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Climate change and forest fires

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Abstract

This paper addresses the impacts of climate change on forest fires and describes how this, in turn, will impact on the forests of the United States. In addition to reviewing existing studies on climate change and forest fires we have used two transient general circulation models (GCMs), namely the Hadley Centre and the Canadian GCMs, to estimate fire season severity in the middle of the next century. Ratios of $2 \times CO_2$ seasonal severity rating (SSR) over present day SSR were calculated for the means and maximums for North America. The results suggest that the SSR will increase by 10–50% over most of North America; although, there are regions of little change or where the SSR may decrease by the middle of the next century. Increased SSRs should translate into increased forest fire activity. Thus, forest fires could be viewed as an agent of change for US forests as the fire regime will respond rapidly to climate warming. This change in the fire regime has the potential to overshadow the direct effects of climate change on species distribution and migration. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Climate change; Forest fires; Forests; General circulation models

1. Introduction

Fire is one of the dominant disturbances in the forests of the United States. Forest fire is a primary process that influences the vegetation composition and structure of any given location; fire helps shape the landscape mosaic and influence biogeochemical cycles such as the carbon cycle. Forest structure and composition, now and in the past, is influenced by the fire regime (Heinselman, 1973; Wright and Bailey, 1982). The fire regime has six components; fire frequency, size, intensity, seasonality, type and severity. The ecological importance of some of these component parts of the fire regime has been put into perspective by Malanson (1987), Whelan (1995). Fire frequency affects ecosystems through interrupting

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or terminating individuals' life cycles. If fires recur more or less regularly, selection pressure will favor those organisms that better take advantage of the recurrence at a given interval. Fire size determines landscape patchiness and determines the distance seed will have to travel for regeneration. Fire intensity is equivalent to the amount of energy released during a fire, and within the confines of a single burn, can vary greatly depending on fuel type and loading, topography, meteorological influences and characteristics of the previous disturbance, among others. The season of the year in which fire occurs is one of the determinants of the successional trajectories on which ecosystems embark after fire. Time of year may affect fire intensity through differences in surface and crown fuel moisture contents. Seasonal phenological state of the plants burned will determine the characteristics of the vegetative or seed reproductive response and have a pronounced effect on the structure of post-fire ecosystems and landscapes. Fire type refers to crown, surface and ground fires, which are largely controlled by fire intensity and fuel characteristics (structure, load and moisture). Fire type can vary across the area of the burn, giving rise to a mosaic of post-fire plant communities that might be initiated by crowning, surface fires, intermittent crowning or a combination thereof. Fire severity is a measure of fuel consumption, primarily the depth of burn in surface soil organic layers and is therefore another important controlling factor of post-fire ecosystem structure and function through direct impacts on underground plant root and reproductive tissues, soil seed bank, and forest floor microbial populations. These component parts of fire regime with their intricate linkage to forest ecosystem structure and function are, in turn, highly dependent on weather and climate (Flannigan and Harrington, 1988; Johnson, 1992; Swetnam, 1993). The rapid response of the fire regime to changes in climate is noteworthy. Thus, if the expected changes in climate become a reality in the next century, an altered fire regime could have the most immediate and significant impact on ecosystems.

In this paper we use an index called the seasonal severity rating (SSR) to examine changes in fire severity on the landscape. The SSR is a final component of the Canadian forest fire weather index (FWI) system (Van Wagner, 1987). This SSR index is a seasonal mean of the daily estimate of the control difficulty of a potential fire which, in turn, derives from an estimate of the potential intensity of a fire. The FWI system is a system of daily meteorological-based indexes designed and used universally in Canada to estimate fire danger in a generalized fuel type. The success of this system in both Canada and beyond is due, apart from the simplicity of its calculation procedures, to the three fuel moisture models which form its core. The FWI system includes a litter moisture model, an upper organic moisture model and a deep organic or soil moisture model. The different fuels represented by these models allow a range of factors to enter into the final estimation of a particular day's fire danger (from rapidly changing surface litter moisture which would affect rates of spread of a fire, to the effect of long term drought on the difficulty of suppression). Though developed for a generalized fuel type, the FWI system has been found to model fire potential in a broad range of fuel types from closed forest stands to grass quite well (Van Wagner, 1975). Indeed fire management systems using the FWI system have been implemented in fuel types that differ significantly from the boreal, such as Mexico and the state of Florida.

