SIMULATING THE CONSEQUENCES OF FIRE AND CLIMATE REGIMES ON A COMPLEX LANDSCAPE IN GLACIER NATIONAL PARK, MONTANA

Robert E. Keane and Kevin C. Ryan
U.S. Department of Agriculture, Forest Service, Intermountain Fire Sciences Laboratory, Rocky Mountain Research Station, P.O. Box 8089, Missoula, MT 59807

Mark A. Finney
Systems for Environmental Management, P.O. Box 8868, Missoula, MT 59807-8868

ABSTRACT

We investigated long-term consequences of modified fire and climate regimes on ecosystems for a landscape in Glacier National Park, Montana, using the mechanistic forest successional model, Fire-BGC (a Fire BioGeoChemical succession model). Changes in various ecosystem components such as stand composition, structure and fuel loadings, and changes in ecosystem processes such as fire behavior, fuel consumption, and productivity are evaluated over 250 years under historical, present, and future fire regimes and climatic conditions. Fire-BGC is an individual tree model in a landscape application created by merging the gap-phase process model FIRESUM with the mechanistic ecosystem biogeochemical model FOREST-BGC. Ecological processes that act at a landscape level, such as fire and seed dispersal, are simulated annually from stand and topographic information contained in spatial data layers. Stand-level processes such as tree establishment, growth, and mortality; organic matter accumulation and decomposition; and undergrowth plant dynamics are simulated annually. Tree growth is mechanistically modeled from the daily net carbon gain (photosynthesis minus respiration) that is allocated to the stem to generate a corresponding diameter and height growth. Fire-BGC application includes the simulation of fire behavior using the FARSITE spatial model and fire effects such as tree mortality, smoke generation, and fuel consumption. Direct and indirect fire effects are compared across the 90,000 hectare McDonald and St. Mary watersheds in Glacier National Park for four simulation scenarios: (1) current climate and complete fire exclusion, (2) current climate and historical wildfire occurrence, (3) a future climate and complete fire exclusion, and (4) a future climate and future fire occurrence. Simulation results indicate future fires will be three times more intense and twice as extensive under the warmer, wetter future climate simulated here. Duff depths, fuel loading, and standing biomass all increase when fire is excluded from the landscape, and landscape species composition is dominated by late seral, shade-tolerant tree species. Future landscapes are 10 to 20% more productive under a future climate. A test of the model shows some intermediate calculations are within 15% of observed values.

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INTRODUCTION

Wildland fire is the dominant disturbance process in most Northern Rocky Mountain ecosystems (Habeck and Mutch 1973, Wright and Bailey 1982, Peet 1988). Fire influences nearly all ecosystem processes and components in most forest and rangeland communities (Heinselman 1981). Fire's impact is manifest across many temporal and spatial scales because the environmental and cultural conditions that favor fire initiation and spread vary in time and space. Indeed, climate change and human migration have and will continue to influence fire and ecosystem dynamics at plant, stand, landscape, and regional scales (Van Wagner 1978, Clark 1988, Baker 1989, Turner and Romme 1994).

Since fire's effect on many landscapes is so predominant and pervasive, it would follow that any change in fire regime or climate should lead to major changes in the associated ecosystems. The successful fire suppression policy of the U.S. Forest Service and other federal agencies, in place since the late 1920's, has resulted in major modifications of Northern Rocky Mountain historical fire regimes (Mutch et al. 1993, Morgan et al. 1996). Attempted exclusion of fire from fire-dominated ecosystems has precipitated high fuel accumulations and successional advancement to more shade-tolerant conifers (Keane et al. 1990a, Mutch 1994). This, in turn, has caused major changes to the nutrient, water, and carbon cycles that directly affect forest health (Keane et al. 1996b).

Many scientists speculate that the predicted global climate warming caused by increasing atmospheric carbon dioxide concentrations will cause an increase in growing season length, annual temperatures, large fire occurrence, and fire severity, and thereby cause major shifts in ecosystem processes, structure, and composition (Clark 1988, Overpeck et al. 1990, Fried and Torn 1991, Ryan 1991, Balling et al. 1992, Kasischke et al. 1995). Flannigan and Van Wagner (1991) estimate a 40% increase in land area burned in Canada under a climate created by a doubling of atmospheric carbon dioxide. This increase in fire occurrence will affect many ecosystem properties and might serve to accelerate species migration on the landscape (Ryan 1991). New fire regimes may favor those species that are adapted to survive fire or those species able to quickly colonize postfire landscapes (Ryan and Reinhardt 1988, Crutzen and Goldammer 1993). Warmer, wetter climates will probably increase ecosystem productivities (McGuire and Joyce 1995), and this will result in higher fuel loadings and ultimately in higher fire intensities (Ryan 1991). The longer fire seasons in the future could reduce effectiveness of suppression efforts to prevent large fires (Fried and Torn 1991), and active fire suppression programs under a changing climate may further elevate fuel loadings and cause fire events of extreme intensity and severity.

The problem then is how to assess the effect of changing climates and fire regimes on ecosystem properties over long time spans. Long-term responses of ecosystem processes to fire and fire exclusion have not been studied in detail because comprehensive field studies are costly, complex, and often inconclusive (Arno et al. 1985, Stickney 1985). Mechanistic ecosystem process models offer a means to explore the role of fire and climate in forested ecosystems (Reed 1980, Bossel and Schäfer 1990, Dixon et al. 1990, Kimmins 1993). This simulation study investigates the effect of fire regime modification and climate change on ecosystem characteristics using a mechanistic ecosystem model called Fire-BGC (a FIRE BioGeoChemical succession model) (Keane et al. 1996a). Fire-BGC simulates the interaction of disturbance processes such as fire with stand development processes of tree regeneration, growth and mortality, and landscape processes of weather, species migration, and hydrology. The model is applied to two 45,000 hectare drainages in Glacier National Park, Montana. The spatial and temporal distributions of species, structure, fuels and biomass are used to characterize landscape changes.

METHODS

The Simulation Model

Fire-BGC is a mechanistic, individual tree succession model with stochastic properties implemented in a spatial domain. Tree growth, organic matter decomposition, litterfall, and other ecological processes are simulated using fundamental physical and biological relationships. Tree establishment and mortality are modeled using probability functions with ecologically derived parameters. Fire-BGC also includes a spatial simulation of fire behavior and fire effects on ecosystem components across the landscape. A detailed discussion of Fire-BGC is presented in Keane et al. (1996a).

Fire-BGC is the fusion of two ecosystem process models that were developed from different approaches. The gap-replacement model FIRESUM (Keane et al. 1989, 1990a, 1990b) was merged with the mechanistic biogeochemical simulation model FOREST-BGC (Running and Coughlan 1988, Running and Gower 1991) to build a model to predict species and ecosystem dynamics over long periods (Keane et al. 1996a). The mechanistic approach of FOREST-BGC improved the level of detail needed to understand those ecosystem processes that govern successional dynamics. FIRESUM's comprehensive simulation of forest dynamics in multi-species, multi-aged stands, and its integration of fire interactions with ecosystem components allow Fire-BGC to simulate changes in species composition and abundance as a consequence of multiple disturbances over long time spans (Levine et al. 1993).

