking the microclimatic deterioration on the Avalon Peninsula to any global climatic change.

AUCLAIR (1987) attributed decline of the hardwood forest in southeastern Quebec as a consequence of a warming trend punctuated by periods of cold, snowless winters with deep penetrating soil frosts and summer droughts which cause severe root mortality. However, replacement of red spruce (*Picea rubens* Sarg.) by maple (*Acer spp.*) and birch (*Betula spp.*) on the lower and middle slopes of the Appalachian Mountains (HAMBURG and COGBILL, 1990) suggests that hardwood forests will thrive during a warming trend.

Wind Shaped Forests

Balsam fir (*Abies balsamea* (L.) Mill.) forests in the subalpine zone (800 - 1600 m) of the Appalachians and in oceanic boreal areas of the Maritime Provinces of eastern Canada are among the windiest in the world. Wind-induced crown and root damage in these forests (HARRINGTON, 1986, RIZZO and HARRINGTON, 1988) often result in patch disturbance leading to a phenomenon known as 'wave forests' (ROBERTSON, 1987b). The term wave forest is synonymous with the ancient 'wave-dieback' in subalpine fir forests on Hokkaido, Japan (KIMURA, 1982), and 'wave-regeneration' in the Appalachians (SPRUGEL, 1976).

Subalpine and coastal fir wave forests are easily recognized by a series of dead tree strips followed by a curvature of stand growth progressing from regeneration to decadence. The profile of a wave forest resembles saw teeth which move across the landscape in 55 - 80 year cycles in balsam fir forests in eastern North America and 60 - 100 year cycles in Veitch's fir (*Abies vietzii* Lindt.) forests in northern Japan. Because wave forests are known to have existed in Japan for centuries (IWAKI and TOTSUKA, 1959) they may provide a unique opportunity to study the impact of wind on forests in a changing climate.

Basic aerodynamic processes which create and maintain natural wave forests also create gaps and cause progressive decline, usually followed by wind throw, along the edges of semi-mature coniferous plantations and forests opened up by patch and/or strip cutting. The rate of artificially induced wave forest decline in boreal pulpwood forest exposed by logging ranges from 2 - 10 m yr⁻¹ in coniferous pulpwood forests in Newfoundland (ROBERTSON, 1987a). An early experiment in Newfoundland (GILMOUR, 1926) showed that the annual volume of wind throw in forest blocks (approximately 1 - 2 ha in size) can exceed the mean annual increment of the stand: the rate of wind throw in blocks ranged from 7 - 15 m³ ha⁻¹ yr⁻¹ and along edges of strips ranged from 3 - 6 m³ ha⁻¹ yr⁻¹. Wind throw in residual stands of strip cut upland black spruce (*Picea Mariana* (Mill.) BSP) forests in northwestern Ontario, which are essentially artificial wave forests, can account for as much as 2 - 10 per cent of the merchantable volume over a 2 - 4 year period following cutting (FLEMMING and CROSSFIELD, 1983).

The extent of decline in coniferous forests disturbed by humans is not only a function of wind stress, but also the level of intensity and type of silvicultural intervention. For example, in a naturally disturbed wave forest, decline is immediately followed by a dense, more or less monospecific, regeneration (up to 40 stems m⁻²) (ROBERTSON, 1987b). In a wave forest, trees die standing so that there is a gradual transfer of canopy debris before the surface is disturbed by wind throw and the soils undergo a cyclical taxonomic transformation. By contrast, in artificially-induced wave forests, changes in soil taxonomy are not cyclical and the rate of physical and chemical transformation may vary considerably, resulting in unpredictable paths of vegetation succession. In most cases, on clearcuts in plantations and cutovers, where reseeding of the crop species is restricted and management intervention is minimal, weed species (particularly wind-dispersed pioneer herbs, shrubs and trees) are more likely to replace the desirable crop species.

Conclusions Any warming trend, due to abnormal increases in atmospheric CO₂, will invoke substantial changes in surface wind patterns. While mean wind speed and storm frequency are predicted to decrease somewhat over land, the intensity of storms (including top wind speed) will be more destructive.

Under natural conditions there will be a considerable lag in the response of boreal forests to a warming trend. However, the scale of human disturbance on northern forests will override any natural responses to climatic change. This will include a transformation from slow growing, shade tolerant (coniferous) species to light-demanding pioneer species. By necessity, 'weed' species may become crop species. Also, large-scale human disturbance may eliminate advanced disjunct colonies and, hence, restrict the efficiency of tree species range extensions and cause some to become extinct.

The biotic and abiotic aspects of wind are a major contributor to forest decline in northern Europe and North America. Studies of wind-shaped forests, such as wave forests, may provide evidence of the effects of wind on forests during short- and medium-term climatic oscillations. In many regions wind may have a more direct effect on genetic variation than temperature and precipitation. National and global forests policies, conservation and management strategies must include prediction of changes in surface wind patterns with respect to climatic change.

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