2. Current impacts

In the United States, during the last 10 years (1989–1998) an average of approximately 100 000 fires burn over an area of 3 300 000 acres annually. There is a great deal of variability in the fire statistics from year-to-year from a low in 1992 with area burned of just over 1 000 000 acres to a high of over 6 500 000 acres in 1996. Typically, most of the area burned occurs in the west (including Alaska) and the south-east (USDA Forest Service, 1998). Most of the area burned occurs in May and June in the south-west and south-east while July and August are the most active months in terms of area burned in the north-west and Alaska. Humans start most of the fires whether accidentally or deliberately. From a suppression perspective, however, lightning-ignited wildfires pose the most serious threat because detection and response times can be significant, as lightning fires often start in remote areas that can be difficult to reach. In terms of area burned statistics, a relatively small percentage of the fires are responsible for the majority of the area burned. For example, 1% of all wildland fires in the western United States are responsible for 98% of the area burned (Strauss et al., 1989). From a historical perspective it appears that current levels of area burned are low compared to the last 500 years (Leenhouts, 1998). This amount of fire activity significantly influences forest ecosystems. Schmoldt et al. (1999) provide a good overview of the effects of fire disturbance on US ecosystems.

The fire regime at any given location is the result of complex interactions between fuel, topography, ignitions and weather. Fuel type, structure, moisture and spatial continuity are important aspects in determining the fire regime. The topography can influence the spread of fire through natural fire breaks such as lakes, rivers and ridges; also, slope and orientation influence the fire spread. The frequency and timing of ignitions, whether natural or human-caused, can play a role in the fire regime. Weather is crucial to the occurrence and growth of forest fires. Weather is important in terms of ignition agents where lightning is the key ignition agent for naturally caused forest fires. Lightning is the result of an electrical discharge from a thunderstorm, which itself is a result of the appropriate meteorological conditions, namely, atmospheric instability, moisture and a lifting agent. The weather prior to ignition is important in determining the fuel moisture, which, in turn, will determine if ignition will occur and if the fire will grow. These weather conditions that influence fuel moisture include temperature, precipitation, wind speed and atmospheric moisture (vapor pressure deficient). Fire growth is a function of a number of variables; but, if fuels are available and dry then wind speed is the key factor. The fire regime at any location will probably change over time due to these interactions between weather, fuel and ignitions. This is important if land managers want their activities to emulate natural disturbance over the landscape; they should view the disturbance regime as dynamic and not static (Bergeron et al., 1998). Presently, the fire regime varies greatly across the United States. In the south-east, loblolly pine (*Pinus taeda* L.) dominates as the historical fire regime of frequent surface fires (2–15 years), which favored longleaf and slash pine (*Pinus elliotii* Engelm.) and has been replaced by a fire regime of infrequent surface/crown fires every 50–100 years primarily due to the influence of humans. In the pinyon-juniper forests of the south-west, grazing and fire suppression has reduced the fire frequency and has allowed the expansion of juniper (Wright and Bailey, 1982). In the west, frequent surface fires are common in the Ponderosa pine (*Pinus ponderosa* Dougl.) communities. A complex fire regime prevails over the wet northwestern forests where surface fires occur every 50 years or so and stand replacing fires can range from 300–500 years or more. For interior Alaska, Yarie (1981) found stand replacing fire frequencies of 26–113 years depending on the vegetation type.

Fire does not influence the forest in isolation but rather interacts with other disturbances. After a fire, windthrow is more prevalent due to increased exposure. Stocks (1987) suggests that spruce budworm [*Choristoneura fumiferana* Clemens (Lepidoptera: Tortricidae)] damaged forests may be more prone to fire and would burn more intensely due to increased fire loads. Swetnam and Betancourt (1998) found regional synchrony in relationships between climate, fire and insect disturbances in the American south-west. McCullough et al. (1998) have reviewed the interaction between fire and insects, which often affects succession, nutrient cycling and forest composition. These interactions between disturbances could be synergistic and may change rapidly as the climate changes.