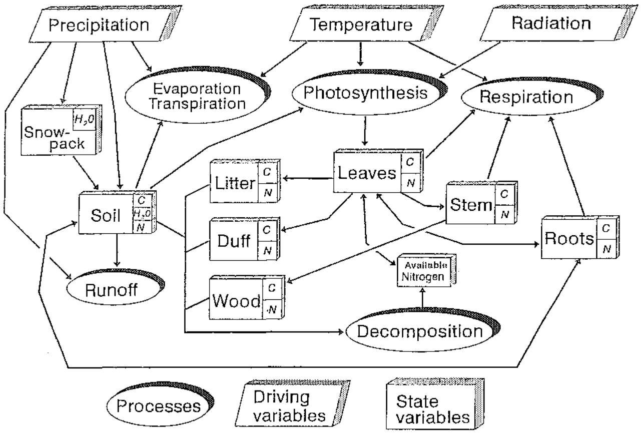
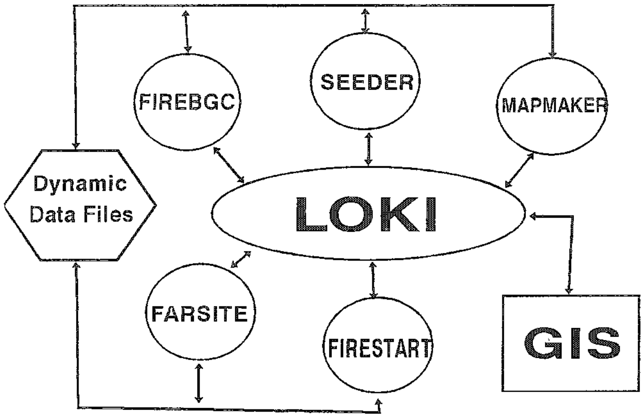


Fig. 1. Modeling flow diagram of the mechanistic process model Fire-BGC (abbreviations: C—carbon, N—nitrogen, H_2O—water).

The Fire-BGC mechanistic simulation accounts for the flux of carbon, nitrogen and water across various ecosystem components (Figure 1). Carbon is fixed by tree needles via photosynthesis using solar radiation, temperature, and precipitation inputs, and then the carbon is distributed to leaves, stems, and roots of individual trees based on leaf area and species ecophysiology. A portion of the leaves, stems, and roots are lost each year and accumulate on the forest floor in the litter, duff, and soil (Figure 1). These forest floor compartments lose carbon through decomposition. Nitrogen is cycled through the system from the available nitrogen pool. Carbon and nitrogen are allocated to each tree's stem, roots, and leaves at year's end. Stem carbon allocation is used to calculate diameter and height growth.

Fire-BGC has a mixed temporal and spatial resolution built into the simulation design. Primary canopy processes of interception, evaporation, transpiration, photosynthesis, and respiration are simulated at a daily time step. Secondary canopy processes of carbon and nitrogen allocation are accomplished at a yearly time step. Tree mortality, regeneration, and growth are computed annually whereas seed dispersal is simulated at approximately ten-year time steps. Ecosystem processes that occur at the landscape level, such as seed dispersal and fire, are modeled in spatially from GIS raster data layers using external programs directly linked to Fire-BGC. Stand-level processes, such as tree growth and regeneration, are modeled independently of the spatial environment. Dynamic databases provide



LOKI FIREBGC Application

Fig. 2. Diagram of the various models and software packages used in the Fire-BGC Glacier National Park application of the Loki simulation platform (abbreviations: GIS—Geographic Information System).

the linkage between landscape, stand, and tree level process simulation.

Five hierarchical levels of organization are implemented into Fire-BGC design. The coarsest level is the simulation landscape that is divided into static delineations called sites that have similar topography, soils, weather, and potential vegetation. Each site is divided into stands that are different in vegetation composition and structure. By definition, stand boundaries cannot extend past site boundaries but can change within a site. Fire-BGC simulates ecosystem processes in a small portion of the stand called the simulation plot because of computation limitations. Any number of species can inhabit a stand, and species composition influences many modeled processes such as canopy dynamics and tree regeneration. The finest level of organization is the tree and each tree within a simulation plot is explicitly represented in the Fire-BGC architecture. Many attributes of each tree, such as leaf carbon, diameter, and height, are recognized in Fire-BGC. However, these trees are not spatially defined in the model.

Fire-BGC was written in the C programming language using a modular approach based on organizational levels implemented in model design (Keane et al. 1996a). Relationships and parameters are shared across modules as objects or functions. The program was developed on a SUN Sparc Model 10 workstation with UNIX operating system and accesses several software packages and databases during execution.

The Fire-BGC Application

The Loki simulation architecture is used to link and schedule execution of the Fire-BGC program and associated models SEEDER (seed dispersal model), MAPMAKER (an ecological mapping routine), FIRESTART (a fire occurrence simulator), and FARSITE (fire growth model, Finney 1994) at the appropriate time intervals (Bevins et al. 1994, Bevins and Andrews 1994, Figure 2). Loki also provides routines for Fire-BGC and other models to query, modify, and create digital landscape maps during simulation. The GRASS spatial Geographic Information System (GIS) package is used for organizing, displaying, and analyzing raster files created by Loki (USA CERL 1990). The coupling of these models in Loki to simulate long-term ecosystem dynamics is called the Fire-BGC application.

Occurrence and points of origin of simulated fires are stochastically predicted each year on the simulation landscape using the model FIRESTART (Figure 2). FIRESTART uses site-level fire frequency inputs to compute a probability of fire ignition for each pixel (Keane et al. 1989, Keane et al. 1996b). Fire occurrence is computed from fire frequency probabilities calculated from Weibull probability distributions and average fire size estimates (Van Wagner 1978, Baker 1989, Fox 1989, Johnson 1979, Marsden 1983, Johnson and Van Wagner 1985).

The fire growth model FARSITE (Finney 1994) is called by Loki routines to spatially simulate fire intensity and spread rate from the points of origin provided by FIRESTART. FARSITE uses the fire behavior models of Albini (1976) and Rothermal (1972) to simulate fire spread and intensity as it moves across a heterogeneous landscape. The model uses spatial data layers of topography, surface and crown fuels, and weather to predict fire behavior. Topography is described by a digital elevation model (DEM) raster layer imported to Loki and made available to all linked models. Fuel biomass is computed from carbon pools comprising the forest floor compartments in Fire-BGC. Stand structure values required by FARSITE are taken from simulated stand attributes explicitly computed by Fire-BGC. FARSITE creates a raster layer of computed fire intensity (kilowatts meter^{-1}) that Fire-BGC then uses to create new stands in areas where fire intensity is greater than a user-defined threshold (i.e., burned-over areas). Fire effects at the stand- and tree-level, such as fuel consumption and tree mortality, are calculated from fire intensity estimates averaged across all pixels within the burned stand.

The probability that a tree species will disperse seed to each simulation stand is computed by the model SEEDER (Figure 2). Seed production potential by species is computed from number of cone-producing trees on each simulation stand by Fire-BGC. SEEDER obtains these statistics from the dynamic stand data file mentioned above. Then, probability of seed dispersal to every landscape pixel is computed using a form of the McCaughey et al. (1985) equations for tree species whose seeds are wind-dispersed. Probabilities of seed dispersal for the bird-disseminated whitebark pine seed are calculated from the Tomback et al. (1990) equation.

Study Area

The McDonald and St. Mary Drainages of Glacier National Park, Montana (MDSM-GNP) are long, narrow, glaciated valleys surrounded by rugged mountains that contain large lakes at the base of each wa-

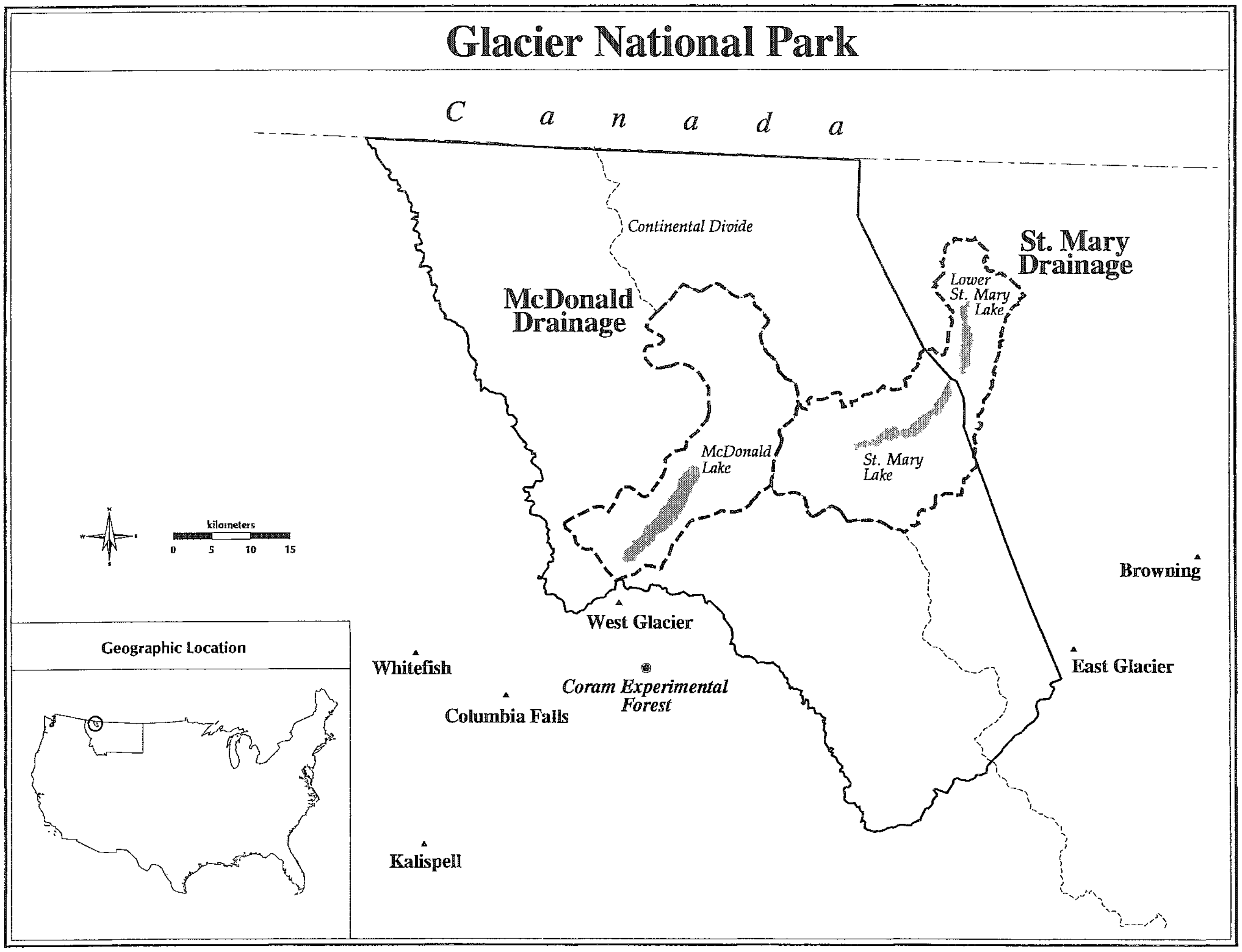


Fig. 3. The McDonald and St. Mary watersheds (MDSM-GNP) study area, Glacier National Park, Montana.

tershed. They join at the Continental Divide and flow west and east from Logan Pass (Figure 3). These 45,000 hectare landscapes are distinctive in the Northern Rocky Mountains because of their great diversity in vegetation, topography, and climate. Relatively warm, moist forest environments support western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*) at low elevation, lakeside settings in the McDonald watershed, while subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engelmannii*) forests are common in low areas in glacial valleys subject to cold air ponding, like the St. Mary's watershed east of the continental divide (Habeck 1968). Western larch (*Larix occidentalis*), western white pine (*Pinus monticola*), interior Douglas-fir (*Pseudotsuga menziesii* var *glauca*), and lodgepole pine (*Pinus contorta* var. *contorta*) comprise the McDonald-drainage mixed forests at lower elevations, but most St. Mary lower elevation stands are primarily composed of lodgepole and subalpine fir (Habeck 1970b, Kessell 1979). Upper subalpine forests consist primarily of subalpine fir, Engelmann spruce, and whitebark pine (*Pinus albicaulis*) in both drainages (Habeck 1970b). Krummholz conifer and forb meadow communities are found in the alpine environments (2200 to over 3000 meters elevation) (Habeck and Choate 1963, 1967). Aspen (*Populus tremuloides*) and Douglas-fir communities are common at the eastern edge of the St. Mary drainage.

Climate is quite variable across the McDonald and St. Mary watersheds. McDonald watershed climate is mostly inland-maritime with cool, wet winters and short, warm-dry summers (Finklin 1986). Average annual precipitation ranges from 760 millimeters at West Glacier (Figure 3) to over 1,980 millimeters at Flattop Mountain (Finklin 1986). Maximum July daily temperatures range from 28°C in the valleys to 24°C at 2000 meters elevation. Climate in the St. Mary drainage is distinctly continental with dry, cold winters and warm, dry and often windy summers (Finklin 1986). Average annual precipitation ranges from 1,700 millimeters at Logan Pass and 40 millimeters at St. Mary, and maximum July temperatures range from 26°C around the bottom of the watershed to 20°C at Logan Pass. However, the differences in climatic extremes seem to be primarily responsible for the differences in vegetation across the watersheds (Habeck 1970b). Killing frosts, extreme wind events, and desiccating Chinook winds are more frequent in the continental climate of the St. Mary drainage (Finklin 1986).

Two distinct fire regimes are evident on the MDSM-GNP landscape, although there is little detailed knowledge of the fire history in the St. Mary drainage. Large, stand-replacement fires were most common over the last four centuries on moist MDSM-GNP sites with return intervals of 120 to 350 years (Barrett et al. 1991, Habeck 1970b). Some sites in the drier areas of MDSM-GNP contain evidence of surface fires of variable severities with approximately the same return intervals (Barrett et al. 1991, Barrett 1986). This "mixed" fire regime has fires that kill all trees in some areas, as well as nonlethal underburns that kill only small trees and fire-intolerant species in other areas (Habeck 1970a). The complex topography of MDSM-GNP has considerable influence on fire behavior and effects. Fire behavior and pattern are strongly influenced by the spatial arrangement of fuels on the landscape. Rocklands with little woody fuel impede fire spread across and within watersheds. Moist conditions on north-facing slopes often prevent spread of fire from the drier south-facing slopes (Habeck 1970a). Fuel discontinuity across alpine and rocky environments is probably a major determinate of landscape structure in both drainages.

Simulation Methods

Many site and stand spatial data layers were needed to initialize the simulation landscape for the MDSM-GNP application of Fire-BGC (Keane et al. 1996a). Ecosystem attributes characterizing these data layers were quantified from an extensive ecological inventory of the MDSM-GNP performed during the 1993 to 1995 summer field seasons. Details of field data collection and raster map creation are presented below.

Field Data Collection

Ecological characteristics of important plant communities present in MDSM-GNP were evaluated from 110, 0.04 hectare circular plots established in representative portions of stands that characterize communities based on species composition, stand structure, and biophysical environment. (Keane et al. 1990b). Site descriptions, tree structure and composition, duff, litter, and woody material loadings, and undergrowth species canopy cover were measured on each plot using ECODATA methodology (Keane et al. 1990b, Jensen et al. 1993). Leaf area index was measured on each plot using both a Sunfleck Ceptometer (Pierce and Running 1988) and a LI-COR LAI-2000 (Welles and Norman 1991). A small soil pit was excavated at each plot to determine soil depth and texture, and a sample of soil was taken for analysis of soil water-holding capacity. Each plot was georeferenced using a Global Positioning System (GPS) receiver. Another 98 ground-truth plots were established across both drainages during the summer of 1995 for validation of satellite imagery classifications discussed later.

Site Data Layer Creation

Sites that compose the MDSM-GNP simulation landscape were delineated as potential vegetation types (Pfister et al. 1977) using satellite imagery, topography, and plant autecology information (Minore 1979). Plant community information from Kessell's (1979) gradient model and the mentioned sampled field data were used to map the most shade-tolerant (i.e., climax) tree species' distributions across the study area (Keane et al. 1996b). Potential vegetation was first coarsely predicted spatially from several environmental gradients including elevation, aspect, landform position, and slope (Kessell 1979) using GRASS GIS software (USA CERL 1990). Ranges of some important topographic variables are shown in Table 1. The site classification was then refined using MDSM-GNP field data and a spectral classification of satellite imagery.