Forests are of vital importance for the economy of many regions across the country. Fires can affect the forest industry by competing for wood fibre especially in pulp and paper operations where charcoal is difficult to remove from the pulp and paper making process. Fire can also affect the recreational value of the landscape, although as the public becomes educated, fire will be more acceptable [e.g. Yellowstone National Park-Baskin (1999)]. Finally, fire can pose a health concern as smoke from wild or prescribed fires can cause respiratory problems.

Human activities greatly influence the fire regime. Since European settlement, fire suppression has been practised across much of the United States. The principal goal for many land management agencies was to exclude fire. It is only recently that the positive aspects of fire in preserving our landscapes have been recognized. Other human activities such as land use change have influenced the fire regime. Clearing the forest for agriculture or urban development has reduced or fragmented forested areas.

Not only does climate influence fire, but fire activity also can influence climate. Regionally, large fires with their change in albedo and removal of vegetation with the accompanying drop in evapotranspiration, can influence the energy budget and climate. Recent evidence suggests that local to regional changes in the land surface characteristics can significantly alter the climate of that region (Couzin, 1999).

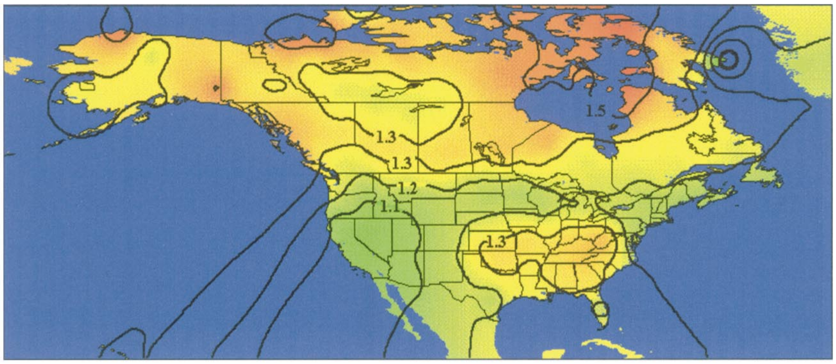
3. Impact of climate change on the fire regime

There are many general circulation models (GCMs) that enable researchers to simulate the future climate. Although there are a number of shortcomings associated with GCMs, they provide the best means available to estimate the impact of changes in the future climate on the fire regime at larger scales. Most models are in agreement in predicting the greatest warming at high latitudes and over land. In addition to temperature, other weather variables will be altered in the new climate such as precipitation, wind, cloudiness, etc. The variability of extreme events may be altered as well (Mearns et al., 1989; Solomon and Leemans 1997). Some studies suggest universal increases in fire frequency with climatic warming (Overpeck et al., 1990; Intergovernmental Panel on Climate Change (IPCC) 1996). The universality of these results is questionable because an individual fire is a result of the complex set of interactions that include ignition agents, fuel conditions, topography and weather including temperature, relative humidity, wind velocity and the amount and frequency of precipitation. Increasing temperature alone does not necessarily guarantee greater fire disturbance.

Price and Rind (1994) modelled lightning fires in the United States and then used the Goddard Institute for Space Studies GCM to estimate the change in lightning fires and area burned in the United States for a $2 \times CO_2$ scenario. Their results suggest a 44% increase in lightning-caused fires with an associated 78% increase in area burned for the $2 \times CO_2$ scenario. Tackle et al. (1994) looked at the impacts on surface pressure patterns on forest fires in the north-east United States and then used the Canadian GCM to project future impacts. Their results suggested an increased frequency of drying in the $2 \times CO_2$ scenario but the results were not statistically significant. Other studies also indicate significant increases in fire weather severity for Canada, Alaska and Russia (Stocks et al., 1998), which should be accompanied by increases in the area burned. Results from Flannigan et al. (1998) show a great deal of regional variation in the $2 \times CO_2$ fire weather for central and northern North America and Europe with some regions showing a significant increase in fire weather while other areas show a decrease in fire weather severity due to increased precipitation amount and frequency.