A July 15, 1990 Thematic Mapper (TM) scene was classified to several forest, shrub, herb, and rockland cover categories using an unsupervised approach with MDSM-GNP field data. The field data were used to characterize and validate the spectral classification. This land cover classification improved the topographic model by identifying permanent shrubfields, herblands, glaciers, lakes, and rocklands. Some nonforested lands, especially those in high elevations (above 1,600 meters elevation) were assumed to be incapable of maintaining tree cover due to heavy snow and cold conditions based on field data and literature (Habeck 1970b). Below 2,000 meters these shrub and herb lands were assumed to be early seral stages of forest potential vegetation types. A comparison of the final MDSM-GNP site classification with georeferenced field data showed the layer is approximately 74% accurate. Fire-BGC inputs that describe each classified site were derived from field data using an average of all plots keyed to each site. Model parameters not sampled, such as understory species ecophysiological parameters, were summarized from current literature citations (Keane et al. 1996b).

Stand Data Layer Creation

A spatially explicit, raster map of dominant vegetation types based on a plurality of canopy cover was generated from the same TM imagery using a more detailed supervised image classification. Field data and Kessell's (1979) gradient model were again used to assign cover type descriptions based on the spectral classification. This cover type raster map was combined with the site layer to produce a raster layer of stands hierarchically nested within the sites.

Fire-BGC input data and parameters that describe classified stands were taken from field data using one plot that best represented each stand. Tree age and size structure data measured on the field plot representative of each cover type/site combination were entered into Fire-BGC tree input tables for each stand. Most other stand level input data such as fuel loadings and understory biomass were either quantified from the plot data or from available literature (Habeck 1970b).

Table 1. Topographic and fire regime description used to map Fire-BGC sites on the MDSM-GNP landscape.

Site ID	Site name[1] (potential vegetation type)	Aspects (°)	Slopes (%)	Elevation range (m)	Historical fire frequency (years)	Future fire frequency (years)
1	TSHE/THPL	270–120	<70%	915–1370	300	250
2	TSHE/THPL	120–270	10 to 70%	915–1525	250	208
3	Lower Subalpine North Aspect	270–120	<70%	1370–1830	150	125
4	Lower Subalpine South Aspect	120–270	10 to 50%	915–1980	150	125
5	Upper Subalpine North Aspect	270–120	10 to 50%	1830-2285	200	167
6	Upper Subalpine South Aspect	120–270	10 to 50%	1980-244(0)	200	167
7	Dry PSME	220–270	0–90%	1340–1465	70	58
8	ABLA/CLUN	All	All	1340–1705	250	208
9	ABLA/XETE	120–270	5–90%	1705–1980	200	167
10	ABLA/MEFE	270–120	5–90%	1705–1920	250	208
11	ABLA/LUHI	120–270	All	1980–2135	300	250
		270–120	All	1920–1075		
12	ABLA-PIAL	120–270	All	2135–2410	500	417
		270–120	All	2075–2380		
13	Shrub	All	All	All	200	167
14	Herb	All	All	All	500	417
15	Alpine	All	All	1980+	500	417
16	Rock	All	All	All	1000	833

[1] Site names are taken from Pfister et al. (1977). Species abbreviations are: ABLA-Abies lasiocarpa, TSHE-Tsuga heterophylla, THPL-Thuja plicata, PIAL-Pinus albicaulis, PSME-Pseudotsuga menziesii, CLUN-Clintonia uniflora, XETE-Xerophyllum tenax, MEFE-Menziesia ferruginea, LUHI-Luzula hitchcockii.

Simulation Scenarios

Consequences of altered fire regimes and changing climates were evaluated from the following Fire-BGC simulation scenarios as implemented on the MDSM-GNP landscape.

1. No Fires—Current Climate (NF-CC)—A fire exclusion scenario where all fires are successfully suppressed within the study area. Only the process of succession affects plant community composition and structure. This scenario simulates potential impacts of a fully successful fire exclusion program. Meteorological data from 1950 to 1994 are used to simulate the current climate.
2. Historical Fire Occurrence—Current Climate (HF-CC)—Fires are stochastically simulated on the study area at approximately the same frequency as they occurred prior to Euroamerican settlement (circa 1900) with weather from the last 44 years. This attempts to mimic current "natural" fire processes in MDSM-GNP study area.
3. No Fires—Future Climate (NF-FC)—A fire exclusion scenario using weather compiled from Ferguson's (1997) climate warming data set (discussed below). This scenario attempts to describe differences in ecosystem properties as the climate warms and all fires are suppressed.
4. Future Fire Occurrence—Future Climate (FF-FC)—Fires are stochastically simulated under a possible future fire regime scenario (discussed below) with the Ferguson (1997) climate warming data set.

Each scenario was simulated for 250 years using the same initial conditions at the start of model execution. No insect and disease epidemics were simulated in this application. Some questionable model parameters were adjusted during the initialization process to produce more realistic results based on preliminary model outcomes (Keane et al. 1996a). Ecosystem characteristics by stand are written to output files annually for subsequent analysis using other software analysis packages.

Climate Description

The current climate for each site was quantified from 44 years (1950–1994) of daily weather data taken from nearby West Glacier (McDonald Drainage) and Babb (St. Mary Drainage) National Weather Service Stations. These data were used to compute daily observations of temperature, humidity, solar radiation, and precipitation for each site using the MTCLIM climate model (Hungerford et al. 1989). Fire-BGC cycles the 44 years of weather data in sequence during the 250 years of simulation. This weather sequence was also used for the historic fire scenario (HF-CC) because of the lack of daily weather records prior to 1900.

Ferguson (1997) constructed a generalized future climate scenario for the Interior Columbia River Basin Scientific Assessment from summarized outputs of three Global Circulation Models (GCM's). This scenario was implemented in a program used to modify the current 44 year daily weather record to portray a future climate. This climate change scenario has warmer and wetter summers (approximately 2–5°C, 30% increase precipitation) and warmer, wetter winters (approximately 2–4°C, 25% increase precipitation). The future climate used in this study represents only one possibility of a global climate warming future and is not a prediction of future weather conditions.

Fire Occurrence

Historical fire-free intervals by site were taken from Davis (1981), Barrett (1986), Fischer and Bradley (1987), and Barrett et al. (1991, Table 1). Stand age distributions and fire scar information collected in this field study were also used to estimate site fire frequency. Average fire sizes and other Weibull parameters needed by FIRESTART were estimated from Johnson (1979), Clark (1990), Reed (1994), and from fire atlases compiled by Glacier National Park.

This Fire-BGC application did not contain a model that would explicitly simulate the effect of changing climate on fire frequency. Therefore, future fire regimes (Table 1) under the Ferguson (1997) climate change scenario were estimated mostly from the global change literature (Clark 1988, Overpeck et al. 1990, Peters 1990, Flannigan and Van Wagner 1991, Fried and Torn 1991, Ryan 1991, Balling et al. 1992, Kasischke et al. 1995). These sources speculate an 8 to 48% increase in historical fire occurrence mainly because predicted higher temperatures will prolong fire seasons. We estimate a 20% increase in fire frequency for all MDSM-GNP sites based on an analysis of the differences in fire weather for the summer months in both the current and future weather files. Fire history data from a fire history data base developed by Barrett (1988) were also used to refine future fire occurrence estimates (Table 1). This is only one possible portrayal of future wildfire dynamics and does not constitute an actual forecast of fire occurrence under new climatic conditions.

Table 2. Fire characteristics for the historical fire-current climate (HF-CC) and future fire-future climate (FF-FC) simulation scenarios.

Fire characteristic	Historical fire scenario (HF-CC)	Future fire scenario (FF-FC)
Number of fire years	15	18
Average fire size (hectare)	4,551	6,050
Fireline intensity (kilowatt meter^{-2})	903	3,055
Average flame length (meter)	2.2	3.1
Average scorch height (meter)	11.3	24.2
Fuel consumption (kilogram meter^{-2})	101.4	98.2
Landscape unburned (%)[1]	45.8	39.6
Area with multiple burns (%)[2]	17.1	37.6
Total area burned (hectare)	68,273	108,896

[1] Percentage of the simulation area that did not burn over the 250 simulation years.

[2] Percentage of the simulation area that burned more than once.

Model Output

The MAPMAKER program included in the Loki Fire-BGC application (Figure 2) was used to create and summarize spatial distributions of important vegetation characteristics and dead organic biomass dynamics. The vegetation characteristics include the proportion of the MDSM-GNP landscape dominated by shade-tolerant tree species, basal area, standing biomass, and net primary productivity (NPP). Dead organic biomass descriptors include downed, dead twigwood and branchwood (less than 12 centimeters in diameter) loading, duff depth, snag density, and coarse woody debris loading. Dominant species classification is computed as the tree species with the majority of basal area (meters^2 hectare^{-1}), and tree species categorized as shade-tolerants include western hemlock, western red cedar, subalpine fir, and spruce (Minore 1979). Shade-intolerant species were western larch, lodgepole pine, Douglas-fir, whitebark pine and aspen (Minore 1979). Standing biomass (Megagrams hectare^{-1}) is defined as aboveground tree and undergrowth biomass and includes only leaf and stem components. Duff depths (centimeters) include both duff and litter layers. Coarse woody debris is described as downed logs over 12 centimeters in diameter. Spatial and temporal distributions of these predicted characteristics are summarized in this paper. Ouput maps are not presented due to space limitations but are available from the authors.

Model Test and Verification

Few data were available to compare long-term model predictions with actual conditions observed in MDSM-GNP. However, needlefall, leaf area, stemwood growth, and woody fuel accumulation were measured on two high elevation stands established on south- and north-facing aspects, and two low elevation stands on south and north slopes from 1993 to 1995. These four permanent plots were established in the Coram Experimental Forest adjacent to Glacier National Park on sites that were ecologically similar to many areas in the MDSM-GNP landscape (Keane et al. 1996b). Temporal measurements for each plot were compared to Fire-BGC predictions for that plot for the year 1994. The Fire-BGC simulations used ecological information gathered for these plots as initial conditions and also for quantification of some model parameters.

RESULTS

Fire and Landscape Dynamics

The FIRESTART model simulated 15 fire years (24 separate fires) under the historical fire occurrence (HF-CC) scenario and 18 fire years (22 fires) under the future fire occurrence scenario (FF-FC) over the 250 years of simulation (Table 2). Fires simulated under the current climate (HF-CC) tended to be smaller and less intense, and these fires burned a much smaller portion of the landscape (Table 2). Crown fires were prevalent under the future fire scenario (FF-FC) resulting in high fireline intensities and high fuel consumption. Fires were more intense in the productive, low-elevation sites because of the high fuel loadings and the great amounts of crown biomass in the stands. Simulated scorch heights were seldom small enough to allow the survival of fire-tolerant trees. Therefore, most wildfires killed all trees in a stand (stand-replacement) and created nonforest patches on the landscape. This was especially true for the future fire (FF-FC) scenario. The simulated fire rotation of 315 years for the historical scenario agreed well with Glacier National Park fire histories (Barrett 1986, Barrett et al. 1991). The future fire scenario had a simulated fire rotation of 213 years, which was lower than the expected 235 years as computed from Table 1.

Fires burned a majority of the MDSM-GNP landscape after 250 years of simulation with 46% remaining unburned under the historical fire regime while only 39% was unburned at the end of the future fire simulation (FF-FC) (Table 2). Some areas (17%) were burned more than once under the HF-CC scenario. However, this proportion more than doubled to 37% under the future fire scenario (FF-FC). South-facing, low elevation sites in the St. Mary Drainage (Sites 7 and 8, Table 1) tended to have more multiple fires, especially under the FF-FC scenario. Some areas in Site 7 (Dry Douglas-fir) at the eastern edge of the St. Mary Drainage experienced five fires over the 250 years of future climate simulation, which corresponded well to the input fire frequency of 58 years for that type (Table 1). Fires simulated under the future fire and climate scenario (FF-FC) burned across many nonforested areas, such as alpine and upper timberline, that rarely burned under current climate conditions. This is probably because the high productivity under a future climate regime results in greater biomass on the landscape thereby allowing fire to spread across areas that normally would not have enough fuel to carry fire.

Vegetation Characteristics

Major characteristics of the MDSM-GNP vegetation are contrasted in Figures 4a to 4e over the 250 years of simulation. Net primary productivity (NPP) predictions are compared across landscapes with and without fires for the current climate in Figure 4a and for the future climate in Figure 4b. Landscapes without fire (NF-CC, NF-FC) appear to have higher productivities over the simulation, but this is because a larger majority of the productive land is in early seral shrub and forbfields on landscapes with fire (HF-CC, FF-FC). These communities have lower leaf areas than developed forests and therefore often have lower productivities. Landscapes with fire (HF-CC, FF-FC) appear to have about 20 to 30% less standing biomass than landscapes where fires were excluded (Figure 4c), and landscapes that develop under the future climate scenario have approximately 5 to 10% higher biomass than landscapes experiencing the current climate. Average basal area across the 250 years is highest under the warmer, wetter future climate with no fires (Figure 4d) and is lowest under the historical fire regime with current climate (HF-CC). Fires reduce landscape basal area by killing trees and keeping a large portion of the landscape in the early seral conditions with sapling and pole size trees.

The percent of the MDSM-GNP landscape composed of communities dominated by shade-tolerant and shade-intolerant tree species is portrayed across the 250 year simulation period for the four scenarios in Figures 4e and 4f. Shade-tolerant tree species usually dominate the later stages of succession, and, as expected, landscapes where fire was excluded had a higher proportion of shade-tolerant tree communities (Figure 4e). The highest proportion of shade-intolerant (i.e., seral) tree cover types occurred under fire exclusion and future climate (NF-FC). Landscapes that experienced fire (HF-CC and FF-CC) have nearly the same proportion of land in the shade-intolerant type.

Dead Organic Biomass Description

Predicted downed woody fuel loadings are depicted in Figures 5a and 5b for small twigwood and branchwood (material less than 12 centimeters diameter) and coarse woody debris (greater than 12 centimeters diameter), respectively. Trends are nearly the same for both classes of woody fuels with the highest fuel loadings predicted under a future climate with no fire (NF-FC). Landscapes with fire (HF-CC and FF-FC) tend to have approximately the same amount of coarse and fine woody fuels regardless of climate. The large gains in woody fuel loadings are usually a result of large mortality events in the low elevation forests.

There appears to be no difference in the abundance of snags on the MDSM-GNP landscape across the four simulation scenarios (Figure 5c). Snags are extremely high at the beginning of the simulation because of some large mortality events that occurred during the first 50 years of simulation, probably because of inappropriate parameterization. However, the number of snags reaches realistic densities by simulation year 125. Duff depth predictions are shown in Figure 5d with the deepest duff occurring on landscapes without fire (NF-CC and NF-FC). Duff depths are approximately 20 to 30% lower on landscapes where fire is simulated. Simulated duff thicknesses are high because some site-level litter and duff bulk densities parameters used to estimate depth are probably inappropriate.