Figs. 1 and 2 show the ratio of the mean seasonal severity rating (SSR) for 2060 (approx. $2 \times CO_2$) over present day (1985–1994) using the Canadian GCM and the Hadley GCM, respectively. The higher the SSR the greater likelihood of increased fire activity given everything else being equal (fuels, ignitions, etc.). Note that the 1.0 contour indicates no change while areas above 1.0 suggest an increase in the SSR whereas values below 1.0 denote areas where SSR decreases. There is a great deal of regional variation in the results. The Canadian GCM suggests over 30% increase in SSR for sections of the south-east, midwest and Alaska whereas the Hadley GCM suggests increases near 20% for the north-east and decreases in the Northern Plains. Figs. 3 and

1



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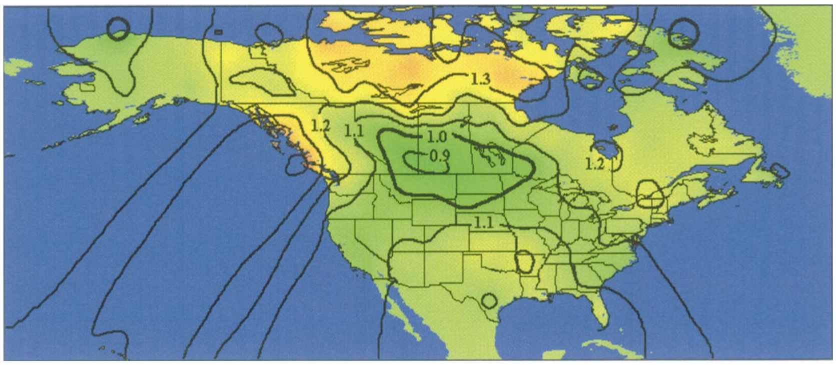

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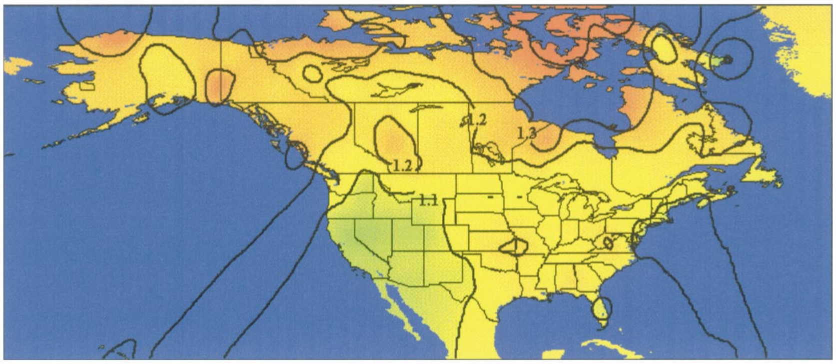

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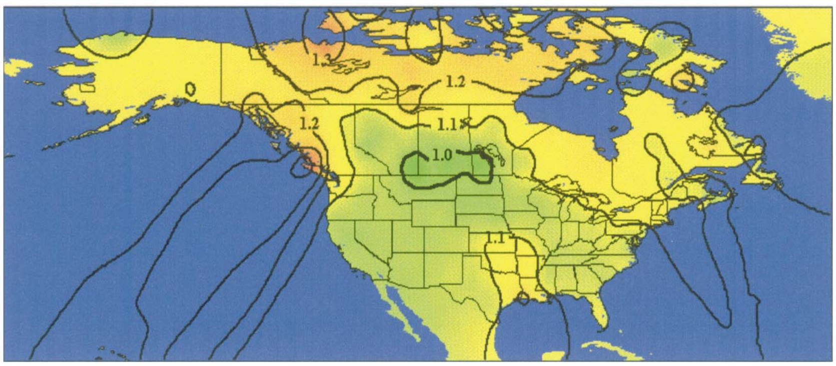

Figs. 1–4. (*See legends on opposite page*).