Model Test

Predicted ecosystem characteristics compared well with those attributes measured on the four Coram Experimental Forest plots (Table 3). Annual needlefall predictions were higher than observed values probably because leaf longevity input parameters were underestimated for subalpine fir and western hemlock. Woody fuel accumulations included only material less than 7 centimeters in diameter, and the predictions seemed close to measured values, especially for the high elevation plots. Predicted stemwood production was low because the predicted leaf areas were also low and this meant less photosynthesis and less carbon available for stem growth (Table 3). Fire-BGC did not accurately calculate the Leaf Area Index (LAI) for two

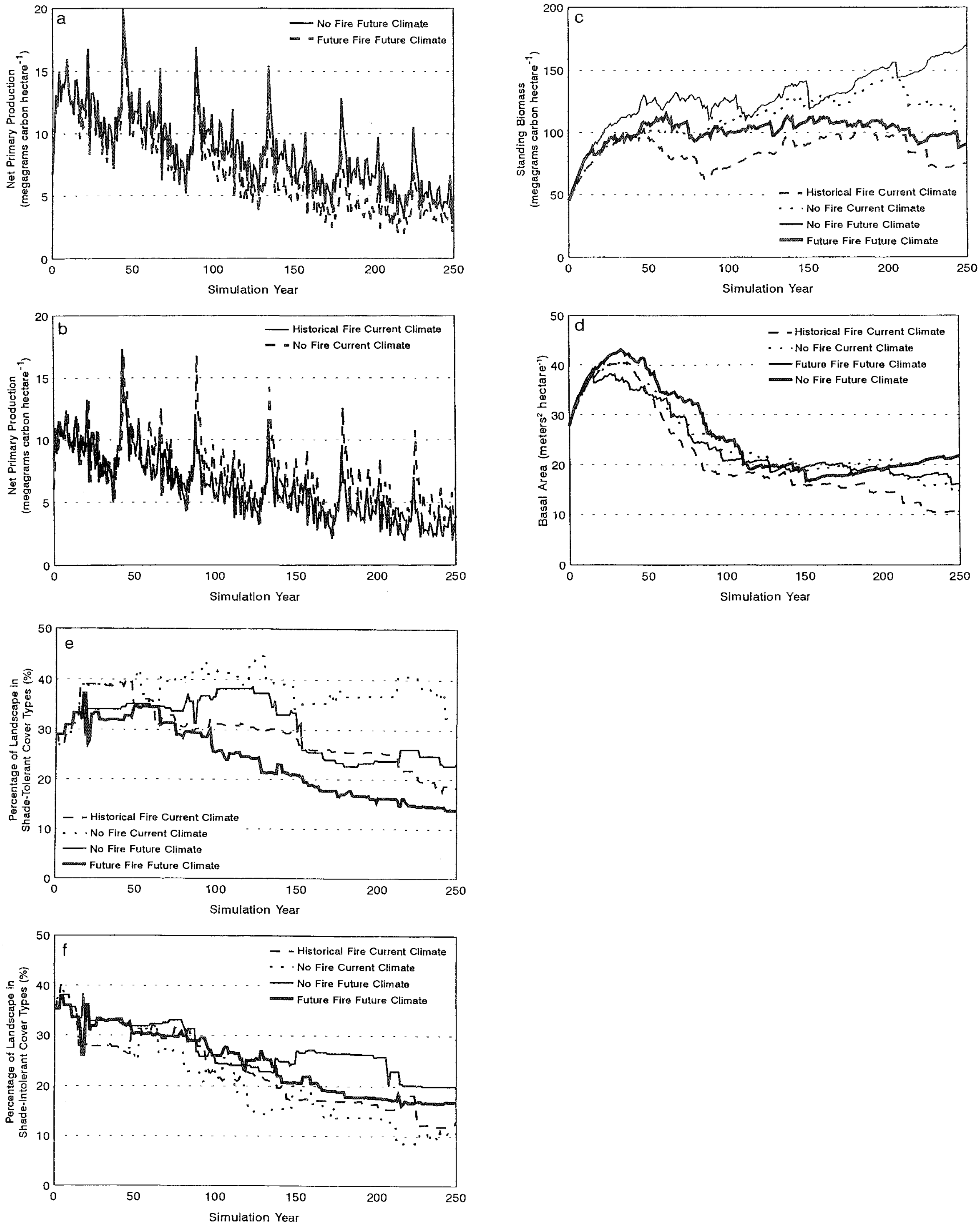


Fig. 4. Fire-BGC predictions of important vegetation characteristics over the 250 years of simulation contrasted across the four scenarios. (a) net primary productivity (NPP, Megagrams Carbon per hectare) for current climate, (b) net primary productivity (NPP, Megagrams Carbon per hectare) for future climate, (c) standing biomass (Megagrams Carbon per hectare), (d) tree basal area (meters^2 per hectare), (e) percent of landscape dominated by shade-tolerant tree species (%), (f) percent of landscape dominated by shade-intolerant tree species (%).

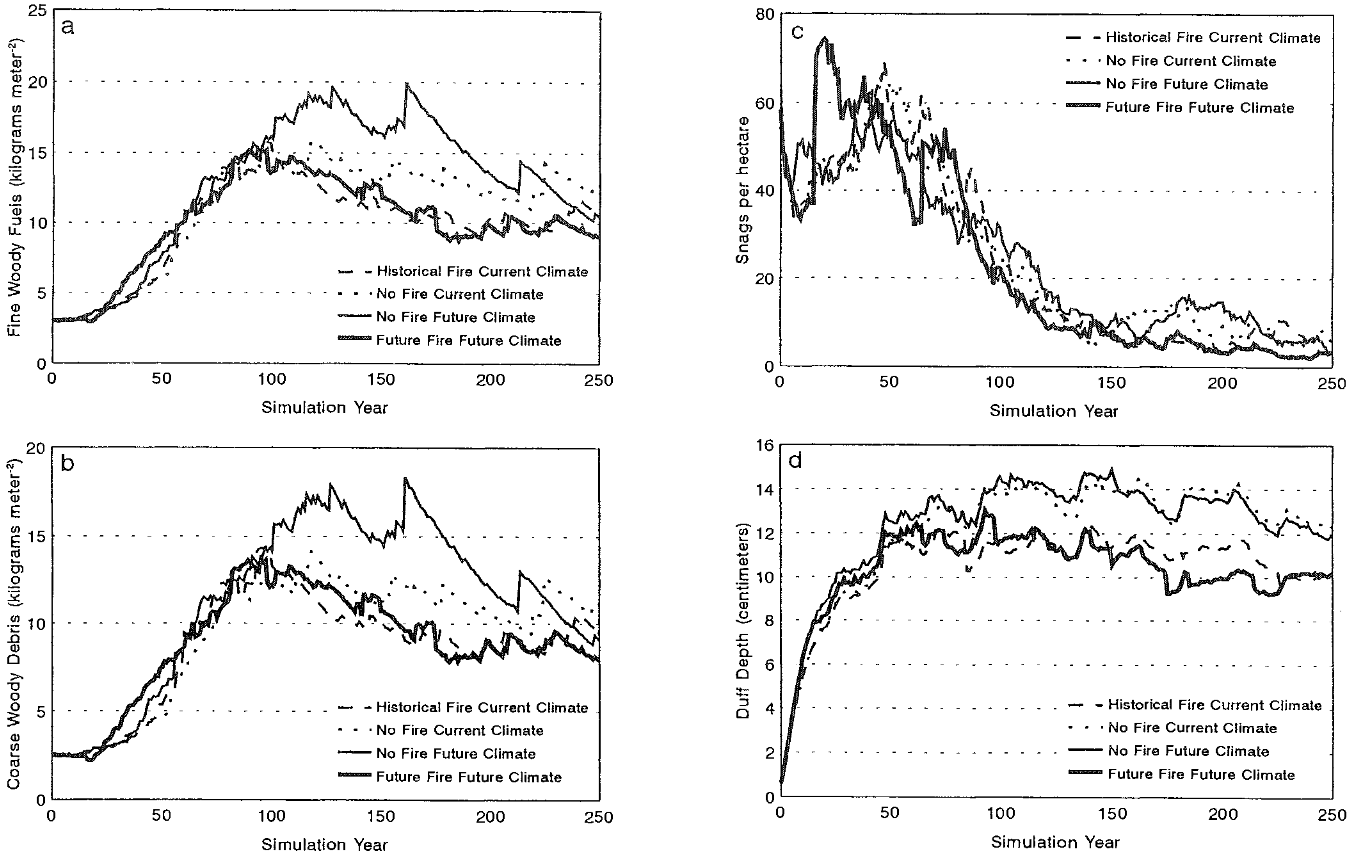


Fig. 5. Fire-BGC predictions of important dead organic matter characteristics contrasted across the four scenarios for the 250 year simulation period. (a) Down woody twig and branchwood (kilograms per meter²), (b) Coarse woody debris (logs, kilograms per meter²), (c) Snag density (dead trees per hectare), (d) Duff depth (centimeters).