4 show the ratio of the maximum SSR for $2 \times CO_2$/present day (1985–1994) using the Canadian Climate Model and Hadley model, respectively. Maximum values were used as fire typically occurs during extreme weather conditions rather than mean conditions. The Canadian Model (Fig. 3) shows SSR increases of approximately 30% for parts of Alaska and increases of less than 10% for most of the western United States. The Hadley model (Fig. 4) shows most of the country with increases of less than 10% except most of Alaska and a section from eastern Texas–Louisiana to eastern Kansas and southwestern Missouri. These figures indicate that changes in the climate can have dramatic changes in the fire regime. These increases in SSR should translate to corresponding increases in fire activity, in particular area burned. As a first guess we would expect increases in area burned for the United States of 25–50% by the middle of the 21st century with most of the increases occurring in Alaska and the southeastern United States. However, there may be regions in America like the Northern Plain States (Fig. 2) that may experience no change or even reduced fire activity in the next century due to increases in precipitation amount and frequency. Due to the coarse spatial resolution of the GCM (approx. 400 km) confidence in the results over complex terrain-like mountainous areas is low. In such areas, a regional climate model (RCM) should be used (Giorgi, 1990) where the finer spatial resolution (approx. 40 km) can resolve mountain ranges, etc.

In addition to climatic influences on the fire regime other factors such as ignition agents, length of the fire season, vegetation characteristics and human activities such as fire management policies and landscape fragmentation may greatly influence the fire regime in the next century. Ignition probabilities may increase in a warmer world due to increased cloud-to-ground lightning discharges with warming (Price and Rind, 1994). The fire season will start earlier in the spring and extend longer into the autumn, yielding a longer fire season. Wotton and Flannigan (1993) have found that the fire season length in Canada on average will increase by 22% or 30 days in a $2 \times CO_2$ climate. Vegetation type, amount and structure influence the fire regime characteristics; thus any changes in vegetation due to changes in climate or fire regime would have a feedback on the fire regime. Human activities such as fire management policies and effectiveness will continue to change. Other human activities such as conversion of forest lands to agriculture or urban areas along with the fragmentation of the landscape will influence the fire regime. Also, research has suggested that the persistence of blocking ridges in the upper atmosphere will increase in a $2 \times CO_2$ climate (Lupo et al., 1997). This could have a significant impact on forest fires as these upper ridges are associated with dry and warm conditions at the surface, which are conducive to forest fires (Skinner et al., 1999). These are all confounding effects that may dampen or amplify the impact of a changing climate on the fire regime.

The important aspect of the impact of climate change on forest fires with respect to the influence on vegetation is that fire may be more important than the direct effects of climate change with respect to species distribution, migration, substitution and extinction (Weber and Flannigan, 1997). Fire can act as an agent of change to hasten the modification of the vegetation landscape into a new equilibrium with the climate if species are able to migrate fast enough. This might be true where the fire activity is expected to increase in the next century and thus accelerate changes in vegetation. In those areas of America that experience a reduced fire frequency due to the altered climate or human activities, the transition of vegetation types may be retarded. As the climate warms, the favorable region for many

Fig. 1. The ratio of the mean seasonal severity rating (SSR) for 2060/present day (1985–1994) using the Canadian GCM.
Fig. 2. The ratio of the mean seasonal severity rating (SSR) for 2060/present day (1985–1994) using the Hadley GCM.
Fig. 3. The ratio of the maximum seasonal severity rating (SSR) for 2060/present day (1985–1994) using the Canadian GCM.
Fig. 4. The ratio of the maximum seasonal severity rating (SSR) for 2060/present day (1985–1994) using the Hadley GCM.

species shifts northward. This poleward migration of the southern species would be enhanced by the presence of disturbed areas such as burns that would allow establishment of these migrating competitors. For example, increased fire frequency would hasten the change from forest to parkland to grassland. In areas of decreased fire activity, shade tolerant species and long-lived species would dominate the landscape and would be hard to displace thus retarding the poleward migration of the southern species. Of course, it is possible that in some regions increases in other disturbance regimes such as pests, diseases and windthrow could offset any decreases due to an altered fire regime. Changes in climate and disturbance regimes may lead to assemblages of species that have never been encountered before (Martin, 1993).