reasons. First, the crown weight allometric equations developed by Brown (1978) and used by Fire-BGC to compute leaf area (Keane et al. 1996a) were probably not accurate for some dense stands. Second, the LAI-2000 device used to measure LAI in the field does not accurately estimate LAI for forested communities with an abundance of stem and branchwood (Welles and Norman 1991). A comparison of predicted ring widths with ring widths measured from Glacier National Park found shade-intolerant tree growth is difficult to predict (Keane et al. 1996b). But overall, tree growth is simulated within 30% of observed ring widths.

DISCUSSION

Fire

Wildland fire has been and will continue to be a fundamental disturbance process that defines landscapes and influences ecosystem properties. This is evidenced from the 250 years of Fire-BGC simulation where fires burned over 55% of the MDSM-GNP landscape under a current climate regime and 67% under the future climate scenario (Table 3). Moreover, a large portion (37%) of the landscape burned more than once under the future climate scenario (Table 2), and about 1,000 hectares experienced seven burns. Although fire-dominated landscapes tended to retain the more productive early and mid-seral communities, the overall net primary productivity was less because the frequent disturbance tended to reduce leaf areas and photosynthetic capacity. The distribution of productivity on the landscape may be important to many wildlife species including grizzly bears and ungulates. The fire exclusion scenarios presented here are highly unlikely because, despite attempts to exclude fire, severe fires continue to occur in Glacier National Park (Barrett et al. 1991).

The majority of simulated fires were stand-replacement where entire stands of trees were killed. Other low severity fires only killed tree species and sizes that have little fire resistance and were unable to survive such burns (Ryan and Reinhardt 1988). Some fires, in both the current and future climate scenarios, had a mixed fire severity and left a patchy burn pattern on the landscape. Simulated fires in warmer, wetter climates (FF-FC scenario) were more intense and severe (Table 2) than fires simulated under the current climate (HF-CC). This may indicate that future fires could be more dangerous and more difficult to suppress, especially in severe fire seasons. And, not only were fire intensities nearly three times greater under a future climate, but scorch heights more than doubled. This may mean that few fire-tolerant tree species will be able to survive these intense fires which could result in a landscape composed of tree species that are the

Table 3. Fire-BGC simulation results (Pre=Predicted) compared to actual measurements (Obs=Observed) from the four ecosystem plots established on the Coram Experimental Forest, Montana.

	Low elevation plots				High elevation plots			
	South		North		South		North	
Ecosystem characteristic	Obs	Pre	Obs	Pre	Obs	Pre	Obs	Pre
Needlefall (grams meter^{-2})	107	89	106	120	19	33	33	59
Woody fuel accumulation (grams meter^{-2})	13	8	16	11	8	9	2	2
Soil respiration (grams carbon meter^{-2})	578	337	810	482	720	385	554	286
Stemwood production (kilograms carbon hectare^{-2})	693	660	1208	997	321	428	206	160
Leaf area index (meter^{2} meter^{-2})	2.9	2.1	3.2	3.7	1.4	1.3	2.8	2.7

best colonizers in a postburn setting rather than tree species adapted to survive fires (Overpeck et al. 1990).

Simulated fires under the future weather scenario were intense and extensive because of a combination of warmer weather, higher fuel loadings, and more contiguous fuels. Fire season temperatures could be 1–3°C higher than current conditions. The simulated increase in precipitation, coupled with higher temperatures and longer growing seasons, caused a 5 to 20% increase in productivity (NPP) across the entire MDSM-GNP landscape (Figure 4a and 4b). This, in turn, resulted in an increase of litter and woody fuel loadings on the forest floor (Figure 5a and 5c). And, since this increase in fuel loading was occurring across the entire landscape, there were increasing portions of the landscape that had enough fuels to carry fire. Areas that rarely experienced fire and functioned more as a fuel break historically, such as the upper subalpine and alpine zones, were now able to carry fire into the next forested area or next drainage.

Landscape Characteristics

Average annual estimates of the important structural and compositional characteristics of the vegetation on the MDSM-GNP landscape are quite different across the four scenarios (Table 4). Nearly all landscape attributes are greater when fires are not included in the simulation, mainly because fire kills trees and consumes living and dead biomass. Basal area, standing biomass, and crown closures are computed from tree compositional and structural attributes, so any disturbance that removes trees and creates early seral communities will reduce these characteristics. However, NPP estimates are related to both leaf areas and structural characteristics. Early to mid-seral stands of trees have somewhat high NPP predicted values because of high leaf areas coupled with low respirative demands of the small but actively growing trees. In fact, landscape estimates of NPP are 10 to 20% greater than Table 4 values if only stands with greater than 10 meter^{2} hectare^{-1} are included in the analysis.

Shade-intolerant tree cover types dominate fire-excluded landscapes under a future climate scenario (Figure 4f) primarily because sites that were nonforested under the current climate, such as alpine and shrubfields, are now experiencing tree invasion under the warmer, wetter climate regime. In addition, the new climate seems to be more favorable for growth and establishment of some shade-intolerant tree species including western larch and Douglas-fir. Fires occurring in the future climate seemed to be so severe that most forest and nonforest sites are primarily composed of shrubs or herbs (Table 4). It seems obvious that shade-tolerant species will dominate the landscape without fire for up to 250 years, and early seral species will continue to decline under the current climate (Figures 4e and 4f). This results in homogeneous landscapes that are more prone to insect and disease infections, and more susceptible to large, stand-replacement fires (Mutch et al. 1993).

A comparison of average dead organic layer attributes across the four scenarios reveals some interesting consequences (Table 5). Organic necromass tends to accumulate on the forest floor in the absence of fires

Table 4. Vegetation characteristics predicted by Fire-BGC compared across all scenarios. Values are annual estimates averaged across the entire 250 year simulation period.

Vegetation characteristics	No fires— current climate (NF-CC)	Historical fires— current climate (HF-CC)	No fires— future climate (NF-FC)	Future fires— future climate (FF-FC)
Shade intolerants[1] (%)	20.1	29.4	27.2	24.7
Shade tolerants[1] (%)	38.1	22.4	30.7	23.8
Basal area (meter^{2} hectare^{-1})	24.9	21.3	26.0	24.3
Standing biomass[2] (megagrams carbon hectare^{-1})	110.9	84.7	127.9	100.1
Net primary productivity—NPP (megagrams carbon hectare^{-1})	7.1	6.2	8.7	7.2
Leaf area index (meter^{2} meter^{-2})	5.3	4.5	5.8	4.8
Crown closure (%)	34.0	30.8	34.1	30.9

[1] Percent of the MDSM-GNP landscape composed of tree species that are shade tolerant or intolerant. Shade tolerants: western hemlock, western red cedar, subalpine fir, and spruce. Shade intolerants: ponderosa pine, Douglas-fir, western larch, lodgepole pine, whitebark pine, quaking aspen. Remaining percentage of landscape in non-forest cover type.

[2] Standing biomass is the average annual amount of carbon in the aboveground biomass at the end of a simulation year.

Table 5. Dead organic matter characteristics predicted by Fire-BGC compared across all scenarios. Values are annual estimates averaged across the entire 250 year simulation period.

Dead organic matter characteristics	No fires— current climate (NF-CC)	Historical fires— current climate (HF-CC)	No fires— future climate (NF-FC)	Future fires— future climate (FF-FC)
Woody twig and branch[1] (kilograms meter^{-2})	9.5	9.9	12.7	10.0
Coarse woody debris[2] (kilograms meter^{-2})	11.1	8.7	11.3	8.9
Duff depth (centimeters)	12.3	10.5	12.4	10.3
Snag density (snag hectare^{-1})	24.6	23.3	24.9	23.0
Duff and litter loading (megagrams carbon hectare^{-1})	1.8	1.4	1.9	1.6

[1] Fine woody material includes twigs, branches and logs under 12 cm diameter.
[2] Logs greater than 12 cm in diameter.

because of the relatively slow decomposition rates in most of Glacier National Park (Habeck 1968, Keane et al. 1990a, Waring and Schlesinger 1985). Fire is the primary factor for reducing forest floor material and releasing important nutrients needed for forest growth (Heinselman 1981). Therefore, landscapes simulated without fire tended to have more fine and coarse woody debris and greater duff and litter depths and loadings at a stand level, and these higher loadings occurred over a larger portion of the landscape (Table 5). High fuel loadings could create the potential for fire regimes of high-intensity crown fires that could severely burn larger portions of the landscape that may have occurred infrequently prior to 1900.

Snag densities simulated by Fire-BGC depict little differences between simulation scenarios (Table 5). There were major tree mortality events during the first 100 years of Fire-BGC simulation that caused the high snag recruitment (Figure 5c). This was a result of inaccurate or incompatible input parameters and algorithms (Keane et al. 1996b). Also, the snag retention and decomposition algorithm implemented in Fire-BGC does not as yet seem to replicate snag dynamics in an acceptable manner. Further work on this routine is necessary to investigate snag populations in future landscapes.

Simulation Limitations

Results generated from this Fire-BGC application represent only one set of possible future ecosystem predictions and are not actual projections of ecosystem changes under climate warming and fire regime modification. One major source of prediction error may be that many initial conditions and model parameters were quantified from general data extrapolated to the study area. Weather data were taken from weather stations that were outside the simulation area. These daily observations, for both future and present climates, represented only 44 years of climate (18% of the 250 year simulation) which does not reflect the climatic range of variability over the last two centuries. MTCLIM weather extrapolations do not predict fine-scale micrometeorological phenomenon such as frost pockets or warm-air drainages that directly influence vegetation patterns in many MDSM-GNP settings (Habeck 1968, 1970a). Lastly, the initial landscape was described by only 60 stands over 16 sites for computational efficiency and this may be too general for accurately contrasting simulation scenarios.

Fire frequencies for historical and future fire scenarios (Table 1) were based on fire history studies conducted in either portions of the simulation area or stands that were adjacent to the MDSM-GNP drainages (Barrett et al. 1991). Although these areas are similar in terms of vegetation and soils, they differ from MDSM-GNP in topography, landscape structure, and human settlement that may directly affect fire regimes. Estimation of future fire regimes for this study was more qualitative than quantitative and does not represent a comprehensive analysis of the data that govern fire and its effects. Therefore, we believe it is the difference in simulated trends that is important in Fire-BGC results interpretation, rather than the comparison of absolute values.

Future and historical fire occurrence estimates were not mechanistically linked to climate and vegetation predictions. Fire occurrence should be predicted using a more intensive approach that simulates fire ignition from fuel moistures, daily weather, lightning strikes, and fuel loadings. Higher-scale vegetation and climate interactions must be more intimately linked to ignitions so fire regimes can be more dynamically simulated. However, the process of fire ignition is so complex that a mechanistic approach may be difficult because of the intricate detail needed to accurately simulate this system and the lack of information currently available to quantify the fundamental relationships. It may be difficult to mechanistically model fire ignition, fire spread, fire intensity, and fire effects in a comprehensive application, and then expect simulated fire regimes to mimic observed fire regimes on the landscape. Future versions of Fire-BGC will attempt to include a more detailed FIRESTART program that will be less stochastic and more mechanistic.

The input landscape layers created for this simulation exercise described current (circa 1995) MDSM-GNP forest floor and vegetation conditions after approximately 50 to 60 years of fire suppression (except for two fires that occurred about 30 years ago). This input landscape was probably not indicative of historical MDSM-GNP conditions, and imposing an historical fire regime scenario on these conditions may not accurately recreate historical ecosystem characteristics. Indeed, fire history and stand structure maps produced by Barrett et al. (1991) and Barrett (1986) indicate fire areas predicted by Fire-BGC are larger that those that occurred on the historical landscape. However, the current climate, historical fire regime scenario (HF-CC) might portray the possible effects of reintroducing, into the MDSM-GNP ecosystem, fires which are larger and possibly more intense.

The Fire-BGC and FARSITE simulation consumed enormous amounts of computer resources and time. Simulation of the HF-CC and FF-FC scenarios took over 700 hours (30 days) of computer time on a Sun SPARC 10 workstation. At times, FARSITE would simulate the spread of fire slower than the fire would have spread in real time. This intensive use of computer resources necessitated simplification of the construction and design of Fire-BGC input data. To increase simulation speed, the MDSM-GNP initial simulation area was classified to only 60 stands over the 16 sites on over 90,000 hectares. This probably does not accurately represent the diversity and structure of this complex landscape. The seed dispersal model SEEDER (Figure 3) was only executed once every 50 years and after each fire because it required over 4 hours of computing time.

Simulation results indicate 250 years was probably not sufficient to adequately investigate vegetation and fire dynamics on the MDSM-GNP landscape. Fire-BGC seems to need at least 50 to 100 years to reconcile the input data with algorithm parameters. Relative differences between scenarios would have been more marked if only the last 100 years of simulation were summarized (see Figures 4c and 4d). However, a century of simulation would not adequately portray successional dynamics for this area. The model should have simulated several fire rotations (600 to 1,000 years) to obtain more robust estimates of the change in ecosystem characteristics over time. Unfortunately, the time required to simulate 1,000 years on the current computer system would have exceeded 2 months for each scenario. Millennia simulation intervals will be possible as computer speeds increase and data storage media improve.

CONCLUSIONS

Fire-BGC is a useful tool for investigating successional dynamics on a landscape under changing climate and fire regimes. The mechanistic approach of Fire-BGC allows a comprehensive understanding of how important ecosystem processes interact with fire to form resultant landscapes. Fire-BGC simulations provide the detail needed to understand predicted landscape dynamics because the model integrates ecophysiological processes with tree growth, regeneration, and mortality. Predictions of vegetation and fuel conditions on future landscapes seem particularly relevant to investigate the consequences of fire, fire exclusion, and climate on ecosystem properties. A test of the model has shown that model predictions compare well with measurements taken on the Coram Experimental Forest.

The climate warming predicted to occur within the next 25 to 50 years will have a profound influence on Glacier Park ecosystems. Future vegetation communities probably will be more productive and have more living and dead biomass. Wildland fires allowed to burn on these future landscapes would be more intense and would burn larger areas. However, landscapes that evolve with fire, either the current or future climate, appear to have similar ecosystem characteristics through time. Fire seems to play an important role in ecosystem stability and function by recycling dead and living biomass and creating patchy mosaics on the landscape. The interaction of future climate and fires will presumably create a landscape composed of different plant assemblages than those of today. Because of the predictions of larger, high-severity fires in the future, it is hypothesized that species adapted to extensive migration and colonization of postburn settings will probably survive better than species adapted to survive fires. Moreover, a greater majority of the landscape will be in the early to mid-seral stages.

Future landscapes where fires are excluded are predicted to have high fuel loadings and standing biomass. Wildfires occurring on these landscapes will probably have high intensities and high severities, and therefore will probably pose a threat to human life and ecosystem health. Prescribed fire, already successfully used in Glacier National Park, will be an important tool to fire managers in the future for controlling the intensity, severity, timing, and smoke emissions from fires that burn on landscapes where fire has been actively suppressed.

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