The various aspects of the fire regime can have significant influences on successional pathways as discussed above. Changes in climate and the fire regime will have an affect on carbon, nitrogen cycling and budgets. Disturbances such as fire could be critical factors in determining if US forests are a carbon sink or source on a year-to-year basis. The very close coupling of nitrogen and carbon cycles within the plant and the ecosystem as a whole makes them particularly susceptible to modifications under global change as one or the other cycle may be altered by elevated CO_2 and climate change. Alteration in one of these two cycles can be expected to have immediate repercussions on the other because of the interaction and feedback between the two (Pastor and Post, 1986; Reynolds et al., 1996). For example, the ability for increased carbon acquisition by plants in a higher CO_2 atmosphere could be limited by available soil nitrogen (N), which is in turn controlled by decomposition rates. The main avenue for interaction between carbon (C) and N cycles actually may be via decomposition and litter quality. The reciprocal linkage between ecosystem cycles (N and C) and attributes (decomposition rates and litter quality) assumes added importance in northern and boreal forest biomes for several reasons: (1) greater temperature impacts are predicted for northern latitudes under climate change, affecting all temperature-sensitive processes, including decomposition and nutrient cycling (Anderson, 1992); (2) northern forest ecosystems are typically nitrogen-limited and can be expected to respond to ameliorated nutrient conditions (Van Cleve et al., 1986); and (3) effects of altered decomposition rates on fire regime via fire severity and changed organic layer thickness.

The forests of the United States will respond directly to changes in the climate gradually over time. However, the almost instantaneous response of the fire regime to changes in climate has the potential to overshadow importance of direct effects of global warming on species distribution, migration, substitution and extinction. Thus, fire is a catalyst for vegetation change.

4. Conclusions

The two GCMs in this study suggest increases in SSR of 10–50% across much of the United States by 2060 (Figs. 1–4). The impact of climate change on the fire regime in the United States could have an almost immediate and significant impact on ecosystems, due to likely increases in area burned and fire intensity/severity. Possible manipulations of fuel type, load and arrangement could be used to help protect local areas of high value (Pyne et al. 1996). At the larger scale, however, fuel management would not be feasible. A fine balancing act is required by land managers to protect values (people and resources) from fire while at the same time allowing fire to resume more of its natural role in ecosystem functioning and maintenance. Fire may be becoming increasingly important in terms of determining whether American forests are a carbon sink. Additionally, in regions where there is potential for fires to increase, the result may be competition between the forest industry and fire for wood fiber. Continued research is required to further explore the relationships between the climate–fire association as well as the interaction between fire and other disturbances and their impacts on vegetation.

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References

Anderson JM. Response of soils to climate change. Adv Ecol Res 1992;22:163–210.

Baskin Y. Yellowstone fires: a decade later — ecological lessons learned in the wake of the conflagration. Bioscience 1999;49:93–97.

Bergeron Y, Richard JH, Christopher C, Gauthier S, Flannigan M, Prairie YT. Variability in fire frequency and forest composition in Canada's southeastern boreal forest: a challenge for sustainable forest management. Conserv Ecol 1998; [online] 2(2): Available from the Internet. URL: http://www.consecol.org/vol2/iss2/art6

Couzin J. Landscape changes make regional climate run hot and cold. Science 1999;283:317–318.

Flannigan MD, Harrington JB. A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada 1953–80. J Appl Meteorol 1988;27: 441–452.

Flannigan MD, Bergeron Y, Engelmark O, Wotton BM. Future wildfire in circumboreal forests in relation to global warming. J Veg Sci 1998;9:469–476.

Giorgi F. Simulation of regional climate using a limited area model nested in a general circulation model. J Clim 1990;3:941–963.

Heinselman ML. Fire in the virgin forests of the boundary waters canoe area, Minnesota. Q Res 1973;3:329–382.

Intergovernmental Panel on Climate Change (IPCC). Climate change 1995 impacts, adaptations and mitigation of climate change: scientific–technical analyses. Cambridge: Cambridge Univ Press, 1996:878.

Johnson EA. Fire and vegetation dynamics: studies from the North American boreal forest. Cambridge: Cambridge University Press, 1992:129.

Leenhouts B. Assessment of biomass burning in the conterminous United States. Conserv Ecol 1998; [online] 2:(1) Available on the Internet URL://www.consecol.org/vol2/iss1/art1

Lupo AR, Oglesby RJ, Mokhov II. Climatological features of blocking anticyclones: a study of Northern Hemisphere CCM1 model blocking events in present-day and couble CO2 concentration atmosphere. Clim Dynam 1997; 13:181–195.

Malanson GP. Diversity, stability, and resilience: effects of fire regime. In: Trabaud L, editor. The role of fire in ecological systems. The Hague: SPB Academic Publishing, 1987:49–63.

Martin P. Vegetation responses and feedbacks to climate: a review of models and processes. Clim Dynam 1993;8: 201–210.

McCullough DG, Werner RA, Neumann D. Fire and insects in northern and boreal forest ecosystems of North America. Ann Rev Entomol 1998;43:107–127.

Mearns LO, Schneider SH, Thompson SL, McDaniel LR. Climate variability statistics from general circulation models as applied to climate change analysis. In: Malanson GP, editor. Natural areas facing climate change. The Hague: SPB Academic Publishing, 1989:51–73.

Overpeck JT, Rind D, Goldberg R. Climate-induced changes in forest disturbance and vegetation. Nature 1990;343: 51–53.

Pastor J, Post WM. Influence of climate, soil moisture, and succession on forest carbon and nitrogen cycles. Biogeochemistry 1986;2:3–27.

Price C, Rind D. The impact of a $2 \times CO_2$ climate on lightning-caused fires. J Clim 1994;7:1484–1494.

Pyne SJ, Andrews PL, Laven RD. Introduction to wildland fire. 2 New York, NY: John Wiley and Sons, 1996:769.

Reynolds JF, Kemp PR, Acock B, Chen J-L, Moorhead DL. Progress, limitations, and challenges in modeling the effects of elevated CO_2 on plants and ecosystems. In: Mooney HA, editor. Carbon dioxide and terrestrial ecosystems. San Diego: Academic Press, Inc, 1996:347–380.

Schmoldt DL, Peterson D., Keane RE et al. Assessing the effects of fire disturbance on ecosystems: a scientific agenda for research and management. Gen Tech Rep GTR- PNW 455 US Dep Agric, For Serv, Pac Northwest Res Stn, 1999, 104 pp.

Skinner WR, Stocks J, Martell DL, Bonsal B, Shabbar A. The association between circulation anomalies in the mid-troposphere and area burned by wildland fire in Canada. Theor Appl Clim 1999;63:89–105.

Solomon AM, Leemans R. Boreal forest carbon stocks and wood supply: past, present and future responses to changing climate, agriculture and species availability. Agric For Meteorol 1997;84:137–151.

Strauss D, Bednar L, Mees R. Do one percent of the forest fires cause ninety-nine percent of the damage? For Sci 1989;35:319–328.

Stocks BJ. Fire potential in the spruce-budworm damaged forests of Ontario. For Chron 1987;63:8–14.

Stocks BJ, Fosberg MA, Lynham TJ et al. Climate change and forest fire potential in Russian and Canadian boreal forests. Clim Change 1998;38:1–13.

Swetnam TW. Fire history and climate change in giant sequoia groves. Science 1993;262:885–889.

Swetnam TW, Betancourt JL. Mesoscale disturbance and ecological response to decadal climatic variability in the American southwest. J Clim 1998;11:3128–3147.

Tackle ES, Bramer DJ, Heilman WE, Thompson MR. A synoptic climatology for forest fires in the NE US and future implications from GCM simulations. Int J Wildland Fire 1994;4:217–224.

USDA Forest Service. 1991–1997 Wildland fire statistics. US Dep Agric, For Serv, Fire and Aviation Management, 1998:141.

Van Cleve K, Chapin FS III, Flanagan PW, Viereck LA, Dyrness CT. Forest ecosystems in the Alaskan taiga. Ecological Studies 57. New York: Springer-Verlag, 1986:230.

Van Wagner CE. A comparison of the Canadian and American forest fire danger rating systems. Can For Serv, Info Rep PS-X-59. 1975

Van Wagner CE. The development and structure of the Canadian forest fire weather index system. Can For Serv, For Tech Rep 35. Ottawa, Ontario, 1987

Weber MG, Flannigan MD. Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. Environ Rev 1997;5:145–166.

Whelan RJ. The ecology of fire. Cambridge: Cambridge Univ Press, 1995:346.

Wotton BM, Flannigan MD. Length of the fire season in a changing climate. For Chron 1993;69:187–192.

Wright HA, Bailey AW. Fire ecology: United States and southern Canada. New York, NY: John Wiley and Sons, 1982:501.

Yarie J. Forest fire cycles and life tables: a case study from interior Alaska. Can J For Res 1981;11:554–562.